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Review Article

Challenges and opportunities in restoring European free-flowing rivers

Twan Stoffers[1,2], Ann-Kristin Schultze[3], Thomas Ehlert[4], Laura Kaiser[4], Mathias Scholz[5], Leopold A. J. Nagelkerke[2]

1 *Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), Department of Community and Ecosystem Ecology, Berlin, Germany*
2 *Wageningen University & Research (WUR), Aquaculture Biology and Fisheries Ecology Group, Wageningen, Netherlands*
3 *North Rhine-Westphalia State Agency for Nature, Environment and Consumer Protection, Recklinghausen, Germany*
4 *Federal Agency for Nature Conservation (BfN), Bonn, Germany*
5 *Helmholtz-Centre for Environmental Research (UFZ), Department Conservation Biology & Social-Ecological Systems, Leipzig, Germany*

Corresponding author: Twan Stoffers (twan.stoffers@wur.nl)

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Abstract

Free-flowing rivers (FFRs) across Europe hold high ecological value and clear economic benefits. They support biodiversity by providing habitats for a wide range of aquatic and terrestrial species and strengthen local economies through sustainable practices while reducing the need for costly artificial flood control and water treatment. Rivers also carry deep cultural meaning for European communities, shaping identity, belonging, and wellbeing. Given this ecological, economic, and cultural weight, we argue that safeguarding remaining near-natural or pristine rivers should be the first priority, alongside restoring degraded systems, where meaningful gains are feasible. Herein, we review definitions, restoration objectives, and historical changes in FFRs, and highlight the importance of setting realistic reference conditions that recognise both ecological constraints and future climate change. We stress the value of combining multiple temporal and spatial perspectives in project design and discuss practical restoration and rehabilitation approaches, including the role of stakeholder involvement and public awareness, to achieve successful outcomes. We then consider how biodiversity and climate policies can support protection, restoration, and long-term management of river ecosystems across Europe. Finally, we examine the opportunities and challenges tied to implementing the Nature Restoration Regulation and the EU Biodiversity Strategy for 2030, as well as other policy initiatives, that can help remove obstacles and create better conditions for accelerating progress in restoring free-flowing rivers.

Highlights

- Near-pristine rivers should be protected immediately, even with incomplete data.
- Freshwater systems need more political attention and stronger stakeholder involvement.
- Solutions for FFR restoration should be tailor-made for each unique situation.
- FFRs connect diverse ecosystems, needing both meta- and local ecosystem approaches.
- Few reference rivers exist; clarifying reference sites and ecological conditions is needed.

Key words: Freshwater biodiversity, freshwater conservation, river connectivity, river restoration, science-policy interface, stakeholder involvement

Free-flowing rivers in Europe

History of river modifications and recent restoration targets

Free-flowing rivers (FFRs) have been shaping landscapes and ecosystems for millions of years. They have traditionally provided water, food, and transportation to early human settlements (Smith 2020). In Europe, the late Bronze Age (~1300-800 BCE) marked the beginning of significant changes in river sediment transport and discharge patterns due to extensive agricultural activity and deforestation, which accelerated during the Roman period. These human interventions had significant environmental consequences, including increased sediment accumulation in river valleys. By the Middle Ages, this led to the first human-made channels on river valley floors to re-establish water flow hampered by increased sediment loads (Petts et al. 1989).

Initially, river modifications were quite primitive, with the primary focus on securing water flow, building embankments for flood control, and clearing land along the riverbanks for agricultural purposes. These early efforts also spurred the development of various crafts, including mill crafting, mining, and the production of ironware and textiles. As human populations grew and mechanisation progressed, river interventions became more advanced (Smith 2020). In the late Middle Ages, the Netherlands pioneered innovative river management techniques, such as dredging for land reclamation, building retaining dams and groynes to direct rivers to the North Sea (Fig. 1), and installing floodgates to regulate water levels (Lenders 2003; Ten Brinke 2005). Many European countries were able to improve their management of their rivers due to such innovations (e.g., Blackbourn 2007).

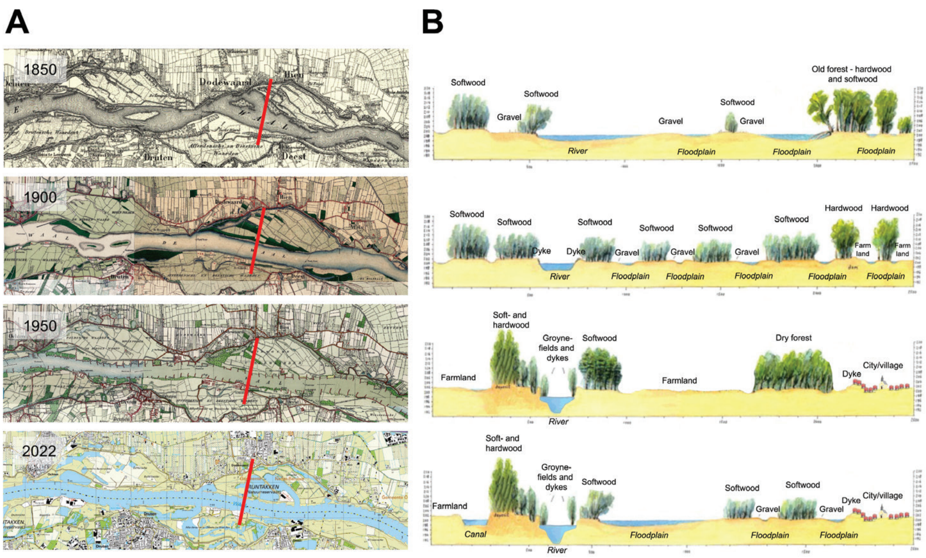

Figure 1. Typical changes in river-floodplain morphology in the lower Rhine (the Netherlands) from 1850 to the present, caused by anthropogenic interventions in the nineteenth and twentieth centuries. **A.** Top view of the river Waal near Dodewaard in 1850, 1900, 1950, and 2022, based on historic and current cartography (http://www.nationaalarchief.nl); **B.** A cross-sectional view of the river, floodplains, and surrounding land use at the location specified by the red line in (**A**). Original drawings in panel B by Jeroen Helmer.

The Industrial Revolution of the 19th and 20th centuries marked a watershed moment in the development of Europe's river systems. The demand for energy and efficient transportation resulted in the widespread construction of dams, weirs, and locks to generate hydroelectric power, control flooding, and facilitate commercial shipping (Haidvogl 2018; Pander and Geist 2018). These large-scale interventions had a dramatic impact on the river ecosystems, and the effects can be seen today by, for example, the high level of river fragmentation in Europe. Over 6,000 dams and approximately 1.2 million instream barriers disrupt river connectivity across the continent, only one of the 20 largest rivers (Russia's Northern Dvina) flows freely from source to sea (Belletti et al. 2020), and only 23% of large European rivers are still free-flowing (Grill et al. 2019). Furthermore, land reclamation, drainage, excessive irrigation, and river embankment have all contributed to the loss of nearly half of Europe's wetlands and floodplains, which are critical to the ecological health of river systems, acting as nurseries for a wide range of species (Tockner and Stanford 2002; Gardner and Finlayson 2018; Kaden et al. 2026; for fishes, see: Stoffers et al. 2022). As a result of the cumulative impact of anthropogenic stressors, the hydrology and ecology of many European rivers have become more homogeneous, leading to decreased biodiversity (Villéger et al. 2011; Peipoch et al. 2015). These levels of river degradation and homogenisation are especially alarming in light of climate change, as healthy, diverse river ecosystems are essential for natural resilience to climate impacts such as increased flooding and droughts (Palmer et al. 2009).

Against this backdrop of widespread river fragmentation, biodiversity loss, and increasing climate pressure, restoring FFRs has gained growing attention in European environmental policy. The Water Framework Directive (WFD; Directive 2000/60/EC), adopted in 2000, already includes objectives related to river connectivity, although these primarily focus on the longitudinal dimension. More recently, the EU Biodiversity Strategy for 2030 (BDS2030) set a target to restore at least 25,000 km of free-flowing rivers within the EU by 2030. This target was subsequently incorporated into the legally binding EU Nature Restoration Regulation (NRR; Regulation (EU) 2024/1991), adopted in 2024, thereby substantially strengthening the policy framework for river restoration across Europe.

Under the NRR, EU Member States are required to inventory artificial barriers affecting the connectivity of surface waters and to identify those that should be removed to achieve the Union-wide target of 25,000 km of free-flowing rivers (NRR Art. 9.1). Barrier removal is to be implemented through National Restoration Plans, with a primary focus on obsolete structures (NRR Art. 9.2). In addition, Member States are obliged to complement barrier removal with measures that improve the natural functions of associated floodplains (NRR Art. 9.3) and to ensure that the outcomes of restoration actions are maintained over time (NRR Art. 9.4). For further details on wetland restoration targets under the NRR and related EU policies, see Klusmann et al. (2026) in this Special Issue.

Defining and identifying free-flowing rivers

Successful river management needs a clear and universally applicable definition of FFRs. Without this, management and conservation objectives often fail to be translated into concrete and quantifiable protection measures (Pander and Geist 2013; Wohl et al. 2019; Opperman et al. 2021; Keeley et al. 2022).

However, creating such a definition is not an easy task, due to the complex interplay of various types of river modifications. Here, we propose to use the holistic definition proposed by Grill et al. (2019) and the European Commission (2022), defining free-flowing rivers as fluvial systems in which ecosystem functions and services are not affected by any human-induced change in connectivity. This allows for the unrestricted movement and exchange of water, energy, material, and biodiversity within the river system and across surrounding landscapes. Connectivity of FFRs is to be considered along the four dimensions of riverine systems: longitudinal (along the river's course), lateral (across the floodplain), vertical (between the river and groundwater), and temporal (across different time periods/seasons) (Fig. 2). Grill et al. (2019) integrated these four dimensions in a Connectivity Status Index (CSI), which quantifies connectivity ranging from 0% to 100%. These authors also suggest that only rivers with a CSI of ≥ 95% along their entire length should be classified as FFRs. This implies that human-induced changes in river connectivity should have minimal impact on ecosystem processes or services for a river to be called free-flowing (Grill et al. 2019; European Commission 2022; Van De Bund et al. 2024). The CSI emphasises the importance of ensuring free movement of water, energy, material, and biota within the river system, and implies that restoring rivers to a more natural and eventually free-flowing state involves addressing physical barriers and other human-induced impacts in all four dimensions.

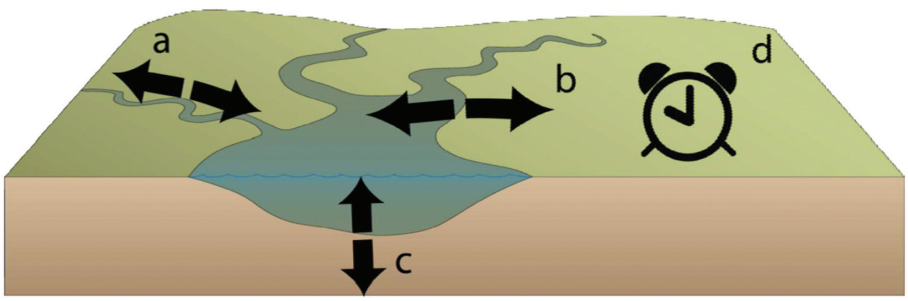

Figure 2. Four dimensions of connectivity within lotic ecosystems (after Ward 1989). **a.** Longitudinal connectivity (channel to channel); **b.** Lateral connectivity (channel to floodplain); **c.** Vertical connectivity (channel to groundwater); **d.** Temporal connectivity (across time). Illustration obtained from European Commission (2022).

To identify FFRs in the field, the European Commission's ECOSTAT (Ecological Status) working group developed criteria for determining whether a river stretch is already free-flowing or whether this status can be achieved by implementing specific restoration measures (Fig. 3). This method considers longitudinal, lateral, and vertical connectivity at local and catchment scales (Van De Bund et al. 2024), and explicitly includes the assessment of sediment connectivity, migration barriers, and hydromorphological and ecological functioning. It thereby enables the necessary actions in terms of restoration within either the stretch or elsewhere in the catchment.

This approach was developed by the European Commission's Joint Research Centre and published as technical guidance on criteria for identifying free-flowing river stretches under the EU Biodiversity Strategy for 2030 (Van de Bund et al. 2024). The framework has since been incorporated into the NRR Reference

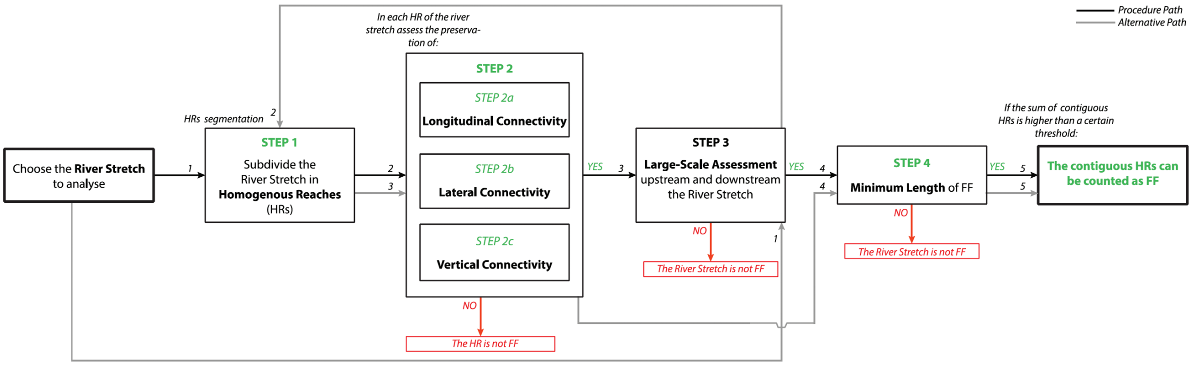

Figure 3. Schematic overview of the procedure to evaluate whether a river stretch meets the criteria to be considered a FFR. Overview taken from Van De Bund et al. (2024).

Portal as guidance for implementing the NRR's free-flowing river targets. Consistent with this guidance, the NRR defines a free-flowing river as "a river or a stretch of river the longitudinal, lateral and vertical connectivity of which is not hindered by artificial structures forming a barrier and the natural functions of which are largely unaffected" (NRR, Article 3(22)).

The network structure of rivers

To address the major impediments to FFRs, such as physical barriers, flow regulation, pollution, and climate-induced temperature changes (Table 1), integrated actions such as improving river connectivity, managing water flows, improving water quality, and preserving biodiversity are required.

Ward and Stanford (1995) originally proposed the river-floodplain ecosystem concept, emphasising the significance of longitudinal, lateral, vertical, and temporal connections in river ecosystems. This framework broadens our understanding of connectivity by identifying the dimensions influenced by dynamic flow behaviour. However, it ignores the spatially explicit, dendritic network structure of rivers, which is essential for biodiversity and ecosystem function (Altermatt 2013). Local connectivity can impact flow patterns, sediment transport, and resource exchange in catchments (Rodriguez-Iturbe and Rinaldo 1997; Erős and Lowe 2019; Carraro and Altermatt 2022). Furthermore, the fractal structure of river networks influences hydrological processes and

Table 1. Examples of major impediments to free-flowing rivers.

Key factors impeding free-flowing rivers	Explanation
Physical barriers	Structures such as dams and weirs within the river channel disrupt longitudinal connectivity, preventing the natural movement of water, sediments, and aquatic organisms (Mueller et al. 2011).
Structures	Efforts for managing rivers as infrastructures and flood protection obstruct lateral connectivity, limiting the river's interaction with its floodplain and reducing habitat complexity (Stoffers et al. 2022).
Water abstraction and flow regulation	These activities alter natural hydrological dynamics, affecting the timing, quantity, and quality of water flows important for maintaining river health (Acreman and Ferguson 2010).
Biodiversity loss	Changes in species composition and abundance can lead to cascading effects on cross-ecosystem resource flows, disrupting ecological balance and function (Gounand et al. 2018).
Pollution and temperature changes due to global warming	Chemical and light pollution, as well as rising temperatures due to global warming further stress river ecosystems, altering temperature regimes and degrading water quality (Grill et al. 2019; Hölker et al. 2023).

ecosystem dynamics (Baldan et al. (2022); Fig. 4). This demonstrates how the complex, branching structure of river networks not only supports but also has a significant impact on biodiversity and ecological functionality, focusing on the importance of these structures for ecosystem management.

Simply restoring longitudinal connectivity is insufficient for effective FFR restoration. The lateral and vertical dimensions are also of vital importance for the ecological functioning of rivers, particularly downstream and on smaller scales where river valleys intersect with riparian lands (and aquifers) heavily influenced by urbanisation and agriculture (Fig. 1). These changes have created barriers to runoff, as well as water and biota movement. Without the physical processes of flooding and erosion, the formation of type-specific structures like oxbow lakes, floodplain forests, and alluvial islands is severely limited (Constantine and Dunne 2008; Havrdová et al. 2023). These features are important for sustaining diverse habitats and species, regulating water quality, and increasing flood resilience. Furthermore, Erős et al. (2018) highlight the importance of also considering the temporal component of FFRs, as seasonal and interannual flow variations maintain ecological balance and support aquatic life at various stages. This complex interplay of dimensions highlights the intricate nature of river ecosystems, and the multifaceted approach required for restoration.

Restoration efforts face significant challenges in densely populated areas due to competing land use and economic interests. As a result, creating a one-size-fits-all criterion for FFR restoration is impractical and unlikely to help

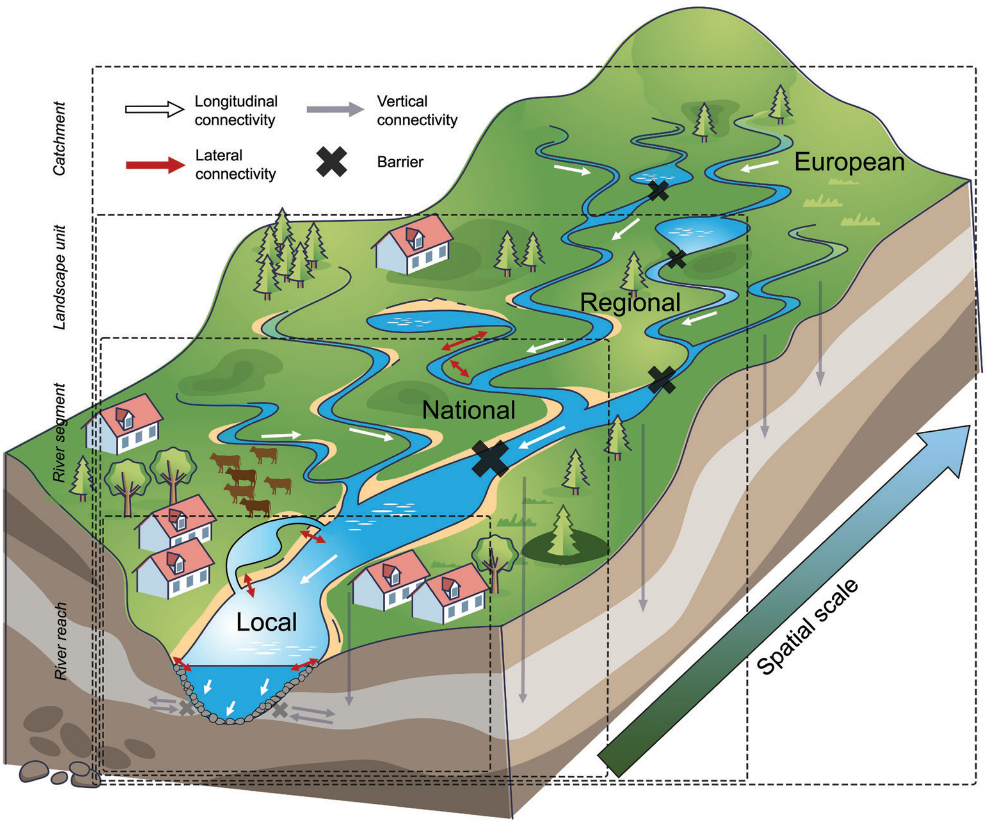

Figure 4. A typical river basin with the three spatial dimensions of connectivity, barriers, and relevant spatial scales for management. Spatial scales in this figure are comparable to the commonly used scales: river reach (local), river segment (national), landscape unit (regional) and catchment scale (European). Note that the temporal scale is not explicitly represented in this figure. Illustration obtained from Stoffers et al. (2024).

conserve and protect freshwater biodiversity. Instead, restoration methods and criteria should be tailored to the river-specific situation. A flexible and adaptive management approach entails constantly updating strategies based on environmental and socioeconomic monitoring, involving local communities in decision-making, and adapting scalable interventions as new data becomes available. This approach enables effective restoration at multiple scales by tailoring conservation efforts to each river's unique ecological and socioeconomic contexts (European Commission 2022), which also entails involving all stakeholders (Nagel et al. 2025).

Furthermore, such a tailor-made approach should prioritise longer and more ecologically valuable river sections, simultaneously incorporating river order, size, and network properties such as centrality, into restoration objectives (Sarker et al. 2019). This allows restoration efforts to be strategically focused on key river sections that are crucial to the overall connectivity and health of the river system, thereby maximising ecological benefits and conservation action efficiency.

Meta-ecosystem thinking

Building on understanding the complexity of river networks, meta-ecosystem thinking becomes important. This approach focuses on interactions between aquatic systems, riparian zones, and terrestrial areas and helps explain how rivers connect different ecosystems, emphasising the importance of ecological processes at multiple spatial and temporal scales (Fig. 4). It also considers how climate change, river fragmentation, and habitat loss affect these interconnected ecosystems. As suggested by Dudgeon et al. (2006), adopting this comprehensive perspective can help us better understand the complex nature of river ecosystems and inform more effective, multifaceted restoration strategies. For example: creating migration corridors, reconnecting rivers with floodplains, and establishing support areas for both land and water ecosystems are strategies for strengthening these connections (Fukui et al. 2006; Stammel et al. 2012; Carlson et al. 2016; Stoffers et al. 2022). Such efforts not only address spatial and temporal heterogeneity in river networks, but they also improve resilience to extreme weather events that are becoming more common as a result of climate change (Jaeger et al. 2014; Lennox et al. 2019).

Integrating meta-ecosystem thinking into restoration efforts promotes cross-border cooperation and enables EU Member States and neighbouring non-EU countries to develop comprehensive restoration plans for a FFR network across Europe. This is particularly relevant for transboundary river basins that span EU and non-EU countries, such as rivers in the Balkan region (e.g. the Vjosa–Aoos Basin). This approach addresses large-scale issues from a network perspective rather than focusing on individual national plans (Cid et al. 2022). The emphasis on ecological interactions at a large scale facilitates restoration planning and collaboration at landscape and catchment levels, including habitat and meta-community dynamics (Erős and Grant 2015; Cid et al. 2022). The International Commission for the Protection of the Danube River (ICPDR) is one example of this approach, as it coordinates efforts among Danube Basin countries to protect and restore the river's ecosystem through collaborative and integrated management strategies (for more details, see Kmetova-Biro et al. 2026).

When weighing the potential benefits and drawbacks of river connectivity restoration measures within this framework, it is important to consider the number of species and habitats impacted (Van Puijenbroek et al. 2019). This prioritises river sections that require immediate action to improve upstream access, thereby benefiting species protected by the EU Habitats Directive (HD; 1992/43/EEC), the Birds Directive (BD; 2009/147/EC), and the Convention on the Conservation of Migratory Species (http://www.cms.int/, Bauer and Hoye 2014), as well as threatened species listed on the IUCN Red List and regionally endemic species that are particularly vulnerable to habitat fragmentation and loss. On much smaller spatial scales, meta-ecosystem thinking suggests a hierarchical restoration approach that prioritises key areas to maintain connectivity and improve habitat quality while considering upstream threats (Hermoso et al. 2016; Erős et al. 2023). It also considers the risks of removing barriers, which can either restore natural flow regimes that benefit native species or harm biodiversity by allowing invasive species to spread (Jones et al. 2020; Jones et al. 2021; Dolan et al. 2025).

Optimising restoration towards FFRs

Protecting the last natural FFRs

Before discussing optimising strategies for restoring FFRs, it is important to note that, while this is becoming a smaller proportion, a part of Europe's river network still remains free-flowing. Preserving these remaining natural FFRs is of paramount importance due to their considerable ecological, economic, and sociocultural value. Such preservation can be achieved through dedicated safeguarding frameworks, including strict protection under national park or protected-area legislation, river-specific legal designations (e.g., wild river or free-flowing river status), strategic environmental assessments, and moratoria on new hydropower development in near-natural river systems (Opperman et al. 2021; Perry et al. 2021). While removing obsolete barriers may appear to be a simple way to meet BDS2030 and NRR targets, it is insufficient to reverse the decline in freshwater biodiversity (see also Stoffers et al. 2024). The priority must be given to stop activities that threaten nearly natural or pristine rivers. Dam construction plans in untouched Balkan rivers pose a threat to Europe's remaining pristine rivers (Schwarz 2020; Fišer et al. 2022). Preserving these rivers should take precedence over restoring connectivity in degraded systems, as conservation efforts such as the Vjosa Wild River National Park have proven successful in preserving biodiversity (Fig. 5). In contrast, restoration projects have produced mixed results, such as the successful recovery of the Allier River in France and the costly failure of the Ems River in Germany due to several ecological and financial issues (Geerling et al. 2006; Brettschneider et al. 2023). The Ems restoration, despite being a source of local pride, failed to address larger-scale connectivity problems essential for the migration and dispersal of aquatic species, leading to limited biodiversity recovery even over the multi-decadal time frame across which restoration measures and ecological responses have been evaluated (Brettschneider et al. 2023). It should be noted, however, that recovery trajectories vary strongly among taxa, with some species and ecological processes requiring substantially longer time frames to respond to restoration measures. Moreover, the high financial investment did not yield proportional

Figure 5. The Vjosa River in the Vjosa Wild River National Park is one of Europe's last FFRs. It originates in Greece's Pindus Mountains and flows through Albania, supporting a rich biodiversity and river ecosystem with only minor anthropogenic influences. The national park preserves this unique natural heritage while encouraging conservation and sustainable tourism. Copyright of this photograph is held by Gregor Subic

ecological benefits, suggesting that resources could have been better allocated to preserving free-flowing rivers or addressing broader ecological issues. This contrast between large-scale and local efforts highlights one of the true challenges in river restoration. Local habitat restoration often fails to provide significant biodiversity benefits due to ongoing larger-scale connectivity issues (Tonkin et al. 2014). This underscores the need for a comprehensive approach that considers both local and regional ecological dynamics.

Ecological impacts of barriers

Prior to exploring strategies for optimising the restoration of FFRs, it is essential to first understand that barriers represent one of the most significant human-induced changes to rivers. Barriers have a significant impact on natural flow regimes, sediment transport, water quality, channel morphology, stream temperature, and nutrient cycling, as well as on biodiversity, population connectivity, and the integrity of aquatic communities, all of which must be considered in comprehensive river restoration efforts (Ward and Stanford 1995; Poff et al. 1997; Tockner and Stanford 2002; Mueller et al. 2011). The amount of these physical barriers in river systems is frequently underestimated due to a lack of a universally accepted definition of a barrier and the dynamic interaction between seasonal flow variations and river network structures (Rinaldi 2021; de Leaniz and O'Hanley 2022), which can result in temporal natural barriers (Van Looy et al. 2019; Messager et al. 2021). These temporal barriers can be caused by low-flow periods that expose riverbeds or high-flow periods that create temporary obstructions due to impassable flow velocities for biota.

Not all barriers have the same impact on river processes. Large storage dams can disrupt sediment transport and organism movement, negatively impacting river ecosystems, communities, and processes (Bizzi and Lerner 2015; Carpenter Bundhoo et al. 2020; Jones et al. 2020; Jacquet et al. 2022). Even small barriers, such as those only 20 cm high, can obstruct the upstream migration of weaker swimmers, whereas low-head barriers can impede the downstream dispersal of sediment, fish larvae, benthic invertebrates, and macrophytes. Furthermore, multiple barriers within a river reach will have a cumulative effect on river flow, complicating the measurement of riverscape permeability (Geist 2021), whereas barriers located in rivers already containing natural obstacles such as cascades may have a lower impact on river processes.

Different freshwater species have developed a variety of adaptations to habitat connectivity, apparent from their life-history traits, ecological niches, and genetic diversity. As the importance of connectivity can vary across spatial and temporal scales throughout a species' life cycle (Olden and Poff 2003; Poff and Zimmerman 2010), the ecological success of removing a barrier for biodiversity restoration varies across species and fluvial systems (Magilligan et al. 2016; Foley et al. 2017). Therefore, limited restoration efforts, for example lowering instead of removing barriers, or implementation of technical solutions aimed at a single organism group (such as fish ladders), should be avoided (Stoffers et al. 2024).

Setting achievable restoration targets

Setting realistic restoration targets for FFRs across Europe is critical for effective resource allocation, stakeholder support, and achieving successful, tangible outcomes. In densely populated regions, however, where most rivers are strongly influenced by long-term anthropogenic change, identifying comparable reference conditions is often not possible, and restoration success may need to be defined in terms of rehabilitation or functional improvement, rather than a full return to an initial natural state. Implementing the free-flowing river target in the BDS2030 and NRR requires clear and realistic reference conditions based on the few remaining least-impaired sections, while recognising that such conditions often represent aspirational benchmarks rather than attainable end states.

It is crucial to understand how the four river connectivity dimensions affect biodiversity and ecosystem functioning. Given the scarcity of reference systems, baseline references on historical conditions could be used, although such information is often incomplete, fragmented, or entirely unavailable for many river systems. To estimate pre-impact states would require collecting baseline information on historical conditions and on how various FFR properties are linked to ecosystem functions (Hohensinner et al. 2004; Hohensinner et al. 2021).

Reference conditions should be defined using ecological criteria such as the presence and abundance of typical species, habitat area coverage, and FFR properties such as channel migration, hydromorphological dynamics, and flow patterns (Stoffers et al. 2024). Across Europe, only a limited number of river systems still approximate such conditions and can therefore serve as contemporary reference systems. A key example is the Tagliamento River, which remains one of the few Alpine rivers with a largely intact, laterally connected, and morphodynamically active braided channel network. Although the Tagliamento is not free from human pressures, these are comparatively low relative to most Alpine rivers, allowing natural sediment dynamics and channel mobility to persist across large sections of the river corridor. As such, the Tagliamento provides an important benchmark for defining reference conditions in braided river systems and for informing restoration targets under the WFD (Ward et al. 1999; Tockner et al. 2003).

In addition to historical or least-impaired references, targets should also reflect future-oriented objectives related to ecosystem resilience and adaptation to climate change, including the capacity to buffer extreme floods and droughts, maintain longitudinal and lateral connectivity under altered flow regimes, and support climate-resilient species assemblages.

Additionally, it is crucial to reliably establish thresholds beyond which the water body's resilience is exceeded, potentially leading to a transformation from one alternative state to another (Lane et al. 2023). For example, if upstream damming significantly reduces a river's flow, the resulting lower water levels may reach a point where fish species are unable to access their spawning grounds. Once this threshold is reached, the local fish population may collapse, causing a permanent shift in the river's ecological dynamics.

Given the limited timeframe in which the BDS2030 and NRR's river target needs to be met, immediate action is required to identify and protect potential reference sites in EU and non-EU countries with similar freshwater ecosystems. This urgent task includes establishing ecological benchmarks for both rehabilitation and long-term climate resilience, and safeguarding key areas, especially in the Balkans, where rivers remain free-flowing but are immediately threatened by extensive hydropower development. (Fišer et al. 2022; Geist 2021; Knez et al. 2022).

Prioritising restoration effort

Prioritising restoration efforts to create FFRs should take into account a variety of factors, including physical location, ease of restoration, economic implications, and expected ecological outcomes as well as the level of community and stakeholder acceptance, which strongly influences feasibility and long-term success (Guetz et al. 2022). Emphasis should be placed on areas where significant ecological improvements are possible, such as removing barriers to reconnect floodplains (see Box 1) and restore riparian habitat (see Box 2). While the NRR focuses on the removal of obsolete barriers, dismantling 'non-obsolete' barriers can often result in greater socioeconomic and ecological benefits (Belletti et al. 2020; Hermoso et al. 2021). In some cases, this may also involve replacing existing barriers with more sustainable alternatives, such as low passes, low-profile bridges, or other structures that maintain necessary functions while improving longitudinal connectivity. This is especially relevant in situations where alternative measures, such as temporary barrier removal or the formation of artificial side channels, are not feasible.

Cost-effectiveness should also be considered, as smaller and simpler barriers can often be removed for less money than larger structures (Cote et al. 2009; de Leaniz and O'Hanley 2022). However, cost-effectiveness must be balanced against the long-term benefits of restoration, such as increased habitat quality, biodiversity, and ecosystem function (Costea et al. 2021). Prioritisation methods, as discussed by Erős et al. (2018) and Guetz et al. (2022), can guide decision-making to ensure efficient and effective restoration efforts. Furthermore, clearly defining the ecological goals of restoration projects is essential from the start, as

Box 1. The 'Room for the Rivers' programme in the Netherlands.

The EU Water Framework Directive (WFD; 2000/60/EC), along with the Birds Directive (BD; 2009/147/EC) and the Habitats Directive (HD; 1992/43/EEC), creates a legislative framework for improving and protecting the ecological quality of European rivers, lakes, and estuaries, as well as freshwater biodiversity. It requires all surface-water and groundwater systems in the European Union to achieve "good ecological status" (EEA 2018; EEA 2019), which is determined by factors such as water quality, hydromorphology, and connectivity. Following major flooding events in the Netherlands in 1993 and 1995, the "Room for the River" program was established to reduce flood risks and, with these directives in mind, improve the ecological quality of Dutch rivers and floodplains. These directives led to more than 1,400 river restoration projects across Europe (Environment Agency 2022), with a focus on balanced fish communities and improved ecological health. This initiative included ввnumerous restoration projects in the lower river Rhine, such as groynes lowering, side channel reopening, reconnecting former floodplains, and dike relocation.

From 2017 to 2020, a comprehensive monitoring program was implemented to assess the effectiveness of these measures. This large-scale field study examined habitat conditions and young-of-the-year (YOY) fish populations in 46 restored floodplains in the lower river Rhine. The findings showed that restoring flowing conditions and permanent lateral connectivity with the main channel greatly benefits fish biodiversity. There was no 'one size fits all' restoration approach (Fig. 6), as each restoration type created distinct nursery habitats that supported different ecological fish groups, species, and community characteristics (for example, biodiversity and abundance). Effective river restoration requires multiple spatial scales of habitat heterogeneity and complementary projects to support the entire fish community, similar to natural river systems.

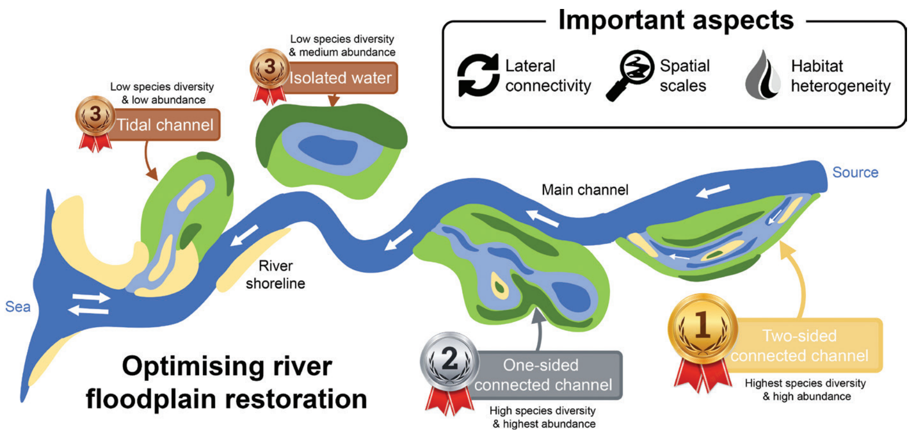

Figure 6. Schematised lowland river with typical floodplain restoration projects: two-sided connected channel, one-sided connected channel, isolated water, tidal channel and river shoreline (control). A ranking of restoration types is shown to demonstrate the importance of each type for different aspects of the young-of-the-year riverine fish community. Permanent lateral connectivity and the availability of habitat heterogeneity are important components of the success of these river restoration projects.

these objectives influence the design, management, monitoring, and evaluation of the efforts (Stoffers et al. 2021; Stoffers et al. 2022; Thieme et al. 2023). Setting these goals early ensures that restoration activities are aligned with desired outcomes, increasing the effectiveness and efficiency of the interventions.

Environmental flow regimes

To maximise the ecological benefits of restoration, efforts should be directed towards re-establishing continuous, free-flowing segments of the original dendritic river network, recognising the four-dimensional nature of river systems. This challenge becomes even more difficult during severe droughts, when maintaining river flow is critical for sustaining ecosystem services such as self-purification and clean water provisioning (Chiu et al. 2017). Droughts exacerbate the effects of excessive water consumption, river channelisation, land use changes, wetland drainage, and climate change (see Kaden et al. 2026 in this issue for more details on drivers of wetland degradation in Europe).

Integrating environmental flow (e-flow) regimes into river management can help address these issues (Bunn and Arthington 2002; Arthington et al. 2006). Here, environmental flows are understood as management-prescribed flow releases designed to support ecological functioning, which differ from ecological flows that describe the flow conditions required by ecosystems themselves, irrespective of management intervention. An environmental flow regime is a planned schedule of water releases from structures such as dams that are intended to closely mimic natural river flow patterns, thereby supporting aquatic ecosystem integrity and biodiversity. When properly implemented, e-flows improve connectivity across spatial and temporal heterogeneity in river networks by simulating natural flow patterns and allocating resources to vulnerable habitats during dry periods. E-flow implementation follows adaptive management principles, which allow for target adjustments in response to changing conditions. The goal is to restore or mimic natural flow regimes rather than simply creating floods (de Jalón et al. 2016; Palmer and Ruhi 2019).

Despite the implementation of e-flow regimes in European river restoration projects to improve longitudinal connectivity and meet WFD standards, implementing appropriate e-flow regimes is frequently hampered by limited resources, knowledge gaps, local capacity constraints, institutional barriers, conflicts of interest, and a lack of political will and public support (Ramos et al. 2017). Dealing with these issues is becoming more pressing, given the global increase in hydropower dam construction (Zarfl et al. 2015; Winemiller et al. 2016; Couto and Olden 2018) and rising water demands in arid or climate-affected regions. It is important to note that, while e-flow regimes frequently resemble scaled-down natural flows, their implementation will not fully restore natural flow dynamics. Nevertheless, well-designed e-flow implementations have demonstrated clear ecological benefits, including improved community composition of fish, macroinvertebrates, and macrophytes, as shown for restored floodplain systems in the upper Danube (Pander et al. 2019).

Collaboration, engagement, and awareness

Engaging with stakeholders

The lack of awareness about the ecological significance of rivers, as highlighted by Flávio et al. (2017), underscores a broader challenge: many freshwater processes are invisible to the naked eye, leading to widespread ignorance among stakeholders and the public about the roles played by FFRs and freshwater biota in sustaining aquatic and terrestrial ecosystems. Vári et al. (2022) emphasise that addressing this issue requires proactive stakeholder engagement and enhanced dissemination of information to better understand and meet human demands on each river network for effective restoration. Such stakeholder engagement is a central building block of freshwater restoration (see Birk et al. 2026).

However, challenges arise from competing economic interests and the misconception that biodiversity targets and nature-based solutions are synergistic and contribute important benefits for society (e.g., Stoffers et al. 2024; Stammel et al. 2026; Macháč et al. 2026). Such perceptions contributed to political headwind during the NRR's adoption process (Hering et al. 2023), which has become even more prevalent in the current EU legislative period (see Klusmann et al. 2026). Given the high relevance of the agricultural sector for wetland management (see also Rouillard et al. 2026), it is especially critical to form strong partnerships with the agricultural sector and raise awareness about the benefits of FFR for the sector. Enhancing these relationships, along with a focused effort to resolve conflicts, promote informed dialogues, and bridge perception gaps among all stakeholders is fundamental (Flávio et al. 2017; Nagel et al. 2025). Moreover, all available planning instruments (National Restoration Plans under the NRR, River Basin Management Plans under the WFD, regional and local initiatives, etc.) should be well integrated, to avoid conflicts and harness synergies. Employing these strategies will help share recent scientific advancements, implement best practices, and make well-informed policy decisions, all of which are essential for fostering and maintaining effective stakeholder collaboration in river restoration efforts. Furthermore, monitoring data should be made publicly available to stakeholders, river basin managers, policymakers, Member States, and the scientific community so that threats to restoration success can be addressed quickly.

Box 2. The 'Blue Belt' programme for river and floodplain restoration along German federal waterways.

In Germany, new opportunities for river and floodplain restoration arise from the Blue Belt programme, which is creating a network of restoration projects along federal waterways (Fig. 7).

Responding to the documented decline of floodplains in the 2009 and 2021 Status Reports (Koenzen et al. 2021), the Federal Government adopted the Blue Belt Programme in 2017 to guide the return of shipping channels to more natural states. The aim is to improve the ecological status of federal waterways and their floodplains, with a particular focus on sections no longer required for commercial navigation, which is about 2,800 km in length (BMUV and BMV 2019).

Jointly led by the Federal Ministry of Transport and the Federal Ministry for the Environment, the programme develops a coherent ecological network aligned with navigation while creating synergies with water management, nature conservation, flood protection, and tourism. Its core pillars are: (1) establishing the legal framework and planning instruments; (2) designing the ecological network of rivers and floodplains; (3) integrating state-owned areas to unlock space for restoration; (4) providing a dedicated floodplain funding scheme; (5) developing restoration concepts for waterways without goods transport; (6) creating ecological stepping stones to reconnect habitats; (7) embedding ecological principles in routine maintenance and engineering works; and (8) conducting regular monitoring to support adaptive management (BMUV and BMV 2019). The programme runs until 2050, with interim targets for 2035, and allocates about €50 million annually for river and embankment restoration and €12–15 million for floodplains. Implementation is coordinated with the Länder, which are responsible for nature conservation and flood-risk management in floodplains.

Since 2019, local authorities, non-governmental organisation (NGOs), associations, and others can apply for funding via the Federal Agency for Nature Conservation (BfN) to develop floodplains along federal waterways as centres of biological diversity and axes of the ecological network. Fifteen projects are currently funded across most river basins, with additional projects implemented by the Federal Waterways and Shipping Administration (Fig. 7; www.blaues-band.bund.de). Several are also part of Germany's Action Plan on nature-based solutions for climate and biodiversity. Measures include morphological improvements to unregulated reaches and banks, restoration or reconnection of side channels, dyke removal, and promotion of near-natural floodplain habitats through succession or extensive grazing.

Figure 7. Ongoing and realised projects of The 'Blue Belt' programme in Germany. Source: BfN, FG II 2.4, date 2/2025, More information: https://www.blaues-band.bund.de.

Furthermore, achieving long-term results requires a multi-actor approach and co-creation of river restoration plans. This approach entails involving a wide range of stakeholders, including local communities, research institutions, environmental organisations, government agencies, and the private sector, in the planning and implementation process. Restoration plans can address the complex interplay between agricultural practices, watercourse management, and broader landscape planning by incorporating multiple perspectives and expertise. This collaborative effort ensures that all stakeholders' diverse interests and needs are addressed, resulting in more effective and resilient river restoration strategies (see also Nagel et al. 2025).

Improving the science-policy interface

Improving the current science-policy interface in Europe is critical to restoring FFRs because it ensures that scientific research informs and improves management practices. A major issue is the gap between academic knowledge and practical application, which is frequently caused by poor communication among scientists, policymakers, and stakeholders (Lindenmayer 2020). At the same time, recent practitioner-led case studies demonstrate that this gap can be successfully bridged through long-term collaboration, institutionalised stakeholder engagement, and knowledge co-production (e.g., Nagel et al. 2025). To close the gap, these groups must engage in focused dialogue to align freshwater biodiversity research with policy objectives. Developing a European-level online platform to facilitate this dialogue while also supporting the European Green Deal and BDS2030 ecological transition goals could greatly facilitate this (see also Box 3).

Citizen engagement is of great importance in gaining support for freshwater biodiversity projects (Hermoso et al. 2022; Maasri et al. 2022). Initiatives that involve stakeholders and community science can improve river flow monitoring (Allen et al. 2019; Truchy et al. 2023), barrier tracking, biological and water quality monitoring, and restoration activities (Huddart et al. 2016). Increased communication (or knowledge transfer) at the science-policy interface is important to ensure that restoration efforts are based on current scientific knowledge, align with policy goals, and address stakeholder concerns, resulting in more effective and sustainable outcomes.

Facilitating participation and collaboration

Large-scale restoration of FFRs and the broader freshwater biodiversity will enrich both human populations and the environment. Such efforts are essential, not only for preserving specific riverine ecosystems, but also for promoting global biodiversity. Member States must take an active role in these restoration and protection efforts, including but not limited to the development and implementation of National Restoration Plans, recognising the role that these ecosystems play in maintaining ecological functions and services. As the requirements of restoration are very locally specific, no generally applicable guidelines can be formulated for the whole of Europe. It is important to regionally identify most appropriate restoration or conservation segments and to implement individual landscape plans.

A significant impediment to achieving these objectives is a lack of political will and sufficient commitment to allocate necessary resources and funding. This challenge is further complicated by the fact of a lack of economic value estimates for biodiversity in general and that freshwater biodiversity research and conservation typically receive even less funding than terrestrial and marine counterparts, impeding comprehensive environmental restoration efforts (Albert et al. 2021; Maasri et al. 2022).

Rivers cross political boundaries; thus, supra-regional and international communication must be promoted to be able to utilise ecological functions of rivers as effectively as possible. Addressing conflicts in barrier removal and ecological flow implementation necessitates multi-stakeholder approaches, initiating negotiations among all actors and stakeholders, similar to the integrated approaches used in water-scarce regions. In many cases, NGOs play a

Box 3. The European Freshwater Science-Policy-Interface.

Bridging the gap between academic research and practical management is essential for restoring FFRs across Europe, and for that reason the efficient use of science-policy interaction plays a key role in freshwater governance. Improved communication among scientists, policymakers, and stakeholders can help align freshwater biodiversity research with policy needs. A European-level online platform would facilitate this dialogue and contribute to the achievement of the European Green Deal and BDS2030 goals (Lindenmayer 2020).

BioAgora, a collaborative project funded by the EU Horizon Europe programme, aims to create this online platform and the scientific pillar of the EU Knowledge Centre for Biodiversity (KCBD), also known as the Science Service for Biodiversity (SSBD) (Fig. 8). The project promotes targeted dialogue among scientists, knowledge holders, and policy actors in the EU biodiversity policy arena. By evaluating existing science-policy interfaces and testing approaches in demonstration cases, BioAgora identifies key knowledge needs and proposes effective pathways for connecting knowledge to policy. The SSBD aims to provide crucial support for the necessary sustainability transformation in Europe, as outlined in the European Green Deal, by facilitating easier access of scientific results to decision-makers at the local, national, and European levels. The project aims at establishing a science service to meet European biodiversity targets and initiate transformative systemic changes in the society. BioAgora uses demonstration cases to show how governance can improve science-based transformative change while also supporting the implementation, monitoring, reporting, and review of the EU Biodiversity targets. This approach seeks to bridge the gap between scientific research and policy implementation, ensuring that efforts to bend the curve of biodiversity decline are informed by innovative scientific knowledge and effectively translated into actionable steps.

One of BioAgora's demonstration cases is centred around the BDS2030 goal of restoring 25,000 km of FFRs. This case will highlight real-life actions and existing processes in freshwater biodiversity management and governance contexts, connecting with existing networks, mapping river restoration efforts, ecological monitoring, and citizen science participation, and identifying capacity gaps and research needs in the network.

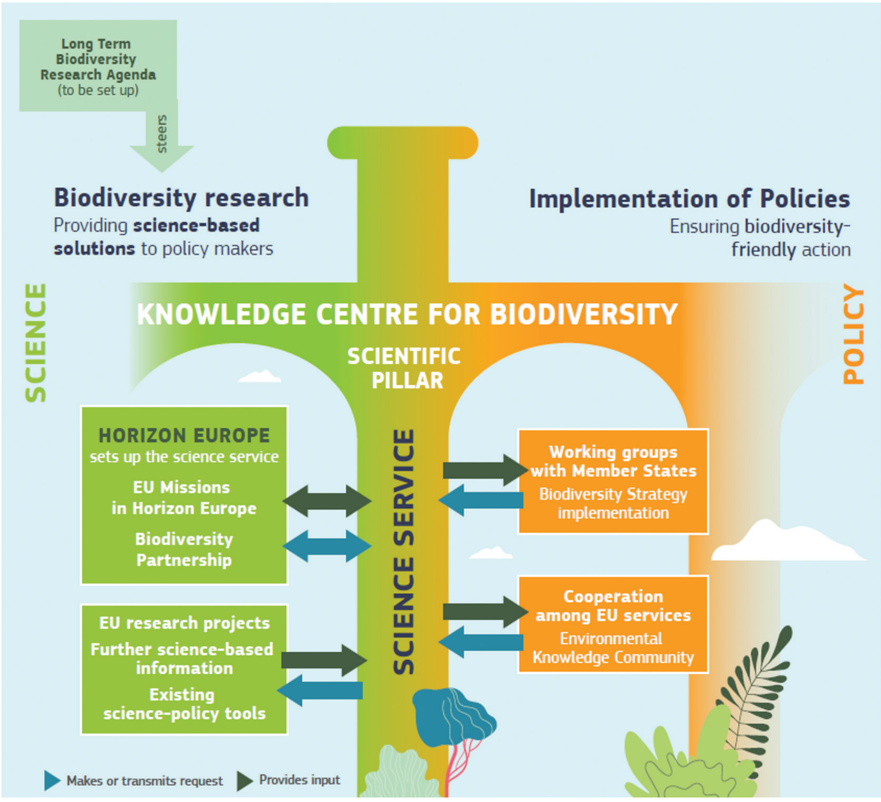

Figure 8. The EU BioAgora project aims to develop an online platform that will serve as the scientific foundation of the EU Knowledge Centre for Biodiversity, also known as the Science Service for Biodiversity. This platform connects biodiversity research and knowledge with policymakers, as well as policy implementation.

crucial facilitating role in these processes by initiating dialogue, building trust, and bringing diverse stakeholders to the same table at early stages of planning and implementation. These processes should establish flow requirements and incorporate comprehensive water planning to promote sustainable water use and ecosystem restoration (Serra-Llobet et al. 2022; Arthington et al. 2023; Jumani et al. 2023). However, recent political developments in parts of Europe indicate increasing pressure on, and in some cases the dismantling of, NGOs, which may undermine their capacity to effectively contribute to participatory river restoration and governance processes. Immediate action is required to protect remaining natural rivers and accelerate the implementation of BDS2030 and NRR goals, for the benefit of both the environment and humanity.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

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Author contributions

TS: Conceptualization (equal), Investigation (lead), Visualization (lead), Writing – original draft (lead), Writing – review and editing (lead). A-KS: Conceptualization (equal), Writing – original draft (equal), Writing – review and editing (equal). TE: Writing – original draft (equal), Writing – review and editing (equal). LK: Writing – original draft (equal), Writing – review and editing (equal). MS: Conceptualization (equal), Visualization (equal), Writing – original draft (equal), Writing – review and editing (equal). LN: Conceptualization (equal), Writing – original draft (equal), Writing – review and editing (equal).

Author ORCIDs

Twan Stoffers https://orcid.org/0000-0002-2329-3032
Ann-Kristin Schultze https://orcid.org/0000-0002-1922-4843
Thomas Ehlert https://orcid.org/0009-0005-3275-8996
Mathias Scholz https://orcid.org/0000-0002-8463-9500
Leopold A. J. Nagelkerke https://orcid.org/0000-0003-1130-749X

Data availability

All of the data that support the findings of this study are available in the main text.

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