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PERSPECTIVE

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Reviving Europe's rivers: Seven challenges in the implementation of the Nature Restoration Law to restore free-flowing rivers

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Abstract

The EU Nature Restoration Law represents an important opportunity for freshwater habitat restoration and, consequently, freshwater biodiversity protection. However, a number of challenges must be anticipated in its implementation, which may compromise its success. Some aspects, particularly those relating to freshwater ecosystems, require more clarification. We use riverine ecosystems to illustrate existing ambiguities in the proposed legislation and the potential consequences of leaving these aspects open to interpretation during the implementation process. We also discuss potential solutions to these problems which could help ensure that the law's objectives are met. We argue that river network structure and connectivity dimensions, which result into river meta-ecosystems, must be explicitly considered. For that purpose, we ask for clear definitions of the critical terms "free-flowing rivers," "barriers," and "reference areas." In addition, we recommend developing methods for integrated assessment of connectivity across river networks. As a key property of river ecosystems, this must be used to prioritize actions to increase the length and number of free-flowing rivers. Adequate restoration planning at larger spatial scales will benefit from a meta-ecosystem perspective and accurate representation of aquatic-terrestrial linkages, which will significantly improve the efficacy of restoration efforts. Furthermore, stakeholder and citizen engagement offer important opportunities at local, national, and European scales, and should be fostered to ensure inclusive decision-making. The conservation challenges outlined here are particularly important for rivers, but they also have implications for other ecosystems. These considerations are useful for policymakers, conservationists, and other stakeholders involved in the Nature Restoration Law and related policy initiatives.

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Water and Life > Stresses and Pressures on Ecosystems
Water and Life > Conservation, Management, and Awareness
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KEYWORDS

conservation, ecosystem functioning, European policy, freshwater biodiversity, river connectivity

1 | PROTECTING AND RESTORING RIVERS IS VITAL FOR BIODIVERSITY

Biodiversity is declining at an alarming rate, and human-induced degradation of natural habitats is one of the leading factors in this decline (Brondizio et al., 2019; Masson-Delmotte et al., 2022; Oberle et al., 2019; Pörtner et al., 2022). One of the greatest challenges that societies face today is halting and reversing global biodiversity loss so that ecosystems can continue to provide for human well-being (Bennett et al., 2015; Harper et al., 2021). Freshwater ecosystems are especially susceptible to human disturbance (Dudgeon, 2019; Vörösmarty et al., 2010), a situation that is expected to worsen in the future as a result of the combined effects of accelerating hydropower development as a renewable energy source, global water demand, and climate change (Erős et al., 2023). In fact, freshwater biodiversity is declining faster than that of terrestrial and marine systems (Harrison et al., 2018; Reid et al., 2019). Since centuries, European rivers have been fragmented by more than a million physical barriers, altering flow and sediment regimes, and interfering with the movement of organisms (Belletti et al., 2020; Grill et al., 2019). As a result, riverine ecosystems in Europe today

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lack vital hydromorphological dynamics and have a limited capacity for ecological rejuvenation (Buijse et al., 2005; Stoffers et al., 2021). Finally, both present and future global change will put additional strains on rivers, including warming, intermittency, and the facilitation of the spread of invasive or harmful species. In this context, methodical and widespread protection efforts (Hermoso et al., 2016; Watson et al., 2014), together with large-scale restoration actions, are urgently needed to combat the freshwater biodiversity crisis (Maasri et al., 2022; Piczak et al., 2023).

The EU recently approved the Nature Restoration Law (NRL), an unprecedented legislative effort that establishes specific ecological goals in order to combat biodiversity loss and ecosystem degradation. So far, the Birds Directive (BD; 2009/147/EC) and the Habitats Directive (HD; 1992/43/EEC) (Nature Directives), as well as the Water Framework Directive (WFD; 2000/60/EC), have established biodiversity targets at the European level. However, because the Nature Directives lack legal deadlines for achieving their objectives, they remain a weak motivator for immediate action. Moreover, within the Habitats Directive, there is a lack of clear motivation for biodiversity conservation or restoration concerning Annex I habitats and the protection of habitats for Annex II species located outside Natura 2000 areas. The WFD, on the other hand, has a legal deadline in 2027, although, it is unclear whether relying solely on water management authorities and on efforts to improve the aquatic environment will be enough to meet the WFD goals of ensuring good ecological status/potential for all surface water bodies by that time. According to the most recent water status report (European Commission, 2021), only 38% of European surface waters are in good chemical status, and only 40% are in good ecological status. When it comes to the conservation status of lake and river habitats in Annex I of the Habitats Directive, 78% of assessments indicate a poor status, and more than 22% of assessments indicate deteriorating trends compared to previous reports, with only 4% detecting improvements (EEA, 2020) (Table 1).

The European Commission proposed the NRL on 22 June 2022 to address ecosystem degradation and biodiversity loss through restoration targets and measures, and it was adopted by the European Parliament on 12 July 2023 after contentious debates and opposition from conservative fractions as well as from agricultural and fisheries lobbies. Interinstitutional negotiations ended on 9 November 2023, with a provisional agreement that significantly modified the Commission's initial proposal. The agreed text was approved in plenary on 29 November 2023, and now awaits formal adoption in early 2024. Although the political process is still ongoing, no changes to the law's content are expected. The NRL aims to help achieve the long-term biodiversity goals outlined in the EU Biodiversity Strategy 2030 (BDS2030) by restoring degraded ecosystems and maintaining them (including forests, wetlands, rivers, coastal and marine environments), as well as ensuring the connectivity and resilience of restored ecosystems through the development of habitat

TABLE 1 Key elements of the European Nature Restoration Law (European Commission, 2023).

Element	Description
Scope	The law applies to all European Union (EU) Member States and aims to restore and protect the region's natural habitats and biodiversity. The law is implemented without ratification by Member States.
Restoration Targets	The law establishes specific goals for restoring degraded ecosystems including forests, wetlands, rivers, and marine environments. Agricultural lands are exempt from the legislation.
Priority Areas	Priority restoration sites are identified as areas of high ecological importance, focusing efforts on their recovery.
Funding	Adequate financial resources, including EU funds and other available financing sources, are allocated to support nature restoration projects. Additional funding should be acquired from private and public funding at national and EU levels.
Monitoring and Reporting	Member States are required to monitor and report on the progress of restoration activities as well as the achievement of set goals.
Collaboration	To coordinate restoration efforts, the law emphasizes collaboration among Member States, stakeholders, and relevant organizations.
Ecological Networks	To ensure the connectivity and resilience of restored habitats, the establishment and protection of ecological networks is encouraged.
Invasive Species Control	Measures are put in place to prevent and control the spread of invasive species, which may negatively impact restored ecosystems.
Public Awareness	Initiatives are being launched to educate the public about the importance of nature restoration and the role that individual persons can play.
Penalties and Enforcement	The law contains provisions for penalties and enforcement mechanisms to ensure that restoration obligations and targets are met.

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networks and corridors, such as restoring 25,000 km of free-flowing rivers. This paper aims to provide a concise summary of the NRL's final version (assessed on 15 December 2023), with a focus on its implications for European riverine ecosystems and the restoration of freshwater biodiversity. We look into the connections between this NRL proposal and previous nature, biodiversity, and water policies and legislation. In addition, we identify key challenges and critical gaps that must be addressed in order for the law's objectives to be met during implementation.

2 | A NATURE RESTORATION LAW FOR RESTORING FREE-FLOWING RIVERS

The NRL combines a long-term goal for nature restoration on the EU's land, freshwater, and sea areas with binding restoration targets for specific habitats and species (overview in Supplementary Table 1). It includes restoration goals for European ecosystems in general, as well as for specific ecosystems and animal groups that are under severe pressure, such as rivers or pollinators. The general part of the proposal states the ambition to restore at least 20% of the EU's land and sea areas by 2030 and all ecosystems in need of restoration by 2050 (Article 1.2). Notably, this target falls short of the 30 × 30 target (30% of land/inland waters/sea restored by 2030) agreed upon by all countries during the 2022 COP15 biodiversity summit to address the ongoing global biodiversity crisis. The NRL aims to (1) put in place restoration actions for habitat types listed in Annex I HD that require restoration actions to achieve good status (Article 4.1), (2) re-establish habitat types listed in Annex I HD where these were lost (Article 4.2), and (3) re-establish habitats of the species listed in Annexes II, IV, and V of the HD and wild birds of the BD (Article 4.3). The most suitable restoration areas will be determined using the best available knowledge and the most recent scientific evidence of the condition of the habitat types listed in Annex I HD, as measured by their structure, functions, and presence of typical species, all of which are required for good long-term ecological functioning (Article 4.4). Furthermore, restoration measures must consider the need for improved connectivity among the habitat types listed in Annex I HD, as well as the ecological requirements of the typical species (Article 4.5). Finally, the NRL states that areas where good condition and adequate quality of the species' habitats have been achieved should not deteriorate (Article 4.6).

Article 7 of the NRL specifically addresses restoration targets for river ecosystems, and one of the NRL's key objectives is the restoration of natural connectivity and functions of running water ecosystems, with the aim to achieve at least an additional 25,000 km of free-flowing rivers in Europe by 2030. To accomplish this, Member States are asked to develop an inventory of artificial barriers of surface-water connectivity, and identify the barriers that must be removed to contribute to the restoration target, considering their socio-economic functions (Article 7.1). The next step would be to remove the identified obsolete barriers in order to restore river connectivity (Article 7.2), as well as to implement measures that would enhance the natural functions of related floodplains (Article 7.3). Member States must prioritize the removal of barriers that are no longer required for renewable energy production, inland navigation, water supply, flood protection, or other purposes (Article 7.2). Furthermore, Member States must ensure that the natural connectivity of rivers and the natural functions of the associated floodplains are maintained (Article 7.4). Notably, Article 7 is closely linked to Article 4 (especially Article 4.1). Any weakening of the latter could potentially undermine Article 7's effectiveness, raising concerns about the NRL's overall impact and enforceability. This potential weakening should be carefully addressed to ensure that the legislation achieves its intended goals.

Furthermore, Member States must prepare national restoration plans for the period until 2050, as well as conduct the preliminary monitoring and research to identify the necessary restoration measures to restore habitats and increase biodiversity (Article 11). The restoration plans should identify the areas to be restored (Article 12.2a), both within and outside the Natura 2000 network (European Commission, 2008) (Article 12.2b). They should also create an inventory of artificial barriers to be removed and establish measures to restore the natural functions of floodplains (Article 12.2e). Furthermore, national plans must include monitoring of restoration areas as well as evaluation of the ecological efficacy of restoration measures (Article 12.2h). They must also ensure long-term effects (Article 12.2i), consider climate change scenarios (Article 12.2j), collaborate with national energy and climate plans (Article 12.2k), and estimate financing needs (Article 12.2l). In general, the plans should consider the quality and quantity of specific habitats needed for species protection, such as nursery and spawning areas, as well as the connectivity between essential habitats for species to complete their life cycles.

The NRL is a much-needed extension of current nature conservation directives (as shown in Table 2) and will contribute to enhancing river restoration efforts throughout Europe. It presents significant improvements such as (1) setting quantitative restoration targets for rivers and floodplains with specific timetables, (2) focusing on large-scale biodiversity assessments, and (3) expanding restoration needs beyond the Natura 2000 network. The NRL complements the

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TABLE 2 Overview of the main characteristics of the Water Framework Directive, Birds and Habitats Directives, and Nature Restoration Law.

Topic	Water Framework Directive	Birds and Habitats Directives	Nature Restoration Law
Ecosystem types	Freshwater and directly depending terrestrial	Freshwater and terrestrial	Freshwater and terrestrial
Species and habitats	Biological quality elements (phytoplankton/benthos, macrophytes, macroinvertebrates, fish, riparian habitats)	Specific habitats and protected species	Specific habitats and protected species
Spatial extent	Catchments (>10 km^2)	Mainly protected areas	Inside and outside protected areas
Administrative units	All surface water bodies within the EU Member States	Natura 2000 sites biogeographic regions	Biogeographic regions
Target	Good status/potential of surface water and groundwater resources	Favorable conditions to protect biodiversity and ensure the conservation of important habitats and species	1. Good condition areas (Natura 2000) 2. Favorable reference areas (outside Natura 2000) 3. Sufficient quality and quantity of habitats for protected species 4. Additional 25,000 km free flowing rivers (longitudinal and lateral connectivity)
Timeline	2015/2027	No timeline	2030/2040/2050
Non-deterioration principle	Yes	Yes	Yes
Exemptions	Yes	Yes	Yes
Reporting focus	Status, trends, measures	Status, trends	National restoration plans
Reporting cycles	6 years	6 years	2 years

monitoring and status assessments of the Birds and Habitats Directives by focusing not only on protecting existing habitats, but also re-establishing degraded habitats. It also expands habitat and species protection by emphasizing the natural functioning of river-floodplain ecosystems. National restoration plans must provide spatially explicit descriptions and definitions of all restoration actions. Although the NRL strives for specificity, it leaves several aspects open for interpretation.

Depending on the criteria used to define a river, estimates of total river length in Europe range from roughly 600,000 to more than 1.6 million km (Belletti et al., 2020) (Figure 1). The NRL aims to establish an additional 25,000 km of free-flowing rivers by 2030, which represents a relatively small portion of Europe's river network and may have a limited impact on the restoration of freshwater biodiversity. Furthermore, it lacks clarity in some areas, such as what criteria should be used to define a (free-flowing) river, putting the implementation process at risk of failing to achieve its goals or even having negative consequences for freshwater biodiversity protection and restoration. For instance, there may be confusion in the interpretation of defining the terms "free-flowing rivers" and "reference areas," measuring and reporting progress toward the 25,000 km target, or prioritizing which rivers to restore first. Additionally, potential conflicts between restoration measures and existing infrastructure or land-use practices are not explicitly addressed. The only reference to potential conflicts is an ambiguous statement about the importance of considering the socioeconomic impact of implementing restoration measures. Thus, it is crucial to ensure that the implementation process addresses these shortcomings in a way that enables the ultimate goal of restoring freshwater ecosystems and biodiversity. Additionally, nature restoration should work in synchrony with other EU directives such as the Common Agricultural Policy (CAP) and the Renewable Energy Directive (RED).

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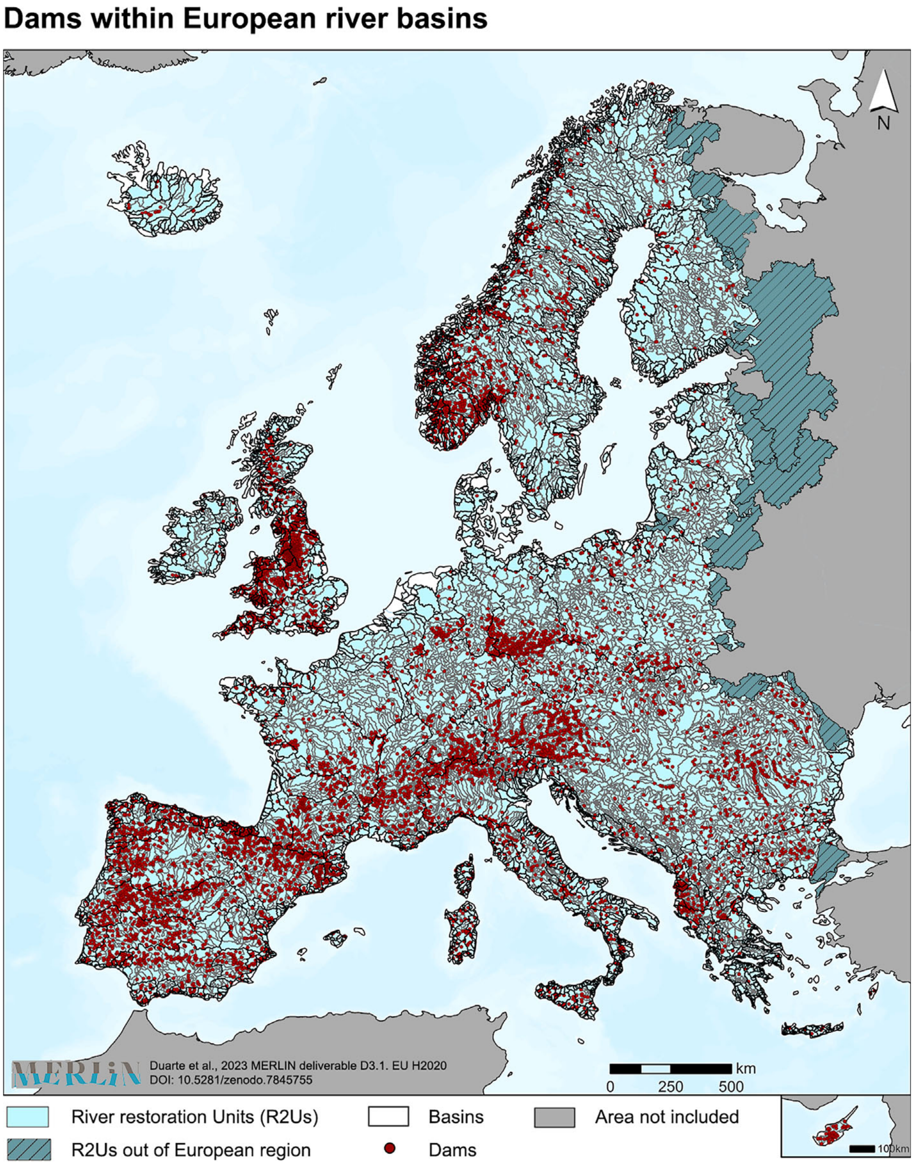

FIGURE 1 Dams per River Restoration Units (R2Us) specified in the MERLIN project. The MERLIN project created an innovative spatial aggregation of European river networks and wetlands integrated into R2Us, by integrating all input data at the same resolution and separating Europe into R2Us for small and large rivers. Blank areas were not classified as R2Us, because they did not meet the project's criteria. The authors are aware of the underrepresentation of dams in Sweden in this figure, as they were not registered in the AMBER data set used to create this map. *Source*: AMBER consortium, MERLIN project, GeoDAR, GOODD data (Duarte et al., 2023).

3 | SEVEN CHALLENGES FOR RESTORING FREE-FLOWING RIVERS

In this section, we identify seven key challenges and practical insights for achieving the NRL's goal of establishing an additional 25,000 km of free-flowing rivers by the end of 2030 (Figure 2). First, we examine the current gaps in the NRL and the potential consequences of leaving these aspects open to interpretation during the implementation process. Second, we propose potential solutions to these challenges that could aid in improving the NRL's implementation and ensure that its objectives are met.

3.1 | Challenge 1: Develop a clear definition of free-flowing rivers, barriers, and reference areas

A free-flowing river receives the amount of water, materials, and energy that would normally result from natural processes such as rainfall, drainage, erosion, and biological production. Developing a well-defined and parameterized

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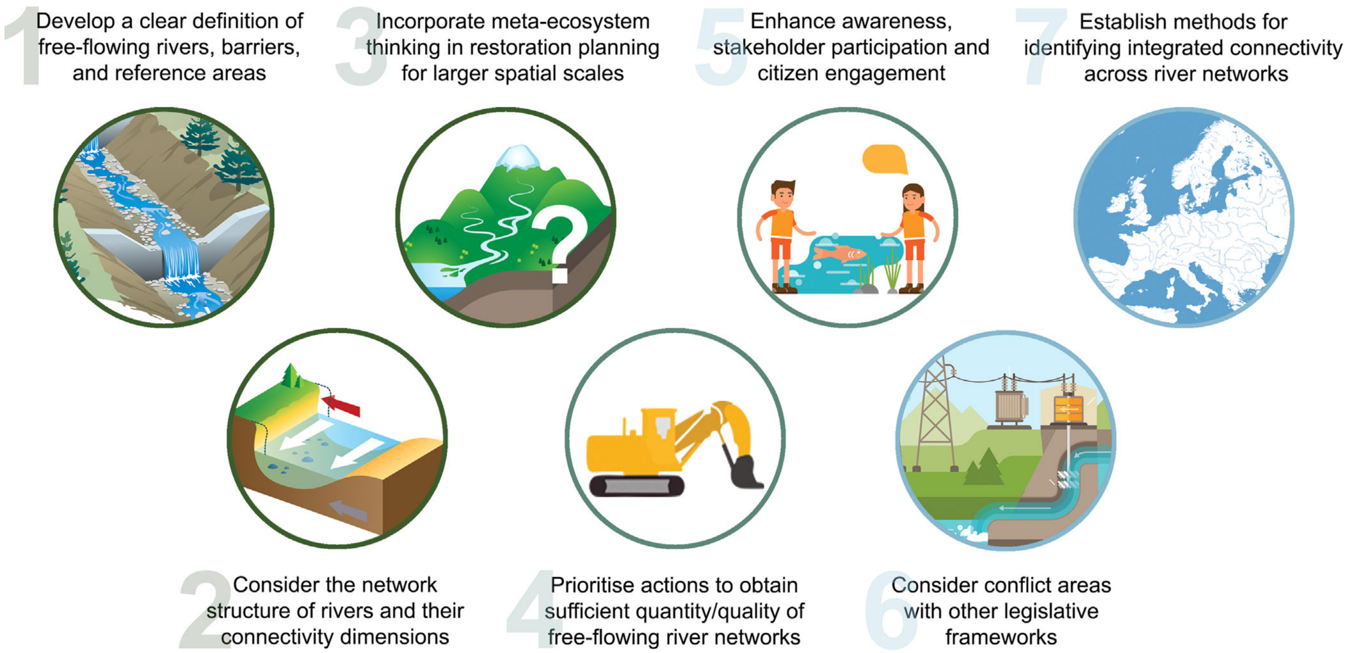

FIGURE 2 Seven challenges for effective implementation of the European Nature Restoration Law that targets establishing an additional 25,000 km of free-flowing rivers by 2030. The seven challenges are interconnected, and the order does not imply a linear approach. All challenges must be addressed concurrently in order to achieve the overarching goal of restoring free-flowing rivers.

definition of free-flowing rivers is critical for NRL purposes, as river conservation planning is frequently hampered by difficulties in translating broad conservation objectives into specific and measurable protection goals (Keeley et al., 2022; Opperman et al., 2021; Wohl et al., 2019). We suggest using the holistic definition proposed by Grill et al. (2019) and the European Commission (2022), defining free-flowing rivers as four-dimensional fluvial systems in which ecosystem functions and services are not affected by any human-induced change in fluvial connectivity. This allows for the unrestricted movement and exchange of water, energy, material, and biodiversity within the river system and across surrounding landscapes. Following Grill et al. (2019), rivers can be classified as free-flowing if they have high connectivity and habitat quality (Connectivity Status Index >95%) along their entire length. Their approach provides a technical definition of river integrity, but it requires solid and reliable data on longitudinal barriers, reservoir volume and retention structures, and water use. Another formal definition can be derived by acknowledging the four dimensions of riverine ecosystems—the longitudinal, lateral, vertical, and temporal extent of a river (European Commission, 2022). Therefore, free-flowing conditions are impaired by: (1) physical infrastructure (barriers) in the river channel impeding longitudinal connectivity; (2) physical infrastructure along riparian zones or adjacent floodplains (flood protection structures, channelization, bank stabilization) obstructing lateral connectivity; (3) water abstraction or flow regulation obstructing hydrological dynamics; (4) pollution or changes in temperature regimes inducing changes in water quality (Grill et al., 2019); and (5) loss or change of biodiversity that results in cascading effects on cross-ecosystem resource flows (Gounand et al., 2018). Thus, restoring rivers to their natural state entails reinstating physical connectivity, establishing environmental flows, improving water quality, and maintaining or rehabilitating biodiversity. Transferring these definitions into restoration targets and practical restoration actions is challenging, particularly in densely populated areas (European Commission, 2022). Conflicting interests arising from this situation may disproportionately limit restoration efforts, particularly for smaller rivers. At the same time, achieving complete restoration of riverscapes toward a perfect free-flow target seems hardly feasible, at least at present. To address this issue, we propose considering river's order and size, and other river network properties such as centrality (Sarker et al., 2019) to be included as an important criterion in restoration targets and to define what should be considered as free-flowing. A discussion on the appropriate length of a river section to be considered free-flowing should be initiated, taking into account factors such as the removal of barriers and the interconnectedness of tributaries. This way, longer and continuously connected sections with higher ecological value should take precedence over numerous smaller sections with the same total length. By taking a balanced approach, such as implementing a gradient of free-flow in river systems connected throughout

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(see also European Commission, 2022), we can develop more effective strategies to restore free-flowing rivers at various scales. This approach keeps free-flowing river restoration manageable and river managers motivated to restore their rivers.

Quantifying barriers and assessing their effects on rivers has proven difficult, and the number of barriers is generally underestimated (De Leaniz & O'Hanley, 2022; Rinaldi, 2021). This is due to the lack of a general definition of what constitutes a barrier and also the complex assessment of spatial and temporal impacts of barriers because of seasonal variations in flow regimes and the network structure of rivers (Messager et al., 2021; Van Looy et al., 2014). Furthermore, a series of barriers obstructing the natural flow of water within a river reach may exert cumulative (potentially more than additive) effects on river flow, resulting in difficult-to-quantify degrees of riverscape permeability (Geist, 2021). Although only larger storage dams have the potential to obstruct hydrological flows, almost all barriers have the potential to disrupt sediment transport (Bizzi & Lerner, 2015) and movement of organisms (Jones et al., 2020), thus impacting the overall structure and dynamics of river meta-ecosystems (Carpenter-Bundhoo et al., 2020; Jacquet et al., 2022; Peller et al., 2022). For example, barriers as low as 20 cm in height can impede poor swimmers to disperse upstream, while low-head barriers can interfere with the downstream dispersal of sediment, fish larvae, benthic invertebrates, and macrophytes (Jones et al., 2021). Furthermore, freshwater species differ in their adaptation to connectivity between suitable habitats, which is reflected in life-history traits, ecological niche requirements, and genetic variability. Additionally, the relevance of connectivity at different spatial and temporal scales may change within a single species throughout their life cycle (Olden & Poff, 2003; Poff & Zimmerman, 2010). These biotic aspects may result in varying levels of ecological efficacy of barrier removal for different fluvial systems in terms of biodiversity rehabilitation (Foley et al., 2017; Magilligan et al., 2016). Therefore, while minimum height thresholds (often >50 cm) have traditionally been used to identify fish movement barriers in the longitudinal continuum, we propose that no specific height threshold should be used for barrier identification, and that lowering barriers or technical measures exclusively targeting one organism group (e.g., fish lifts and ladders) must not be considered barrier removal in the context of the NRL. Barriers to longitudinal, lateral, vertical, and temporal connectivity must be explicitly defined and targeted for removal in order to restore truly free-flowing conditions in European riverscapes that benefit biodiversity, ecosystem processes, and services (Palmer & Ruhi, 2019).

Reinstating free-flowing rivers at the European scale requires achievable targets, which should be defined based on relevant reference conditions. However, defining suitable reference conditions is challenging in any context. For the WFD, systems of reference sites and modeled reference conditions were implemented to overcome limitations of extant sites (Hering et al., 2010). To define reference conditions as targets for river restoration in the framework of the NRL, there is no alternative but to use the few least-impaired free-flowing rivers or sections that still remain. In these systems, a mechanistic understanding of how the four connectivity dimensions shape biodiversity and ecosystem functioning must be developed. This should include establishing relationships of flow-induced habitat dynamics and ecosystem functioning empirically. Additionally, available baseline knowledge on the relevance of different properties of free-flowing rivers for ecosystem functioning should be compiled as well as historical assessments that can be used to estimate ante-hoc conditions (Hohensinner et al., 2004; Hohensinner et al., 2021). Reference conditions will need to be defined based on ecological criteria (presence and abundance of typical species, area coverage of habitat types) and properties of free-flowing rivers (e.g., channel migration, hydromorphological dynamics, flow patterns), but must also include sound thresholds describing transformational states (Lane et al., 2023). In this context, we urge for rapid action: potential reference sites within the EU and in non-EU countries covering the same freshwater ecoregions must be identified as soon as possible and protected. This refers particularly to rivers in the Balkans, many of which have retained a free-flowing character but are under direct threat of massive hydropower development in the region (Fišer et al., 2022; Knez et al., 2022).

3.2 | Challenge 2: Consider the network structure of rivers and their connectivity dimensions

The river-floodplain ecosystem concept developed by Ward and Stanford (1995) recognizes the four dimensions of river ecosystems that can help guide an appropriate understanding of connectivity. First, there are connections to other ecosystems in the landscape along longitudinal (main channel; upstream and downstream), lateral (main channel, floodplains, and riparian zones), and vertical (groundwater, river, and atmosphere) dimensions. Second, connectivity along these three spatial dimensions is modulated by the dynamic behavior of flow, which effectively shrinks or expands

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space based on changes in the velocity and volume of water exchange. Although useful, river four-dimensionality and other seminal river ecology concepts fall short of adequately representing the longitudinal dimension: rivers are not linear landscape features that simply grow in size from a source to the ocean, but rather form spatially explicit, hierarchically organized, dendritic networks that integrate a landscape. This network perspective must be considered when designing efficient protection of their biodiversity and functioning (Altermatt, 2013). The self-organizing and fractal-like river network structure influences hydrological processes and ecosystem dynamics (Carraro & Altermatt, 2022; Erős & Lowe, 2019; Rodriguez-Iturbe & Rinaldo, 1997), and it is an important driver of biodiversity and ecosystem functioning (Altermatt, 2013). Because of the spatial structure, local changes in connectivity may have an impact at the catchment scale through changes in flow regime, sediment transport, and resource exchange (e.g., Baldan et al. (2022); Carraro and Altermatt (2022)). For these reasons, restoring longitudinal connectivity in large river networks in transboundary contexts may prove especially difficult.

We argue that a timely approach to consider connectivity in river ecosystems must conceptualize four-dimensionality embedded in the dendritic river network (Figure 3a). In medium- to large-sized rivers (Strahler Order >4) and on landscape or catchment scale, restoring longitudinal connectivity is often regarded as the most important factor in restoring freshwater biodiversity, with lateral and vertical connectivity supplementing it. The lateral dimension becomes more important downstream and at smaller spatial scales (reach and segment scale) as river valleys widen and interact with riparian land. River valleys often represent the most modified part of a river network as a result of urbanization and agricultural development. This adds an array of new lateral and vertical barriers and pressures to the system, such as impervious surfaces, roads, and ground leveling, all of which alter surface and subsurface runoff and water movement. In these areas, where river management prioritizes specific water resource uses (e.g., water used for irrigation), biodiversity restoration efforts frequently suffer (Erős et al., 2018). Riverscape modifications (e.g., dams, weirs, engineered levees, and changes in riparian land use) have a specific effect on connectivity along any of the network dimensions and influence river connectivity via: (1) physical river fragmentation (longitudinal, lateral and vertical); (2) flow regulation (lateral and temporal; natural flow impairment); (3) sediment trapping (longitudinal, lateral, and vertical); (4) water consumption (lateral, vertical, and temporal); and (5) infrastructure development and flood control (lateral, longitudinal, and temporal) (Grill et al., 2019). Restoring (more) natural river and floodplain functions requires comprehensive consideration of all dimensions of connectivity, as the decline of biodiversity in both freshwater and terrestrial ecosystems is closely linked to the dynamics across these spatial dimensions (Albert et al., 2021).

We argue that full consideration of the four-dimensional network structure of rivers is critical for mitigating the effects of human riverscape modification. As a result, we extend our previous suggestion to include minimum river section length as a restoration target for free-flowing rivers. Wherever possible, restoration should re-establish free-flowing sections that represent continuous subsets of the original dendritic river network, and this must be accomplished in a way that fully represents the four-dimensionality of river networks. However, this can be challenging depending on the context. For example, one of today's most pressing issues is keeping rivers flowing during severe droughts in order to maintain ecosystem services such as self-purification and clean water provisioning (Chiu et al., 2017). This is brought about by a combination of excessive water use, river channelization, land use change, drainage of wetlands and arable land, and climate change. In these cases, we argue that incorporating environmental flow (e-flow) regimes into river management could help to achieve restoration targets (Arthington et al., 2006; Bunn & Arthington, 2002). If used properly, e-flows improve connectivity across the spatial and temporal heterogeneity of river networks by simulating natural flow patterns that allocate water, sediment, and biota to vulnerable habitats during dry periods. Furthermore, e-flow implementation employs adaptive management principles to adapt targets to changing environmental conditions, because e-flows should be designed to restore the flow regime rather than simply creating flood events (De Jalón et al., 2016; Palmer & Ruhi, 2019). While e-flows have been used in river restoration projects across Europe to restore longitudinal connectivity and favorable water status/potential in accordance with the WFD, they have encountered a number of challenges. Implementing appropriate e-flow regimes can be difficult due to limited resources, knowledge gaps, local capacity limitations, institutional barriers, conflicts of interest, and a lack of political will and public support (Ramos et al., 2017). These challenges are especially important in light of the global increase in hydropower dam construction (Couto & Olden, 2018; Winemiller et al., 2016; Zarfl et al., 2015) and growing water demands in arid or climate-affected areas, and must be addressed during NRL implementation as well. It is also important to note that although e-flow regimes may frequently appear as scaled-down versions of natural flows, they implementation will not restore the full dynamics of natural flows.

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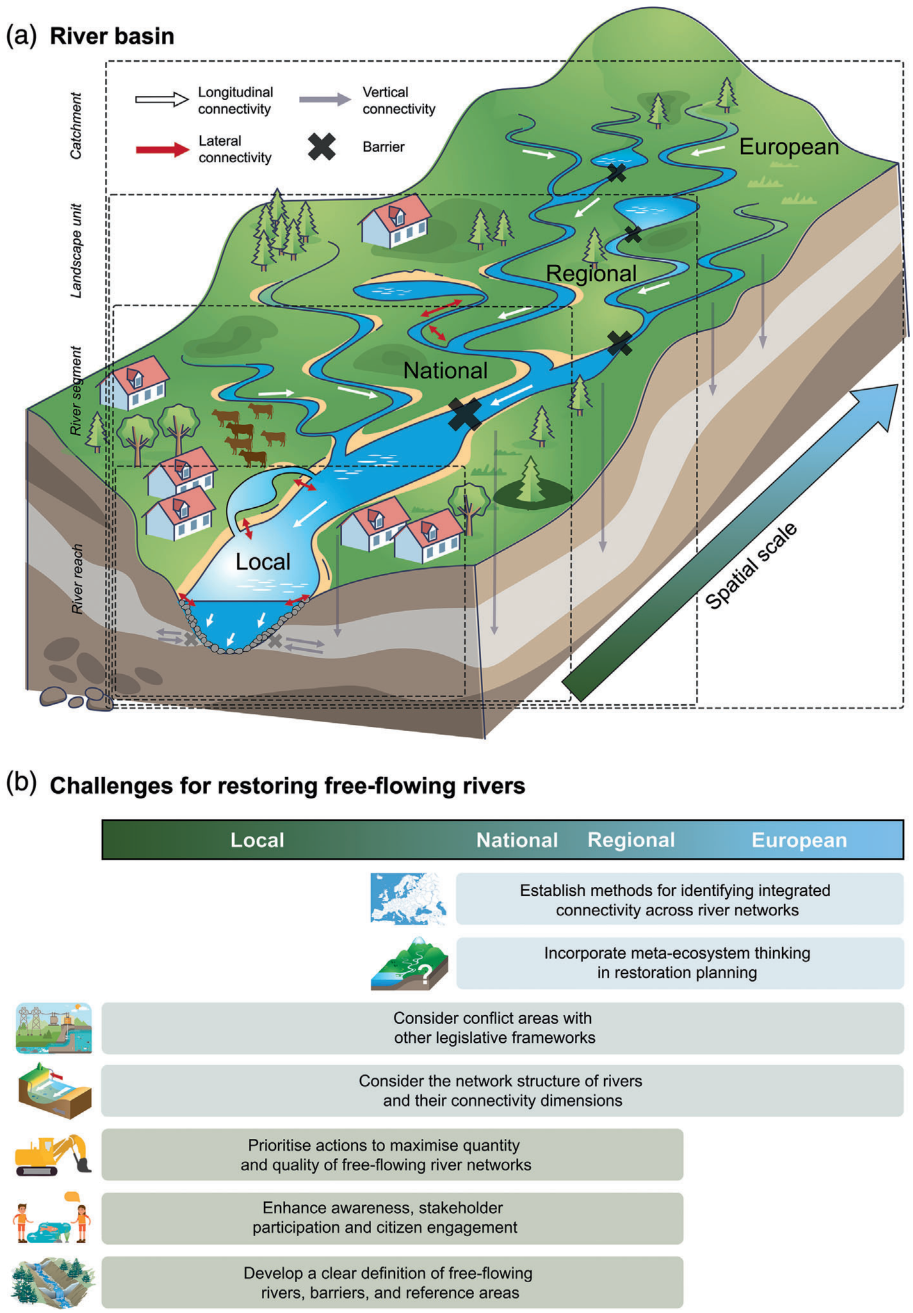

FIGURE 3 (a) A typical river basin with the three dimensions of connectivity, barriers, and relevant spatial scales for management. Spatial scales in this figure are comparable to the commonly used scales: river reach (local), river segment (national), landscape unit (regional), and catchment scale (European). (b) Seven challenges identified by the authors for restoring free-flowing rivers, organized by the spatial scale(s) on which they primarily exert their influence.

3.3 | Challenge 3: Incorporate meta-ecosystem thinking in restoration planning

Addressing challenges 1 and 2 in NRL implementation helps define free-flowing rivers and restoration targets and incorporates the physical nature of river networks. However, to fully integrate the ecological dimension of free-flowing rivers, restoration efforts must consider the interconnectedness and interactions within and among aquatic systems, as well as their riparian and terrestrial matrices (Dudgeon et al., 2006). This requires understanding ecological processes across different scales and their response to river network impairment, to guide suitable restoration strategies and post-restoration monitoring targeting key drivers such as climate change, river fragmentation, and loss of critical habitats. Moreover, creating migration corridors, river-floodplain connections, and hot-spots for reciprocal subsidy provisioning

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is crucial for protecting many freshwater-dependent species (Carlson et al., 2016; Fukui et al., 2006; Nakano & Murakami, 2001; Stoffers et al., 2022). Effectively, meta-ecosystem thinking that explicitly considers interconnectedness and interactions within and among riverscapes should guide European river restoration efforts to foster large-scale planning and collaboration, preferably at the landscape and catchment scale (see also Gounand et al. (2018)). Such large-scale planning should emphasize the critical role of large-scale connectivity, critical habitats, and the dynamics of meta-communities (Cid et al., 2022; Erős & Grant, 2015). For example, restoring meta-ecosystem properties of river networks, such as increasing river connectivity and habitat heterogeneity at larger spatial scales benefits freshwater biodiversity by also improving metacommunity dynamics (Stoffers et al., 2022). Additionally, such restoration efforts may enhance resilience to extreme drought and flooding events (Jaeger et al., 2014), which are anticipated to become more frequent due to climate change (Lennox et al., 2019).

Integration of meta-ecosystem and, thus, metacommunity thinking will also facilitate transboundary collaboration in the NRL framework for the restoration of free-flowing river networks. These approaches formally conceptualize the downstream and upstream directional effects of human activities in river networks, which will assist EU Member States in meeting the NRL timeline. This is collaboratively preparing national restoration plans up to 2050, as well as preliminary monitoring and research to identify the necessary river restoration measures to restore habitats and increase freshwater biodiversity (Article 11). Our recommendation is for Member States to work together in developing comprehensive restoration plans that consider the entire river catchment area, recognizing the transboundary nature of river ecosystems and biodiversity restoration. Thereby, large-scale issues can be addressed at a network perspective, moving beyond individual national plans that often overlook these aspects (see also Cid et al. (2022)). While River Basin Districts (RBD) under the WFD partially cover this concept, it is important to recognize that basin managers, such as the International Commission for the Protection of the Danube River (ICPDR), have limited influence and authority, which is why we urge Member States to join forces for this significant effort. Restoring connectivity between marine and freshwater ecosystems (as required by Article 7.2) is an example of how Member States must work together. Many HD protected diadromous and marine species that are critical to the functioning of healthy ecosystems, as well as those covered by the Convention on the Conservation of Migratory Species of Wild Animals, will benefit from the restoration of marine-freshwater connectivity to access free-flowing river sub-networks (Bauer & Hoye, 2014). The potential benefits and drawbacks of improved accessibility, as well as the number of species that would benefit or suffer from their removal, should be considered across the involved Member States to determine which barriers should be removed (Van Puijenbroek et al., 2019). This method effectively identifies and prioritizes those river network sections that require immediate attention to improve upstream accessibility.

Meta-ecosystem thinking also suggests restoration in a multi-zone hierarchical approach that identifies focal areas, critical management zones, and catchment management zones (e.g., Abell et al. (2007) and Gurnell et al. (2016)). Restoration should pay special attention to critical management zones where the emphasis is on maintaining connectivity and improving habitat quality to rehabilitate freshwater biodiversity. Here, it is crucial that upstream threats to restoration efforts are properly considered, and this can be accomplished through the integration of meta-ecosystem perspectives formalized in a multi-zone hierarchical approach during the planning phase (Erős et al., 2023; Hermoso et al., 2016). Also, this approach offers to estimate the risks of restoration: if barriers physically disconnecting an invader and a protected or threatened native species are removed, important biodiversity may be irreversibly lost. Similar thought experiments can be achieved on water quality or quantity, habitat availability, or pathogens (Hermoso et al., 2021; Liermann et al., 2012; Tickner et al., 2020). However, removing barriers and restoring natural flow regimes have the potential to shift alien-dominated aquatic communities to native-dominated ones (Kiernan et al., 2012; Marchetti & Moyle, 2001). In light of these considerations, we argue that a complete integration of meta-ecosystem and metacommunity perspectives provides significant benefits and should be fully implemented for the NRL to be successful.

3.4 | Challenge 4: Prioritize actions to maximize quantity and quality of free-flowing river networks

Restoring an additional 25,000 km of free-flowing rivers by 2030 to meet the EU biodiversity target will not suffice to halt the decline of freshwater biodiversity, let alone reverse it. Depending on the system, restoration goals can range from initiating hydromorphic dynamics and ecological succession (e.g., in floodplains and wetlands) to maintaining a desired flow regime in free-flowing rivers. For restoration efforts such as dam removal to have a meaningful impact, it is critical to focus on areas where restoration efforts will result in the most substantial improvements to ecological

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conditions, freshwater resources, and ecosystem services (Erös et al., 2018; Guetz et al., 2022). According to the NRL, restoration efforts should focus primarily on obsolete barriers that are no longer required for renewable energy production, inland navigation, water supply, or other uses (Article 7.2).

Although removing obsolete barriers appears to be the simplest way to achieve the EU's biodiversity goal, it probably will not be enough to halt the decline of freshwater biodiversity. First and foremost, we demand a halt to all activities that are likely to harm freshwater ecosystems that are currently in near-natural or even pristine condition until the NRL is fully implemented. For example, current goals of dam construction in pristine rivers, such as those in the Balkan region (Schwarz, 2020), are devastating to some of Europe's last remaining intact rivers (see also Fišer et al. (2022)). In fact, efforts must be made to protect such still-intact landscapes prior to restoration. Restoration costs and benefits vary greatly, with examples of great success achieved seemingly efficiently (e.g., Allier river in France) as well as near failure at great cost (e.g., Ems river in Germany). A common issue is the lack of a benefit for biodiversity following local habitat reconstruction due to missing colonizers as a result of connectivity remaining hampered at a larger spatial scale (Tonkin et al., 2014). In contrast, the efficiency with which biodiversity can be maintained by protecting a large-scale river system (as achieved, for example, through the establishment of the Vjosa Wild River National Park) is unparalleled. In fact, it makes little sense to prioritize restoring degraded systems while degrading near-natural or pristine systems (Erös et al., 2023).

Aligned with our recommendations for addressing Challenges 1–3, we advocate a prioritization approach that considers not only physical location, ease of restoration, and economic factors but also expected ecological outcomes (see also Guetz et al. (2022)). Given this perspective, the NRL's proposal to prioritize the removal of obsolete barriers first may seem contradictory. Instead, to optimize the quantity and quality of free-flowing river networks, priority should be given to areas where restoration efforts, including barrier removal, can lead to substantial improvements and crucial contributions toward achieving the objectives of the Nature Directives, WFD and BDS2030. Even if a key barrier is not obsolete, its removal can have disproportionately large benefits (Belletti et al., 2020; Hermoso et al., 2021), especially when temporary barrier removal (e.g., by opening sluices), artificial side channels (e.g., high-quality fish ladders) or adaptation of e-flow solutions cannot be implemented. In this context, cost-effectiveness may be an issue (Belletti et al., 2020; De Leaniz & O'Hanley, 2022). Cost-effectiveness of barrier removal is determined by barrier size, number and structure, where multiple, simple and smaller barriers can be removed at lower costs than a few large structures (Cote et al., 2009; De Leaniz & O'Hanley, 2022). Yet, cost efficiency should be weighed against the long-term benefits of restoration, that is, habitat quality, biodiversity, and ecosystem functioning (Costea et al., 2021). Furthermore, using prioritization methods such as those discussed in Erös et al. (2018), Guetz et al. (2022), or proposed by expert working groups (such as WG ECOSTAT in the EU) can help with decision-making.

3.5 | Challenge 5: Enhance awareness, stakeholder participation, and citizen engagement

Rivers are predominantly seen as commodities or resources, particularly by policymakers, industrial stakeholders, and for specific economic interests such as extractive industries, agriculture, and infrastructure development. Unfortunately, within these sectors, information sharing aimed at increasing awareness of rivers' ecological roles, riverine biodiversity, and human impacts is often insufficient or goes unheard (Flávio et al., 2017). Freshwater processes, hidden from the human eye, are often not recognized as integral parts of nature, leading to a lack of awareness among stakeholders and citizens regarding the significance of freshwater biota for the functioning of freshwater and adjacent terrestrial ecosystems. Both scientists and basin managers have important roles to play in addressing this issue by engaging with all stakeholder groups and facilitating the dissemination of relevant information. Engaging stakeholders is especially important for understanding the specific human demands relevant for each river network and therefore for successful river restoration (Vári et al., 2022). For example, the weak representation of measures against unsustainable agriculture in the NRL impedes lateral connectivity restoration, especially given that many floodplains have been converted to agricultural land (Hering et al., 2023). Without the involvement of the agricultural sector, it will likely be extremely difficult to achieve a free-flowing state for many rivers. Collaboration with farmers will be critical to finding solutions and ensuring successful restoration at targeted larger scales. In the context of NRL-guided freshwater restoration, comprehensive strategies should aim to resolve conflicts, offer informed discussion, and close perception gaps among stakeholders in an empowering, inclusive setting (Flávio et al., 2017). Here, sharing and disseminating cutting-edge scientific

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discoveries to society, putting good practices in place, and making informed policy decisions are all critical for bringing—and keeping—stakeholders together (see also Gann et al., 2019).

Often, there is a gap between theoretical knowledge (accessible through academic studies) and knowledge actually implemented and integrated in management, caused by a lack of effective communication among scientists, decision-makers, and other stakeholders (Lindenmayer, 2020). To address this issue, we recommend initiating a targeted dialogue among scientists, knowledge holders, and policy actors in order to bridge the gap and connect freshwater biodiversity research findings with the specific needs of policymaking. This dialogue can be facilitated by the creation of a European-level online platform that serves as a "science service" and aids in the ecological transition outlined in the European Green Deal and the BDS2030. In a targeted dialogue between scientists, other knowledge holders, and policy actors, such a platform could connect research results on rivers and freshwater biodiversity to the needs of policy making for free-flowing rivers. In addition, it is important to stimulate citizen engagement to improve support of freshwater biodiversity initiatives (Hermoso et al., 2022; Maasri et al., 2022). Stakeholder engagement and community science are effective means of engaging communities in river-flow monitoring (Allen et al., 2019; Truchy et al., 2023), barrier tracking, biological and water quality monitoring, and restoration efforts (Huddart et al., 2016).

A key role is held by non-governmental organizations (NGOs), which are stakeholders themselves but often also facilitate interactions and exchange among numerous other stakeholders. Often prompted by specific signature ecosystems, which are under threat and thus candidates for protection, NGOs may bring together diverse citizens including scientists, legal professionals, and artists. However, it is essential to acknowledge that there are instances where NGOs, such as those affiliated with agricultural and forestry lobbies (both at European and national levels), actively oppose or seek to restrict river restoration efforts in Europe. Despite the challenges posed by these opposing forces, NGO-facilitated public debates remain crucial events for information dissemination, fostering discussions among protection and development proponents, even if their outcomes may not always translate directly into stakeholder involvement, as seen in obligatory public consultation events during environmental impact assessments. An interesting example is the NGO-facilitated network of "Scientists for the Vjosa," which raised attention for the ecologically valuable Vjosa River in Albania (Schiemer et al., 2020) through two on-site research activities ("Vjosa Science Weeks"), resulting in various media coverage and scientific publications (Schiemer et al., 2018). This bottom-up approach, in collaboration with other NGO activities integrated into the so-called "Blue Heart of Europe campaign," resulted in the establishment of the first Wild River National Park in March 2023. This is why we advocate for the full inclusion of all stakeholders in nature protection and restoration efforts: scientists, managers, policymakers, and the general public.

3.6 | Challenge 6: Consider conflict areas with other legislative frameworks

Given the persistent competition with the still rarely questioned economic growth paradigm, it remains a challenge to achieve the conservation objectives of the BDS2030. These challenges arise from conflicting water usage in various economic sectors, where economic interests, such as agricultural production and hydropower generation, often take precedence. For example, recent experiences with the Common Agricultural Policy have shown that some Member States prioritize short-term economic gains over preserving their natural resources and capital for future generations (Rinaldi, 2021). In general, nature protection needs are considered to a moderate extent, whereas sectoral demands and the influence of political leaders, often justified as "societal demands," tend to be prime considerations. This situation becomes more pronounced in regions with limited water availability. The recent policy landscape for biodiversity conservation in the EU, driven by the BDS2030, offers opportunities to promote greater incorporation of freshwater protection into other policy sectors, with a focus on management beyond Natura 2000 areas (Article 4.5). Current conservation policies and laws, however, tend to disregard the importance of freshwater ecosystems (Lynch et al., 2020; Perry et al., 2021), which have distinct characteristics and needs. It is crucial to understand that river water is a flow resource that is not bound by political boundaries, nor is the biodiversity that depends on the river channel network and the riverscape. These distinguishing characteristics necessitate the development of specific policies and laws to effectively protect and preserve freshwater ecosystems (Hermoso et al., 2016). Furthermore, the complex legal and administrative processes involved in implementing the law at various levels, as well as coordinating actions among different Member States, add to the difficulty.

The EU has several legislative frameworks in place relating to biodiversity, but they regularly contradict one another (Rouillard et al., 2018), often resulting in unintended negative consequences specifically for freshwater ecosystems due to their integrative nature. As downstream recipients and spatial integrators of multiple land uses and activities,

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freshwater systems serve as sentinels, reflecting the consequences of upstream practices and becoming hotspots of conflict. The spatial structure of river networks and importance of connectivity to other ecosystems exacerbates these challenges, as divergent stakeholder interests within a watershed complicate the implementation of cohesive legislative frameworks. Although an updated version of the EU Common Agricultural Policy (CAP) was introduced in January 2023 to align with the objectives of the BDS2030, it is critical to recognize that CAP funding for agricultural production (particularly in unsustainable and intensive practices) also results in the desolation of freshwater habitats. This impact is evident in the promotion of intensive agricultural methods, subsidies for water-intensive crops, and the construction of water diversion barriers (Leventon et al., 2017). The European Agricultural Fund for Rural Development (EAFRD) and Rural Development Programmes (RDPs), on the other hand, seek to alleviate these pressures and restore the water environment (Rouillard & Spray, 2017). Similarly, while the EU's regional funds finance infrastructure investments, they can (in)directly contribute to pressures on rivers. Another important example is the implementation of renewable energy (EU 2022/2577), particularly hydropower, which is in conflict with freshwater biodiversity protection (Geist, 2021; Hermoso, 2017). This regulation states that when balancing legal interests in individual river restoration or barrier removal cases relevant to restoring biodiversity under the Nature Directives and the WFD, renewable energy generated by hydropower plants will be recognized as an overriding public interest. Furthermore, the EU has increased its legally binding renewable energy target for 2030 to at least 42.5%, nearly doubling the current share. According to projections, doubling global hydropower capacity would result in a significant loss of many of the remaining large, free-flowing rivers, resulting, as one example, in the extinction of many more migratory freshwater fishes (Thieme et al., 2021).

Resolving conflicts and finding territorial compromises at the riverscape level is critical for effective water management and aquatic biodiversity protection. To manage conflicts in barrier removal activities and the implementation of e-flows, we propose using a negotiation process similar to the holistic approaches used in water-scarce regions. This includes establishing flow requirements and comprehensive water planning to ensure sustainable water use and ecosystem restoration (e.g., Jumani et al. (2023); Serra-Llobet et al. (2022); Arthington et al. (2023)).

3.7 | Challenge 7: Establish methods for identifying integrated connectivity across river networks

The NRL introduces an additional legislative measure that addresses shortcomings in freshwater ecosystem protection and restoration, complementing existing legal frameworks. Both the NRL and WFD mandate continuous river networks, incorporating free-flowing sub-networks. To assess restored connectivity and effectively monitor continuous restoration progress, innovative tools and methodologies are required, going beyond current approaches, and fully considering meta-ecosystem and metacommunity dynamics at the riverscape scale (Thieme et al., 2023). Regarding specific NRL targets, particularly prioritizing protected species and habitats, existing monitoring concepts can be utilized but should be enhanced by incorporating novel aspects (Cid et al., 2022). For instance, remote sensing applications could be used to develop and provide high-resolution habitat maps that offer functionality to monitor land use and habitat area especially where human infrastructure (levees, roads, railroads, bridges, and cities) intersects or disrupts riverscapes. To assess continuity along and between riverscapes comprehensively, it is critical to integrate existing and new data from various sources, scales, resolutions, and units. This integration may present technical challenges, particularly in the case of coarse mapping grids (Tomscha et al., 2017), but these challenges can be overcome through technological advancements. Remote sensing and satellite imagery, such as the Copernicus dataset, combined with automated image processing techniques can be used to create high-resolution, online habitat maps, although it is critical to recognize the current limitations of these technologies, such as difficulties in mapping smaller rivers within densely forested areas. Alternative remote sensing techniques, such as modeling based on high-resolution topographical maps from laser scans, may provide effective solutions in such cases. Furthermore, remote sensing has proven useful in improving the monitoring and mapping of spatio-temporal variability in flow regimes, contributing to improved e-flow design, particularly in highly dynamic fluvial systems such as floodplains (Powell et al., 2008) or intermittent river networks (Borg Galea et al., 2019).

Here, we explicitly argue for continuous/regular updating and validation of barriers to river network connectivity although the NRL only requires Member States to conduct a single barrier inventory (Article 7.1). This is critical because barriers not accounted for can form or perish over time (Belletti et al., 2020), and changes in barrier structure, permeability, and habitat characteristics need to be documented to guide restoration efforts. Moreover, we recommend

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that to-be-developed habitat maps include small water units outside river networks, floodplains, and larger lakes to take full advantage of their restoration potential and contribution to improving aquatic habitat connectivity. Also, these small water bodies are of high significance for local and regional biodiversity, including protected birds, and offer specific habitats that must be included in integrative freshwater restoration, also because of their importance for meta-ecosystem and metacommunity processes (e.g., Horváth et al. (2019)). In essence, our proposal involves developing and implementing an integrated monitoring framework that combines established knowledge and tools (such as those used in assessments compliant with the WFD and Nature Directives). Additionally, novel approaches will be integrated to assess restoration effectiveness and continuously evaluate restoration success. For this purpose, the monitoring network must align with the dendritic, interconnected structure of riverscapes, encompassing all relevant habitats at various spatial scales (Figure 3a). Moreover, it must employ appropriate methods to monitor biological targets, such as protected species or habitats. Additionally, monitoring data and reports should be public so that stakeholders of nature restoration as well as river basin managers, policymakers and Member States can access the latest results and immediately respond to threats of restoration success.

We propose that monitoring should specifically aim to detect potentially state-changing thresholds at the level of local water and resource flow patterns in order to implement adaptive management measures at the riverscape level (see Lane et al. (2023)). This method also allows for the evaluation of meta-ecosystem processes among river network elements. At the level of biodiversity, we suggest drawing on methodological advances in environmental DNA (eDNA) surveys, which now allow for riverscape biodiversity assessments (Altermatt et al., 2020; Carraro et al., 2020). However, such efforts rely on reference libraries that are far from complete and packed with taxonomic errors (Brasseur et al., 2023; Weigand et al., 2019), and therefore must be used in an integrative monitoring framework that employs a range of methods. Additionally, remote sensing and computer vision (Hugue et al., 2016; Torgersen et al., 2022) should be used at unprecedented riverscape scales, necessitating the development of transboundary monitoring infrastructure in a digitalized EU. In any case, assessing restoration efficacy and success is only possible if clear ecological targets and desired outcomes of restoration efforts are defined ahead of time (see Challenge 1). Also, while ecological targets must be set at realistic timelines, monitoring must continue well beyond implementation of a specific set of measures to enable post-hoc adaptive management as crucial means toward the long-term viability of restoration efforts (Stoffers et al., 2021; Thieme et al., 2023). Finally, in line with our plea for the incorporation of meta-ecosystem thinking in riverscape restoration, we advocate for biodiversity-centered monitoring that aims to describe metacommunity processes as indices of integrated connectivity (e.g., Thompson et al. (2020) and Patrick et al. (2021)). In this case, population genetic/genomic approaches on keystone and protected species, as well as metagenomics, can provide information on ongoing gene flow as a descriptor of connectivity—and this may even be possible using eDNA approaches. Furthermore, knowledge of molecular diversity hotspots within single riverscapes could be used to guide restoration efforts, as restoring connectivity between these river network sections should increase gene pool sizes of individual species and, thus, resilience to global change.

Integrating different kinds of data in a monitoring approach as broad or even broader than outlined above, will undoubtedly be difficult, but we are confident that the NRL's ambitious goals deserve a no-holds-barred approach when conceptualizing adequate monitoring methodologies.

4 | COLLABORATION FOR RESTORATION

The implementation of the NRL is considered an important step toward restoring our rivers and conserving freshwater biodiversity, with benefits not limited to fishes or birds but ultimately extending to the human population. Its success depends on active participation from Member States in restoring and protecting our rivers and their biodiversity, as this is crucial for the very ecosystem processes and services that sustain us. However, a significant challenge lies in the lack of political will and commitment to allocate the necessary resources and funding for effective freshwater restoration measures (Albert et al., 2021), which are essential for ensuring a positive future. It is evident that investments in freshwater biodiversity research and conservation pale in comparison to those in terrestrial and marine realms (Maasri et al., 2022). It is crucial to implement the NRL to maintain the balance of our freshwater ecosystem and ensure a sustainable future. Thus, the situation calls for immediate action to preserve the remaining natural rivers and drive the implementation of the NRL, benefiting both our environment and humanity in the long run.

The challenges discussed in this study occur across different spatial scales (Figure 3b). To restore river connectivity, it is necessary to take a comprehensive approach that considers various human activities at these scales such as

TABLE 3 Overview of urgent actions per challenge to improve the implementation of the NRL and ensure the BDS2030 objective of restoring free-flowing rivers in Europe are met.

Challenge Nr	Topic	Actions
	1. Definition of free-flowing rivers, barriers, and reference conditions	Urgently protect the few remaining near-natural reference sites in Europe
		Include free-flowing river section lengths in restoration targets
		Initiate a discussion on the appropriate length of a river section to be considered as free-flowing
		Find an alternative for the currently-used height threshold for identifying barriers
		Exclude measures that target one organism group as acceptable barrier removal actions
		Explicitly define and prioritize the removal of barriers affecting lateral, vertical, and temporal connectivity
		Establish reference conditions based on ecological criteria and properties of free-flowing rivers, including state-changing conditions
	2. Physical network structure and connectivity	Consider four-dimensionality in the dendritic river network for connectivity in river ecosystems
		Set restoration targets based on minimum river section length
		Prioritize re-establishing continuous subsets of the original dendritic river network
	3. Ecological network structure and connectivity	Consider interconnectivy of aquatic systems and their interactions with riparian and terrestrial matrices in restoration efforts (meta-ecosystem thinking)
		Member States should collaborate on comprehensive restoration plans for the entire river catchment area, considering its transboundary nature
		Prioritize critical management zones in rivers for restoration to enhance connectivity and rehabilitate freshwater biodiversity
	4. Prioritize restoration	Halt all activities that are likely to harm freshwater ecosystems that are currently in near-natural or even pristine condition until the NRL is fully implemented
		Implement a prioritization approach that takes into account expected ecological outcomes
	5. Involve stakeholders	Ensure full inclusion of all stakeholders, including scientists, managers, policymakers, and the general public, in nature protection and restoration efforts
		Share scientific discoveries, implement good practices, and make informed policies to bring stakeholders together
		Stimulate citizen engagement to improve support of freshwater biodiversity initiatives
	6. Address conflicts	Resolve conflicts and find territorial compromises using negotiation processes similar to those in water-scarce regions for barrier removal activities
	7. Establish methods	Develop and implement an integrated monitoring framework that combines established knowledge and tools, and integrates novel approaches
		Establish a system for continuous and regular updating and validation of barriers to river network connectivity
		Include small water units, floodplains, and larger lakes in habitat maps to maximize restoration potential and improve aquatic habitat connectivity
		Provide public access to monitoring data and reports for immediate response to restoration threats and success evaluation

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TABLE 3 (Continued)

Challenge Nr	Topic	Actions
		Monitor local water and resource flow patterns (using eDNA and remote sensing surveys) to detect state-changing thresholds and implement adaptive management at the riverscape level
		Adopt biodiversity-centered monitoring focusing on metacommunity processes as indices of integrated connectivity

agriculture, forestry, transportation, energy production, and urbanization. This necessitates careful planning, monitoring, and implementation from policies to measures that strike a better balance between the competing objectives of various stakeholders. The discussion must include not only communities and investors, but also key government bodies such as energy and environment ministries, which play an important role in policy formulation (Opperman et al., 2023). In Table 3, we listed the actions that we believe are critical as a result of the seven challenges. The goal of these immediate actions is to improve NRL implementation and ensure that the BDS2030 goal of restoring free-flowing rivers in Europe is met. It is the EU's responsibility to take the lead through the EU Green Deal and the NRL, setting an example for Member States to follow (Van Rees et al., 2020).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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