Communications Earth & Environment https://doi.org/10.1038/s43247-026-03428-9

Article in Press

A collaborative research agenda for restoring free-flowing rivers

Received: 5 May 2025

Accepted: 11 March 2026

Cite this article as: Stoffers, T., Vuorinen, K.E., Schroer, S. *et al.* A collaborative research agenda for restoring free-flowing rivers. *Commun Earth Environ* (2026). https://doi.org/10.1038/s43247-026-03428-9

Twan Stoffers, Katariina E. M. Vuorinen, Sibylle Schroer, Phoebe C. Griffith, Miriam Colls, Tibor Erős, Juergen Geist, Mathias Kuemmerlen, Socrates Schouten, Ruben van Treeck, Maria Alp, Damiano Baldan, Sebastian Birk, Olena Bilous, Florian Borgwardt, Mario Brauns, Anthonie D. Buijse, Viola Clausnitzer, Mayra E. Darre, Jelger Elings, Patrick Fink, Teresa Ferreira, Katarzyna Glinska-Lewczuk, Johannes Graupner, Daria Gundermann, Fengzhi He, Thomas Hein, Zeb S. Hogan, Lionel L'Hoste, Paul Meulenbroek, Imanol Miqueleiz, Sathaporn Monprapussorn, Camille L. Musseau, Leopold A. J. Nagelkerke, Joacim Näslund, Paula dos Reis Oliveira, Joachim Pander, Polona Pengal, Marie Pfeiffer, Sebastian L. Rock, Joshua L. Royte, Timo D. Rittweg, Anna Scaini, Astrid Schmidt-Kloiber, Stefan Schmutz, Mathias Scholz, Gabriel A. Singer, Adam Tarkowski, Kimmo T. Tolonen, Jonah Tosney, Martin Tschikof, Jimmy van Rijn, Pieterjan Verhelst, Franziska Walther, Bernhard Wegscheider, Christian Wolter, Chen Xiao, Thomas A. Worthington, Stamatis Zogaris & Sonja C. Jähnig

A collaborative research agenda for restoring free-flowing rivers

Twan Stoffers[1,2]*, Katariina E.M. Vuorinen[3], Sibylle Schroer[1], Phoebe C. Griffith[1], Miriam Colls[4], Tibor Erős[5], Juergen Geist[6], Mathias Kuemmerlen[7], Socrates Schouten[8], Ruben van Treeck[9], Maria Alp[10], Damiano Baldan[11], Sebastian Birk[12], Olena Bilous[13,14], Florian Borgwardt[13], Mario Brauns[15], Anthonie D. Buijse[16,2], Viola Clausnitzer[17], Mayra E. Darre[18], Jelger Elings[19], Patrick Fink[20], Teresa Ferreira[21], Katarzyna Glinska-Lewczuk[22], Johannes Graupner[1], Daria Gundermann[1], Fengzhi He[23,1], Thomas Hein[13], Zeb S. Hogan[24], Lionel L'Hoste[25], Paul Meulenbroek[13], Imanol Miqueleiz[26], Sathaporn Monprapussorn[27], Camille L. Musseau[1], Leopold A.J. Nagelkerke[2], Joacim Näslund[28], Paula dos Reis Oliveira[29], Joachim Pander[6], Polona Pengal[30], Marie Pfeiffer[31], Sebastian L. Rock[32], Joshua L. Royte[33], Timo D. Rittweg[1], Anna Scaini[34], Astrid Schmidt-Kloiber[13], Stefan Schmutz[13], Mathias Scholz[35], Gabriel A. Singer[36], Adam Tarkowski[37], Kimmo T. Tolonen[38], Jonah Tosney[39], Martin Tschikof[13], Jimmy van Rijn[40], Pieterjan Verhelst[41], Franziska Walther[42], Bernhard Wegscheider[43,19], Christian Wolter[1], Chen Xiao[44], Thomas A. Worthington[45], Stamatis Zogaris[46], & Sonja C. Jähnig[1,47]

1 Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin, Germany
2 Aquaculture biology & Fisheries ecology Group, Wageningen University & Research (WUR), Wageningen, The Netherlands
3 Norwegian Institute for Nature Research (NINA), Lillehammer, Norway
4 Department of Plant Biology and Ecology, University of the Basque Country (UPV/EHU), Bilbao, Spain
5 HUN-REN Balaton Limnological Research Institute, Tihany, Hungary
6 Technical University of Munich, Aquatic Systems Biology, Freising, Germany
7 Federal Agency for Nature Conservation (BfN), Bonn, Germany
8 Wageningen Environmental Research, Wageningen, The Netherlands
9 World Wildlife Fund Germany, Berlin, Germany
10 INRAE, RiverLY, Villeurbanne, France
11 National Institute for Oceanography and Applied Geophysics (OGS), Trieste, Italy
12 Aquatic Ecology and Centre for Water and Environmental Research, University of Duisburg-Essen, Essen, Germany
13 Christian Doppler Laboratory for Meta Ecosystem Dynamics in Riverine Landscapes, University of Natural Resources and Life Sciences (BOKU), Vienna, Austria
14 Institute of Hydrobiology, National Academy of Sciences of Ukraine, Kyiv, Ukraine
15 Helmholtz Centre for Environmental Research (UFZ), Leipzig, Germany
16 Department of Freshwater Ecology and Water Quality, Deltares, Delft, The Netherlands
17 Senckenberg Research Institute, Görlitz, Germany
18 Department of Chemistry and Bioscience, Aalborg University, Aalborg, Denmark
19 Department of Fish Ecology and Evolution, EAWAG, Swiss Federal Institute for Aquatic Science and Technology, Kastanienbaum, Switzerland
20 Institute for Zoology, University of Cologne, Cologne, Germany
21 Forest Research Centre, Associate Laboratory TERRA, School of Agriculture, University of Lisbon, Tapada da Ajuda 1349-017, Lisbon, Portugal
22 Department of Water Management and Climatology, University of Warmia and Mazury, Olsztyn, Poland
23 Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun, China
24 University of Nevada, Reno, Nevada, USA
25 Luxembourg Institute of Science and Technology (LIST), Belvaux, Luxembourg
26 Department of Natural Resources and the Environment, Cornell University, Ithaca, USA
27 Department of Geography, Srinakharinwirot University, Bangkok, Thailand
28 Swedish University of Agricultural Sciences, Institute of Freshwater Research, Uppsala, Sweden
29 University of São Paulo (ESALQ), Piracicaba, Brazil
30 Institute for Ichthyological and Ecological Research (REVIVO), Gradcu, Slovenia
31 World Wildlife Fund Austria, Vienna, Austria
32 Karlstad University, River Ecology and Management (RivEM), Karlstad, Sweden
33 The Nature Conservancy, Maine, USA
34 Stockholm University, Department of Physical Geography & Bolin Centre for Climate Research, Stockholm, Sweden
35 Helmholtz Centre for Environmental Research (UFZ), Department Conservation Biology & Social-Ecological Systems,

Leipzig, Germany
36 University of Innsbruck, Department of Ecology, Innsbruck, Austria
37 University of Warsaw, Warsaw, Poland
38 Finnish Environment Institute (SYKE), Helsinki, Finland
39 Norfolk Rivers Trust, Holt, United Kingdom
40 Van Hall Larenstein University of Applied Sciences, Leeuwarden, The Netherlands
41 Research Institute for Nature and Forest (INBO), Brussels, Belgium
42 ETH Zurich, Institute for Spatial and Landscape Development, Zürich, Switzerland
43 University of Bern, Institute of Ecology and Evolution, Bern, Switzerland
44 Anhui Agricultural University, Hefei, China
45 University of Cambridge, Conservation Science Group, Cambridge, UK
46 Hellenic Centre for Marine Research, Anavissos, Greece
47 Geography Department, Humboldt-Universität zu Berlin, Berlin, Germany

* Corresponding author at: Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin, Germany

Email: twan.stoffers@wur.nl

Keywords

River connectivity, freshwater biodiversity, interdisciplinary research, policy implementation, socio-ecological systems, transdisciplinary collaboration, river restoration, Nature Restoration Regulation (NRR)

Running head

Research agenda for restoring free-flowing rivers

Abstract

Rivers are increasingly fragmented and degraded, yet the European Union Nature Restoration Regulation calls for restoring at least 25,000 kilometres of free-flowing rivers by 2030. Translating this ambition into effective implementation remains challenging because restoration priorities differ across ecological, social, economic, and governance contexts. Here we synthesize expert knowledge from 45 countries through a structured, multi-step prioritization process to identify research priorities for restoring free-flowing rivers in Europe. We identified 27 priorities and analysed how expert background and spatial context influenced their ranking. Restoration priorities differed systematically depending on whether experts emphasized ecological integrity, community engagement, economic considerations, or governance capacity, revealing clear patterns in how disciplinary and professional perspectives shape implementation pathways. This demonstrates that restoration strategies cannot be universal but must be adapted to local and regional political, institutional, and ecological conditions. Building on these findings, we propose a structured prioritisation framework that links barrier removal, connectivity restoration, governance mechanisms, and policy instruments to context-specific needs. Together, our results provide an empirically grounded and implementation-oriented roadmap to support European Union Member States in delivering ambitious river restoration targets in a context-sensitive and socially robust manner.

Introduction

Rivers are the lifelines of the planet, supporting biodiversity and providing essential contributions to people and their well-being [1–3]. Yet, river ecosystems are suffering from rapid biodiversity loss caused by fragmentation, habitat degradation, invasive alien species, pollution, all exacerbated by the current context of climate change [4–6]. For centuries, infrastructure has been built to harness goods and services provided by rivers, at a high ecological cost. Structures, such as dams, weirs, dykes, and channelized river sections, have not only disrupted the natural flow regimes along river courses, but have also altered sediment transport, and negatively impact biodiversity and ecosystem functioning along all connectivity dimensions [7–13]. Connectivity, defined as the movement and transformation of materials, energy, and organisms, is vital to river health and operates along four key dimensions: longitudinal (from headwaters to river mouth), lateral (between the channel and floodplains), vertical (from surface water to groundwater), and temporal (seasonal or annual) [14–16]. Thus, disruptions to this connectivity impede, for instance, access to critical habitats for resident and migratory species [17, 18], with cascading effects that ripple far beyond the rivers themselves [19, 20]. Today, over 63% of the world's rivers longer than 1,000 km do not flow freely [15], and global migratory freshwater fish populations have declined by 81% over the last 50 years [21]. In Europe, over one million physical barriers continue to impede river connectivity [22], with 90% of the original floodplains degraded [23], and only 44% of European rivers meeting the supposedly binding targets of the EU Water Framework Directive (WFD; 2000/60/EC) [24].

Global initiatives such as the UN Decade on Ecosystem Restoration (2021–2030), the Ramsar Convention on Wetlands, and the Convention on Biological Diversity seek to guide and coordinate freshwater ecosystem recovery [5, 25]. At the European level, the Nature Restoration Regulation [26] was enforced with the aim of restoring at least 25,000 km of rivers to a free-flowing state by 2030, among other goals [26, 27]. Although the NRR builds on established policies like the WFD and the Habitats Directive (1992/43/EEC), its success depends on the ability of responsible parties to translate its ambitious objectives into practical, effective action on an unprecedented scale. Penca and Tănăsescu (2025) warn that restoration initiatives will be unsuccessful unless the root causes of biodiversity loss are addressed. Other authors also consider it important to look beyond ecological aspects: Hering et al. [36] emphasize that, while the NRR takes a traditional conservationist approach, meeting its objectives requires adequate funding, institutional support, and stakeholder engagement. In fact, responsible parties must go beyond resource allocation to address fundamental conflicts regarding values and priorities [28]. Therefore, to successfully implement the NRR, restoration efforts must integrate ecological, social, and political dimensions through adaptive, cross-sectoral planning, aligning with recent calls for "fundamental, system-wide shifts in views, structures, and practices" [29, 30] and supported by growing empirical evidence that socio-ecohydrological and multi-actor restoration initiatives yield more resilient and lasting outcomes [27, 31–35].

In light of these persistent policy obstacles to implementation and complex socio-ecohydrological interactions, recent advances in structured methodologies have emerged as promising tools to bridge the gap between (and within) research and the practical implementation of restoration initiatives. Techniques such as horizon scanning [37–39], collaborative research prioritization [40, 41], and structured expert elicitation [42, 43] have been demonstrated to be effective in identifying key research needs. For instance, Harper et al. [45] distilled 25 essential research questions aimed at reversing freshwater biodiversity decline. This underscores the imperative for evidence-based management and strong policy frameworks. Similarly, Van Rees et al. [46] emphasized that freshwater biodiversity is disproportionately threatened and under-prioritized relative to marine and terrestrial systems, advocating for policies that address environmental flows, water quality, and integrated water management. While their work emphasizes that research and conservation actions should mutually reinforce one another through sound evidence and multidisciplinary collaboration, our study extends this approach by explicitly aligning research priorities with tangible conservation and restoration objectives for free-flowing rivers. These are defined as four-dimensional fluvial systems, extending from sea to source, in which ecosystem functions and services are minimally affected by human-induced disruptions in connectivity [15, 44].

Yet, despite growing recognition of the need for integration, genuine collaboration between natural and social sciences remains rare. Persistent barriers such as disciplinary paradigms, insufficient institutional support, and limited collaborative skills continue to constrain integration [47]. Empirical analyses show that multidisciplinary research still represents only a small fraction of publications, even in fields where coupled human-natural processes are central [48]. Engaging social sciences is key to producing outcomes that are more legitimate, salient, and effective [49]. Building on these insights, our study advances an implementation-oriented, cross-disciplinary research agenda that explicitly links scientific priorities to (i) the typology and context of river barriers, (ii) mechanisms for collaboration across natural and social domains, and (iii) actionable policy frameworks such as the NRR and BDS 2030. In doing so, we move beyond conceptual appeals for interdisciplinarity toward a context-sensitive roadmap for restoring free-flowing rivers and translating research into practice, building on recent European initiatives that bridge scientific, policy, and stakeholder domains in river restoration [27, 31–33]. This roadmap explicitly acknowledges that restoration decisions are shaped by stakeholder perspectives, governance constraints, and political trade-offs across spatial scales.

Building on this need for more effective integration, we identify research priorities that emerge from the practical requirements of implementing river restoration in Europe as mandated by the legally binding NRR, which is a direct outcome of the EU Biodiversity Strategy 2030 [44]. Our aim is to identify (inter)disciplinary research priorities for successfully and efficiently restoring free-flowing rivers in Europe, thereby bridging the gap between scientific knowledge and practical implementation and accelerating evidence-based restoration efforts. To achieve this, we employed a four-step approach: (1) an online scoping survey to identify key research topics and priorities, (2) an expert workshop to refine these topics, (3) systematic ranking of research areas, and (4) advanced analyses of the ranking results through correspondence analysis to visualize topic clustering and assess how participant characteristics influence topic selection. This integrative methodology, incorporating horizon-scanning, collaborative prioritization, and best practices in expert-elicitation, ensures that the research agenda is scientifically robust and aligned with the needs of policymakers and practitioners working to restore Europe's river ecosystems. We hypothesize that achieving transformative change in the restoration of free-flowing rivers, as well as in the restoration of other ecosystem types, requires an interdisciplinary approach that integrates insights from the natural and social sciences. Our approach therefore serves as a best-practice example by linking research priorities to diverse restoration contexts and barrier-related challenges, aligning them with EU policy frameworks. This provides a clear, operational roadmap for translating research priorities into context-dependent restoration action.

Methods

To establish a research agenda that bridges the gap between scientific insights and practical policy implementation, we conducted a multi-step expert consultation and ranking process using a modified Delphi protocol [39, 43]. The Delphi method is a structured, iterative process used to obtain consensus among experts through multiple rounds of questionnaires. We applied a modified Delphi approach that combined open-ended scoping, in-person refinement, and structured ranking in a single cycle to balance inclusivity and feasibility. The following sections outline our approach (Fig. 1).

Collecting research topics

An online scoping survey was developed to identify key themes or questions (i.e. research topics) to be addressed to support the NRR target of restoring at least 25,000 km of European rivers to be in free-flowing condition by 2030. Free-flowing rivers are defined here as four-dimensional fluvial systems from source to sea with minimal human-induced disruptions [15, 44]. In this study, we use the term “barrier-related challenges” broadly to include structural and operational disruptions to river connectivity (e.g., dams, weirs, sluices, culverts, embankments, and hydropeaking). The survey was distributed within established networks of experts in river ecology, river restoration and environmental management. An overview of the networks through which the scoping survey was initially distributed is provided in Supplementary Material 1. We ensured broad disciplinary and geographical representation by targeting researchers, practitioners, water managers, policymakers, and NGO representatives. Respondents were asked to list up to three research topics or questions, specify the spatial scale at which each topic should be addressed, and provide information regarding their scientific background, professional position, and country of residence (see Suppl. Mat. 2 for the full survey instrument).

A pilot test of the scoping survey was conducted at the Norwegian Institute for Nature Research via internal email lists targeted at both social and natural scientists working on aquatic biodiversity. This pilot yielded 30 responses and was deemed successful, requiring no substantial refinements. The survey was subsequently launched on SurveyMonkey (SurveyMonkey Inc., San Mateo, CA) from 4 to 23 March 2024, using targeted emails, newsletters, list-servers, and social media in a snowball sampling approach initiated by the group of core authors and their freshwater networks (Suppl. Mat. 1). In addition, the authors distributed the initial scoping survey within their own organizations to further increase disciplinary and geographical reach. Although snowball sampling may introduce biases, this method is widely recognized as an effective way to reach the diverse, transdisciplinary community of scientists and practitioners in this field [50].

A total of 714 responses from 237 respondents were manually reviewed for typographical errors, linguistic clarity, and standardized terminology. Responses containing multiple research topics were split into distinct entries, whereas similar responses were combined into single entries. This consolidation process resulted in 425 non-redundant submissions. Using a hierarchical analysis, these were then categorized into eight broad categories, which were further subdivided into 27 preliminary research topics.

Expert workshop and refining research topics

On April 18th, 2024, an expert workshop was convened at the Free Flow 2024 Conference (https://freeflowconference.eu/) in Groningen, the Netherlands. The workshop brought together 18 participants from 13 countries, including 15 European and three non-European participants. Participants represented diverse scientific disciplines (14 from the natural sciences and four from the social sciences), and professional roles, including researchers (10), NGO representatives (5), water management professionals (2), and one ecological consultant. The workshop featured an interactive brainstorming session to refine the preliminary research topics. Participants were also guided by three questions: (1) What are the most pressing research needs for restoring free-flowing rivers? (2) Which of these research needs could be addressed through interdisciplinary collaboration? and (3) What are the potential political and practical barriers to implementing our research topics? Their responses were recorded and incorporated into the discussion section of this paper to help prioritize research needs. Throughout the workshop, participants also contributed to the enhancement of our initial list by formulating concise descriptions for the key research topics and categorizing these topics into scientific disciplines (either "natural science" or "social science") (see Suppl. Mat. 3). Topics classified within natural science predominantly examined ecological processes, while those within social science focused on governance, stakeholder engagement, and economic trade-offs. We acknowledge that the distinctions between natural and social sciences can often be ambiguous, as numerous subjects inherently encompass multiple dimensions, including economic factors.

In addition, our author group assigned each topic to one or more spatial scales (local, regional, national, and global) based on its scope, potential impact, and capacity to influence policies or ecosystems (see Suppl. Mat. 4 for more details). The local scale captures direct, community-level interactions and impacts; the regional scale covers implications across multiple municipalities or within a specific watershed; the national scale reflects country-wide policies and initiatives; and the global scale addresses issues relevant to international governance and cross-border concerns.

Ranking of research priorities

After a preliminary test run at the Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB) (see Suppl. Mat. 2 for survey details), the ranking survey was distributed via SurveyMonkey to the 175 respondents who had expressed interest in further involvement in the study and kept open for participation from October 22nd to November 15th, 2024. Respondents were asked to rank their top 10 research topics from the list of 27 (randomized for each respondent), each accompanied by a detailed description (Suppl. Mat. 3). Only the top 10 rankings from each respondent were retained for analysis.

Analysis and synthesis of ranking data

The ranking data were analyzed, and, for each topic, we calculated the following measures: average ranking score, the frequency of appearance in the top 10, and the number of times the topic was ranked first, second, and third. Once calculated, each measure was ordered by priority, with 1 representing the highest priority and 27 the lowest. For the average ranking score, lower values indicated higher priority and were assigned a better rank (i.e., rank 1). In contrast, higher values received better ranks for frequency-based measures (top 10 appearance, and #1, #2, #3 ranking).

To generate the final overall ranking, we applied weighted percentages to reflect the relative importance of each measure: average score (30%), top 10 frequency (25%), #1 frequency (20%),

#2 frequency (15%), and #3 frequency (10%). This weighting approach assumes that the average score best represents the general perceived importance of a topic, thereby receiving the highest weight. In contrast, the top 10 frequency captures the consensus across respondents and was assigned a moderately high weight. The top three positions were weighted progressively lower (20%, 15%, and 10%, respectively) to reflect that #1 ranking is more influential than lower rankings. This approach is consistent with methods used in similar research prioritization exercises [40, 41]. The weighted values were then summed and normalized to produce a final priority score for each topic, with lower scores indicating higher overall priority. Finally, topics were sorted from 1 (lowest score; highest priority) to 27 (highest score; lowest priority). Ranking data, including calculations, are provided in Supplementary Material 5.

To assess the robustness of our weighting choices, we recalculated the composite ranking using two alternative schemes that modified the weight assigned to the average-score criterion while redistributing the remaining weight proportionally across the other four criteria. In Scenario B, the average-score weight was reduced to 20%, with the remaining weight reallocated proportionally (28.57%, 22.86%, 17.14%, 11.43%). In Scenario C, the average-score weight was increased to 40%, again with proportional redistribution (21.43%, 17.14%, 12.86%, 8.57%). These proportional percentages reflect the same relative differences between the top-10 frequency and the #1, #2, and #3 frequencies as in the original weighting scheme, scaled to the reduced or expanded remaining weight. We compared the resulting rankings using Spearman's ρ and Kendall's τ to evaluate consistency (see Suppl. Mat. 6).

To further explore the relationships among the research topics and assess the influence of participant characteristics, we conducted a Correspondence Analysis (CA). A binary matrix was constructed from the topic selections, where each respondent's inclusion of a topic in their top 10 priorities was coded as 1 and non-selection as 0. The analysis was performed using the ca package [51] in R [52], which simultaneously generated scores for both respondents and topics. Eigenvalues were calculated to determine the percentage of total inertia explained by the first two dimensions, revealing the primary patterns in research priorities. For example, differences along these axes may indicate contrasts between topics that are prioritized by different experts, regardless of traditional disciplinary boundaries. In fact, proximity of topics from distant disciplines would suggest a perceived need for interdisciplinary work to drive transformative change or resolve trade-offs. Respondent scores were merged with participant characteristics (discipline, profession, and country), and topic scores were linked with this background information. Finally, convex hulls were overlaid on the biplots to visualize group patterns.

Data availability

This study used two data types: (1) responses to an online scoping and ranking survey collected via SurveyMonkey, and (2) derived analytical datasets generated from these responses, including ranking matrices, weighting calculations, and correspondence analysis input files. All anonymized survey data, derived datasets supporting the findings of this study are provided in the Supplementary Materials (Supplementary Materials 3, 5, and 6) and in a separate data publication [91], which accompany this article. No external datasets were used. Because the original survey responses were collected anonymously, no personal or identifiable information is included. There are no restrictions on access to the data beyond the materials provided in the Supplementary Information.

Code availability
The code that was used for data analysis has been made available in a separate data publication [91].

Results

Participant information
The scoping survey generated 425 unique responses from 237 respondents from 45 countries (Suppl. Mat. 7), which were consolidated into 27 research topics across the natural and social sciences (Fig. 2; Suppl. Mat. 3). Most respondents were based in Europe, with 185 individuals (78.5%) coming from EU Member States. Among these, Germany had the highest representation with 32 participants (13.5%), followed by Austria (21; 8.9%), Sweden (21; 8.9%), the Netherlands (20; 8.4%), and Spain (17; 7.2%). In terms of professional roles, 152 respondents (64.1%) identified as researchers, 13.1% were NGO staff, 7.2% were water management professionals, and the remainder included ecological consultants, policy specialists, engineers, and science communicators. With regard to their scientific discipline, 209 respondents (88.2%) had a natural-science background, 17 (7.2%) a social-science background, and 11 did not specify. Finally, 104 respondents (43.9%) reported active involvement in river restoration efforts.

Our subsequent ranking survey involved 75 participants from 25 countries and exhibited a similar distribution: 77.3% were from EU Member States, with Germany again leading in representation, followed by Austria, the Netherlands, and Sweden. Professional roles were dominated by researchers (81.3%), and 94.7% of respondents came from natural sciences, with only 5.3% representing the social sciences (Suppl. Mat. 7).

Topics of relevance
Among the 425 unique submissions, social science topics were most frequently mentioned, with '*developing prioritization strategies for targeted restoration*' (82 mentions) and '*enhancing public awareness and communication strategies*' (80 mentions). The leading topic in natural sciences, '*enhancing riverine biodiversity and ecosystem functioning'*, received 79 mentions. Following these top three, the next four most frequently mentioned topics were '*identifying best practices and addressing hydropower impacts'* and '*engaging communities and stakeholders* (56 mentions each), followed by '*improving species migration through connectivity restoration'* (41 mentions) and '*developing effective monitoring frameworks for restored rivers'* (39 mentions). Natural science topics were predominantly associated with regional or local scales (15 out of 18 topics), while social science topics were distributed across all spatial scales, with no clear predominance at any particular level (Suppl. Mat. 3).

Ranked list of research priorities
The ranking analysis of all 27 research topics highlighted the top three as clear priorities: the highest-ranked topic '*enhancing riverine biodiversity and ecosystem functioning*' was included in the priority top 10 by 44 of the 75 respondents, the second-ranked '*developing prioritization strategies for targeted restoration*' by 46 respondents, and the third-ranked '*establishing restoration standards for free-flowing rivers*' by 33 respondents (Fig. 3; Suppl. Mat. 3). Overall, the top 14 topics represent an even balance between natural and social science topics, despite the scoping survey yielding more natural (18) than social science topics (9).

Spatial scale also played an important role in the prioritization of topics. Most of the top 10 topics were considered relevant at larger scales (national to global), while many of the lower-ranked topics were viewed as more pertinent at local and regional scales (Fig. 3). Importantly, the frequency with which a topic was mentioned in the scoping survey did not necessarily correspond with its final ranking. For example, topics such as '*securing long-term financial sustainability*', '*improving governance and stakeholder collaboration*', and '*developing cross-boundary governance models*' received relatively few mentions initially, but were later ranked highly (ranks 7, 9, and 14, respectively). Similarly, '*establishing restoration standards for free-flowing rivers*' was mentioned only 17 times in the first round but ranked third highest in the ranking survey (Fig. 3).

Our sensitivity analysis showed that rankings proved highly stable to alternative weightings (scenario B: ρ=0.996, τ=0.972; scenario C: ρ=0.985, τ=0.937). The composition of the top-10 priorities was unchanged in both scenarios, with only minor within-set reordering (maximum shift of two ranks under scenario B and one rank under scenario C: Suppl. Mat. 6). This indicates that our main conclusions are not driven by the specific weighting of the five criteria.

Clustering of topics

The correspondence analysis (CA) provided deeper insight into the clustering of topics, revealing which topics were often selected together in the top-10 priority lists. CA space clearly distinguishes between natural and social science topics, with minimal overlap. Topics within the same disciplinary category tended to be co-selected in respondents' top 10 lists, except for '*prioritization strategies*' and '*innovative technical solutions*', which spanned disciplinary boundaries (Fig. 4A). Analysis based on respondent background showed that while respondents with a natural science background formed a large cluster (n = 71), those with a social science background (n = 4) were concentrated within the social science portion of the CA space (Fig. 4B). This suggests that respondents with social science expertise preferentially selected topics related to '*stakeholder cooperation*', '*community and stakeholder involvement*', and the '*financing and viability*' of river restoration in their top 10 lists, though the low number of responses from social science experts limits broader interpretation of these findings.

Professional affiliation also influenced topic selection. Researchers (n = 61) generally endorsed a broad range of topics. In contrast, NGO-affiliated respondents (n = 7) tended to prioritize issues related to '*prioritization strategies*', '*financing and viability of restoration*', '*climate change adaptation*', '*cross-boundary governance*', and '*science-policy and legal frameworks.*' In contrast, water managers (n = 3) focused more on natural science topics, including '*invasive alien species management*', '*riparian ecology*', and '*habitat availability*' (Fig. 4C). No clear relationship was observed between participants' country of residence and the topics they included in their top 10 list. However, German respondents more frequently prioritized specialized natural science topics related to '*water quality*', '*pollutant and sediment transport*', and '*riparian ecology*' (Fig. 4D).

Top 10 research priorities to restore free-flowing rivers

The ranking study revealed key insights regarding research priorities for restoring free-flowing rivers. In Table 1, we present the top 10 highest-ranked research priorities in more detail, while the full list of 27 topics and their descriptions is provided in Supplementary Material 8.

Discussion

Our study helps address global challenges faced by river ecosystems through bridging the gap between scientific research and the practical implementation of river restoration policies [53]. Building on previous interdisciplinary agenda-setting efforts [45, 46], it provides the first policy-aligned, implementation-oriented research roadmap specifically tailored to restoring free-flowing rivers. Unlike earlier syntheses, our approach links research priorities to diverse restoration contexts and barrier-related challenges and aligns them directly with the EU NRR and BDS 2030. By integrating diverse expert opinions, our analysis not only maps current research fields in river restoration but also highlights where future scientific work can better support stakeholders in politics, governance, administration, and practice. This integration of ecological knowledge with governance, stakeholder participation, and multi-scale coordination closely reflects Elinor Ostrom's foundational work on the governance of common-pool resources, which emphasises polycentric institutions, participatory decision-making, and adaptive learning as prerequisites for sustainable environmental management [54, 55].

Notably, we identify three top research priorities: (1) enhancing riverine biodiversity and ecosystem functioning, (2) developing prioritization strategies for targeted restoration, and (3) establishing restoration standards. Our survey reconfirms the critical role of these often-mentioned research priorities in river restoration, but it also reveals additional, emerging topics that promise to reshape current paradigms, particularly for environmental scientists. Enhancing riverine biodiversity and ecosystem functioning, which strengthens the natural resilience of river ecosystems, represents the overarching target of free-flowing river restoration under the NRR, and also aligns with global restoration aims in the UN Decade on Ecosystem Restoration (2021–2030), the Ramsar Convention on Wetlands, and the Convention on Biological Diversity. Meanwhile, prioritization strategies and restoration standards serve as essential adaptive management tools guiding effective interventions. Importantly, our work underscores that translating these priorities into actionable policies may benefit from improved understanding of robust stakeholder involvement and communication. In the following sections, we detail how these priorities integrate interdisciplinary approaches, address technical and social challenges, and inform policy.

The presence and future of interdisciplinarity and stakeholder integration

Effective restoration of free-flowing rivers has repeatedly been argued to require an integrated approach that combines ecological, hydrological, sociocultural, and economic dimensions [56, 57]. This integration enables restored rivers to deliver a broad array of ecosystem services, ranging from provisioning (e.g., water and food supply) and regulating (e.g., self-purification and flow regulation) to cultural services (e.g., recreation and heritage preservation) [3, 58], which together have the potential to strengthen community well-being and to support local economies. The portfolio of top-ranked research topics allows us to recognize the importance of this link: the top-ranked priority of enhancing riverine biodiversity is indirectly but closely associated with many ecosystem services, while additional priorities addressing flood, drought, and climate change mitigation (ranks 8 and 10) more directly illustrate the interdependence between ecological integrity and socio-economic resilience (Fig. 3; Table 1). By incorporating these broader societal benefits into restoration strategies, policymakers can design interventions that restore ecological integrity and enhance the adaptive capacity of both aquatic ecosystems and local communities.

However, translating this conceptual integration into practice requires dedicated mechanisms that connect disciplines with management and policy processes [47, 54, 55].

To address this challenge, several workable models have emerged that illustrate how interdisciplinary collaboration can be effectively operationalized. First, structural frameworks such as the "Radically Inter- and Trans-disciplinary Environments (RITE)" model proposed by Holm et al. [59] emphasize the need for long-term institutional support and funding strategies that enable scientists from social, human, natural, and technical disciplines to collaborate from the outset. Such frameworks also underscore that interdisciplinary collaboration requires stable and sustained funding arrangements, as short-term or sequential project cycles rarely provide the continuity needed for shared concepts, methods, and goals to develop. Rather than treating interdisciplinarity as ad hoc or actor-led, such models call for creating dedicated environments where shared knowledge and methods can evolve. Second, boundary-spanning consortia (e.g., the European Centre for River Restoration) help sustain collaboration beyond project cycles by maintaining shared databases, learning platforms, and regular exchanges [48]. Third, embedding researchers directly in policy programs through evidence pipelines and co-production initiatives can enhance the uptake of scientific findings in decision-making [49].

In line with these frameworks, our study confirms that technical and conceptual advances alone are insufficient unless they are supported by social and economic considerations. Research focused on developing prioritization strategies (ranked 2nd) and defining restoration standards (ranked 3rd) remains essential for guiding restoration efforts. However, these measures must be complemented by addressing societal well-being and economic viability to ensure that restoration is cost effective, socially desirable, and fundamentally successful in achieving long-term ecological outcomes [22, 46, 60, 61]. Frameworks for barrier removal that integrate societal aspects [62, 63] demonstrate how such approaches can reconcile conflicting interests and coordinate actions across different spatial scales, ensuring that broad-scale policies translate into context-specific, locally driven initiatives. In practice, this translation often depends on bargaining and compromise among actors with different values, risk perceptions, and objectives. These negotiations are not purely technical or administrative, but inherently political, as they involve competing interests, power relations, and decisions about whose values and priorities guide river management. Compromise can involve quid pro quo agreements between those who support and those who resist removal, for example through staged implementation, partial removal, additional safety or heritage measures, alternative infrastructure solutions, or compensation. It may also be required within the scientific community when evidence supports multiple plausible outcomes and trade offs. Making these political and scientific trade offs explicit, by documenting acceptable compromises, non negotiable ecological thresholds, and clear rules for revisiting decisions as new evidence emerges, can increase legitimacy, reduce conflict, and help move barrier removal decisions from debate to implementation.

Restoration strategies and stakeholder constellations vary substantially across barrier types and regional settings. Recent data from the Dam Removal Europe coalition show that 542 barriers were removed across 23 European countries in 2024, the majority being small weirs and culverts rather than large dams [64]. This highlights how barrier typology and scale influence restoration feasibility, governance complexity, and stakeholder dynamics. The AMBER project advanced adaptive management approaches by mapping more than one million artificial barriers across Europe and developing decision-support tools to prioritize connectivity restoration based on ecological, social, and economic criteria [22]. The MERLIN project [65] complements this perspective by testing large-scale, nature-based solutions through 18 flagship case studies, emphasizing context-tailored restoration portfolios and blended public-private funding mechanisms. Together, these initiatives demonstrate that restoring free-flowing rivers requires flexible, case-specific approaches that recognize differences in barrier typologies, governance systems, and social license to operate, rather than a one-size-fits-all model.

Our findings indicate that these collaborative mechanisms are most successful when clear coordination roles and communication protocols are established early on [48], and when knowledge exchange is embedded in adaptive management loops that link research directly to policy cycles [49]. Importantly, several of the top-ranked social science priorities can be operationalized as structured research programs rather than remaining conceptual or awareness-based. For example, research on long-term financial sustainability (rank 7) can involve evaluating blended finance models, payment-for-ecosystem-services schemes, and outcome-based conservation contracts, as demonstrated in MERLIN's nature-based investment pilots. Likewise, improving science-policy interaction and legal support (rank 11) can be examined through evidence pipeline analysis and policy feedback evaluations [49], while engaging communities and stakeholders (rank 4) can be operationalized through co-production workflows and participatory governance trials, as applied in the AMBER project and in the various activities organised by Dam Removal Europe. These cases illustrate that social and governance-related priorities can be approached through structured, empirical research with clear evaluation criteria, showing that they are substantive research areas in their own right rather than add-on considerations.

Taken together, these insights highlight the need to view interdisciplinarity not as an end in itself but as a dynamic, multi-scalar process of transformation. These scales have also been theorized as distinct levels of change: the practical, structural and paradigmatic [66, 67]. The practical sphere refers to tangible, implementation-oriented actions such as collaboration, co-production, and adaptive management. The structural sphere involves shifts in institutional arrangements, governance, and power relations, while the paradigmatic sphere encompasses deeper changes in values, worldviews, and knowledge systems. The sharp rise in the ranking of "establishing restoration standards" (priority 3, increase of 11 positions) further illustrates that many respondents may not initially perceive epistemic clarity as a core priority, until confronted with the need for shared definitions, criteria, and conceptual alignment across disciplines. Our results suggest that current restoration research and policy agendas predominantly operate within the practical sphere, where coordination needs and concrete management challenges are most visible, while systemic and paradigmatic transformations remain less explicit. This helps explain why respondents emphasized operational solutions and coordination tools over deeper forms of knowledge integration.

Building on this foundation, our results highlight the central role of stakeholder involvement in bridging research, policy-making, and practical implementation. Effective restoration requires sustained collaboration among researchers of multiple disciplines, policy makers, water managers, NGOs, economic sectors, and the public [34, 35, 68, 69]. While stakeholder involvement is formally mandated under EU funding schemes and the WFD, implementation remains uneven at local scales. Strengthening participatory communication with educational efforts to promote broader "river ecosystem literacy" [70] can help reconcile conflicting views and improve support for free-flowing rivers. Recent recommendations from the EU Commission further emphasize the need for broader public engagement and multi-level communication to better integrate local knowledge into restoration planning [71].

Fundamental challenges and multi-scale coordination

In addition to integrating socio-economic dimensions and stakeholder engagement, our work identifies several fundamental challenges within the natural sciences that must be addressed to ensure effective river restoration under the NRR. A primary challenge is to develop clear, parameterized definitions for free-flowing rivers as well as for the reference conditions used to evaluate restoration. Recently, we have seen increasing recognition of the importance of the dendritic, hierarchical spatial structure of river networks, a view reflected in priorities related to both technical (e.g., prioritization strategies (rank 2), connectivity and species migration (rank 6)) and adaptive responses (e.g., drought and flood resilience (rank 8), climate change adaptation (rank 10)). Moreover, experts call for incorporating meta-ecosystem and meta-community perspectives [10, 72] to better understand species movement and the transport of nutrients and organic matter across river networks. Restoring entire free-flowing river networks, that is, achieving full connectivity across all fluvial dimensions through strategies such as barrier removal, floodplain reconnection, environmental flow restoration, and water quality improvement [10, 73, 74], is ecologically ideal. However, extensive modifications in many European rivers render complete restoration unrealistic [75]. Compromise-seeking across spatial scales in restoration planning may also be motivated by different scale-dependency of social compared to ecological effects, which is an unexplored research territory.

Building on these challenges, our results show that research priorities span multiple spatial scales, from basin-wide prioritization and connectivity assessments to locally grounded restoration actions (Fig. 3). Although high-level policies are essential for setting standards and coordinating responses to large-scale drivers such as biodiversity loss and climate change, restoration ultimately depends on locally feasible measures and stakeholder support. However, practitioners frequently encounter contradictions between regulatory frameworks that simultaneously promote river regulation and call for restoration, underscoring the need for better alignment between NRR objectives and sectoral policies. This reinforces the importance of multi-scale coordination, where local implementation is embedded with coherent national and EU-level strategies [76–78].

These challenges also call for adaptive strategies that reflect the dynamic nature of expert perspectives [76, 77]. While our scoping survey primarily highlighted ecological and technical challenges, successive ranking revealed an increasing recognition of social research and governance dimensions (Fig. 3). This evolving perspective may explain why some recommendations remain unimplemented, often due to limited integration of socio-political factors [79]. For example, while researchers focused on technical aspects, NGO representatives and water managers stressed the need for robust governance frameworks, community engagement, and practical measures such as invasive species management and habitat availability (Fig. 4). In practice, aligning these perspectives requires co-designing restoration objectives and performance metrics with stakeholders before technical decisions are made. Such coordination can be operationalized through participatory planning processes with local authorities and communities, the joint development of decision-support tools with practitioners, and restoration portfolios that combine ecological monitoring with socio-economic assessments. Meaningful integration is feasible when collaborative structures are embedded early in project design rather than appended after ecological planning.

Study robustness and limitations

Our study employed a multi-step expert consultation and ranking process anchored in a modified Delphi protocol [39, 43]. This process engaged a diverse international community from 45 countries, with strong representation from EU Member States, which not only enhanced the credibility of our findings but also enabled us to map both current and future research fields, thereby supporting an integrated 'local-to-global' perspective. Although our scoping survey predominantly reflected natural science topics (Fig. 2), the final top 10 list achieved a balance between ecological knowledge and social science insights. A primary gap lies in efficient implementation strategies rather than in further understanding ecological processes.

We further reveal a nuanced interplay among natural, social, and socio-economic considerations in shaping research priorities. Stakeholder backgrounds and spatial context influenced the balance between ecological imperatives and governance, community engagement, and economic needs [80, 81]. Notably, even though our respondent pool was overwhelmingly composed of natural scientists (only 5.3% were social science experts), those with primarily ecological and practical expertise recognized the need for broader social, humanities, and governance dimensions when provided with an integrative framework (Table 1; ranks 7 and 9 collectively increased 24 positions). This observation underscores the challenge of connecting natural and social science topics in river restoration and conservation, where many issues inherently carry normative and political dimensions [79]. However, this recognition does not necessarily imply agreement on how such integration should occur. Ecologists often frame the challenge in terms of improving policy uptake of ecological evidence, whereas social scientists emphasize the design of the governance, incentive, and decision-making processes that enable feedback between knowledge and action. This difference in orientation represents a core barrier to operational interdisciplinarity, highlighting the need to study and co-develop the mechanisms that structure evidence uses, negotiation, and accountability in river restoration.

Moreover, the predominance of natural scientists may reflect the current structure of scientific networks in river restoration, a factor likely reinforced by our snowball sampling approach [50]. Leveraging embedded researchers and practitioners as transdisciplinary boundary spanners may further facilitate knowledge transfer and the implementation of integrated restoration strategies [82]. In light of these findings, future research on the topic should actively recruit more social scientists, practitioners, and scholars from emerging fields such as environmental humanities to enhance interdisciplinary robustness and foster the creation of interdisciplinary research networks. Scalable analytical approaches that support such collaboration already exist, such as multi-criteria prioritization frameworks applied in connectivity restoration [22], participatory governance approaches that facilitate co-design and negotiation among stakeholders [68, 69], and embedded science–policy evidence pipelines that strengthen feedback between monitoring and decision-making [49]. Together, these examples show that interdisciplinary integration can be operationalized as structured, empirical research programs, rather than remaining conceptual aims.

Despite these strengths, several limitations should be acknowledged to clarify the scope of inference. First, the participant pool was strongly European, reflecting both the regional focus of the NRR and the concentration of active river restoration networks; as such, perspectives from regions where restoration unfolds under different governance systems, cultural relationships to rivers, and socio-ecological pressures may be underrepresented. Second, although the study applied a modified Delphi approach, its outcomes depend on the granularity and disciplinary composition of expert input, with fewer contributions from social sciences and policy practitioners. Third, the interdisciplinary integration models and policy linkages discussed in this study are literature-derived rather than empirically tested within the prioritization process itself. They therefore function as conceptual pathways rather than validated implementation mechanisms, aligning with earlier calls for long-term embedded collaboration frameworks that can be trialed and evaluated in practice [47–49, 59]. Consequently, our roadmap should be interpreted as an evolving framework to guide research and policy alignment, rather than a prescriptive blueprint.

Policy implications and future directions

Our study offers a roadmap supporting the EU and its Member States in implementing the NRR and achieving the ambitious target of restoring at least 25,000 km of free-flowing rivers by 2030, building on a structured prioritization process that links diverse restoration contexts and barrier-related challenges to actionable policy guidance. The prioritized research topics, such as establishing restoration standards and developing targeted prioritization strategies, directly align with Article 9 of the NRR. Our results underscore that integrating ecological, hydrological, and socio-economic perspectives is essential for identifying actionable research priorities that can guide policy and restoration planning. To operationalize our research agenda within current EU policy frameworks, we mapped the ten highest-ranked research priorities against relevant legislative articles and potential indicators (Table 2). This alignment is bidirectional: research priorities can be tailored to meet concrete policy needs, while policy frameworks can, in turn, guide the formulation of targeted research questions and associated indicators. This mapping demonstrates how scientific priorities directly support the implementation of the NRR and BDS2030 and provides a concrete entry point for monitoring and adaptive management under National Restoration Plans (NRPs) and river basin management plans. Crucially, under the NRR, Member States are required to inventory and remove artificial barriers (Art. 9), restore floodplain functions, and incorporate these measures into National Restoration Plans (Art. 15), supported by monitoring and regular plan revision (Art. 19–21). Because the NRR specifically targets river connectivity, its implementation must operate in coherence with the wider set of EU environmental laws and strategies, including the WFD, the Habitats and Birds Directives, and the BDS2030, to ensure that connectivity gains translate into basin-scale ecological integrity and species recovery.

We conceptualize a practical roadmap for translating these research priorities into tangible restoration outcomes as six iterative stages: (1) diagnose, to assess river system conditions, barriers, and socio-political contexts using harmonized ecological and governance indicators; (2) co-design, where scientists, policymakers, and stakeholders jointly define restoration targets and success criteria through co-production and boundary work [49]; (3) finance, which mobilizes resources via public-private partnerships and green investment models aligned with NRR Article 19; (4) permit and engage, involving coordinated governance, legal authorization, and local participation to ensure legitimacy and social license; (5) implement and adapt, where adaptive management and context-specific technical solutions guide restoration on the ground; and (6) monitor and report, integrating ecological and socio-economic indicators to inform iterative learning and policy reporting under the NRR and WFD. This staged, participatory approach closely aligns with Elinor Ostrom's principles for governing common-pool resources, which emphasise polycentric governance, stakeholder participation, monitoring, and adaptive learning as essential components of successful environmental management [54, 55]. This roadmap represents an operational framework for moving from scientific priorities to coordinated policy action, supported by programmatic models such as RITE that foster long-term, cross-disciplinary collaboration [59].

Despite these promising frameworks, conflicting policies pose major challenges. Economic interests driven by the Common Agricultural Policy and renewable energy targets often override long-term conservation goals [83–85]. These sectoral misalignments hinder the protection and restoration of freshwater ecosystems, which require integrated policy frameworks that recognize the unique, transboundary nature of river systems [86, 87]. Such coordination challenges reflect the need for polycentric governance structures, where multiple interacting authorities and stakeholder groups operate across scales to manage shared environmental resources effectively [88]. Reconciling these conflicting policy objectives is crucial for ensuring that our research priorities translate into coherent restoration strategies that are both effective and scalable.

We further highlight the need for enhanced platforms and research tenders that foster long-term collaboration among natural scientists, social scientists, practitioners, and emerging fields such as environmental humanities. This collaborative approach must emphasize participative, transparent communication and long-term stakeholder involvement, as mandated by frameworks like the WFD, to capture the normative, political, and socio-cultural dimensions of restoration. As emphasized in Table 2, several of the top-ranked priorities, particularly stakeholder involvement, awareness, and governance, correspond closely with participatory obligations under the NRR, WFD, and BDS2030. The high rankings for community and stakeholder involvement (rank 4), public awareness and communication (rank 5), and stakeholder cooperation (rank 9), underscore this need. In addition, recent EU initiatives, as reflected in the 10th Framework Programme (FP10), stress the importance of transparent science service portals to facilitate effective communication among scientists, policymakers, and stakeholders. As political discourse evolves in response to geopolitical shifts, climate change pressures, and changes in governance, our research prioritization approach should be revisited in four to five years to track the impact of inter- and transdisciplinary efforts and adapt our agenda to these dynamic challenges.

Our findings reveal key aspects of a comprehensive restoration process, such as establishing clear, multi-scale targets and prioritizing actions based not only on ecological potential and cost-effectiveness but also on enhancing ecosystem services and social outcomes. Monitoring both ecosystem functions and socio-economic impacts remains insufficiently addressed in current research priorities and is not consistently implemented in practice [89, 90]. Although many European restoration projects are gradually incorporating these features, our survey highlights a persistent knowledge gap regarding how to integrate these elements into a fully scalable restoration framework. Even respondents with predominantly natural science backgrounds recognize the need to further incorporate governance and socio-economic dimensions. Moreover, growing societal recognition of free-flowing rivers as essential ecosystems underscores the importance of increasing public awareness, especially regarding the plight of iconic and migratory species that have become locally extirpated, to help transform isolated pilot projects into mainstream river management practices. Embedding joint ecological and socio-economic monitoring indicators within the policy levers identified in Table 2 would strengthen accountability and provide a basis for adaptive learning at basin and national scales. In this way, the research priorities identified here, provide a shared agenda that can guide coordinated implementation under the NRR, ensuring that river restoration in Europe advances not only barrier removal but also long-term ecological resilience and socially meaningful outcomes.

References

1. Dudgeon, D. Freshwater biodiversity: Importance, threats, status and conservation challenges. Biol. Rev. 81(2), 163–182. https://doi.org/10.1017/S1464793105006950 (2006).
2. Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., & Liermann, C. R. Global threats to human water security and river biodiversity. Nature 467(7315), 555–561. https://doi.org/10.1038/nature09440 (2010).
3. Lynch, A. J., Cooke, S. J., Arthington, A. H., Baigun, C., Bossenbroek, L., Dickens, C., … & Jähnig, S. C. People need freshwater biodiversity. WIREs Water 10(3), e1633. https://doi.org/10.1002/wat2.1633 (2023).
4. Harrison, I., Abell, R., Darwall, W., Thieme, M. L., Tickner, D., & Timboe, I. The freshwater biodiversity crisis. Science 362(6421), 1369. https://doi.org/10.1126/science.aav9242 (2018).
5. Reid, A. J., Carlson, A. K., Creed, I. F., Eliason, E. J., Gell, P. A., Johnson, P. T., … & Cooke, S. J. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol. Rev. 94(3), 849–873. https://doi.org/10.1111/brv.12480 (2019).
6. Sayer, C. A., Fernando, E., Jimenez, R. R., Macfarlane, N. B., Rapacciuolo, G., Böhm, M., … & Darwall, W. R. One-quarter of freshwater fauna threatened with extinction. Nature 638, 1–8. https://doi.org/10.1038/s41586-024-08375-z (2025).
7. Mueller, M., Pander, J., & Geist, J. The effects of weirs on structural stream habitat and biological communities. J. Appl. Ecol. 48, 1450–1461. https://doi.org/10.1111/j.1365-2664.2011.02035.x (2011).
8. Latrubesse, E. M., Arima, E. Y., Dunne, T., Park, E., Baker, V. R., d'Horta, F. M., ... & Stevaux, J. C. Damming the rivers of the Amazon basin. Nature 546(7658), 363–369. https://doi.org/10.1038/nature22333 (2017).
9. Messager, M.L., Lehner, B., Cockburn, C., Lamouroux, N., Pella, H., Snelder, T., Tockner, K., Trautmann, T., Watt, C., & Datry, T. Global prevalence of non-perennial rivers and streams. Nature 594, 391–397. https://doi.org/10.1038/s41586-021-03565-5 (2021).
10. Stoffers, T., Buijse, A. D., Geerling, G. W., Jans, L. H., Schoor, M. M., Poos, J. J., ... & Nagelkerke, L. A. Freshwater fish biodiversity restoration in floodplain rivers requires connectivity and habitat heterogeneity at multiple spatial scales. Science of the Total Environment, 838, 156509. https://doi.org/10.1016/j.scitotenv.2022.156509 (2022).
11. Spinti, R., Condon, L., & Zhang, J. The evolution of dam induced river fragmentation in the United States. Nat. Commun. 14, 3820 . https://doi.org/10.1038/s41467-023-39194-x (2023).
12. Dethier, E. N., Renshaw, C. E., & Magilligan, F. J. Rapid changes to global river suspended sediment flux by humans. Science 376(6600), 1447–1452. https://doi.org/10.1126/science.abn7980 (2022).
13. Sexton, A.N., Beisel, J.-N., Staentzel, C., Wolter, C., Tales, E., Belliard, J., Buijse, A.D., Martínez Fernández, V., Wantzen, K.M., Jähnig, S.C., Garcia de Leaniz, C., Schmidt-Kloiber, A., Haase, P., Forio, M.A.E., Archambaud, G., Fruget, J.-F., Dohet, A., Evtimova, V., Csabai, Z., Floury, M., Goethals, P., Várbiró, G., Cañedo-Argüelles, M., Larrañaga, A., Maire, A., Schäfer, R.B., Sinclair, J.S., Vannevel, R., Welti, E.A.R., & Jeliazkov, A. Inland navigation and land use interact to impact European freshwater biodiversity. Nat. Ecol. Evol. 8, 1098–1108 https://doi.org/10.1038/s41559-024-02414-8 (2024)
14. Ward, J. V. The four-dimensional nature of lotic ecosystems. J-NABS 8(1), 2–8. https://doi.org/10.2307/1467397 (1989).
15. Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., & Crochetiere, H. Mapping the world's free-flowing rivers. Nature 569(7755), 215–221. https://doi.org/10.1038/s41586-019-1111-9 (2019)
16. McCabe, C. L., Matthaei, C. D., & Tonkin, J. D. The ecological benefits of more room for rivers. Nat. Water. 3, 260–270. https://doi.org/10.1038/s44221-025-00403-0 (2025).
17. Worthington, T. A., van Soesbergen, A., Berkhuysen, A., Brink, K., Royte, J., Thieme, M., ... & Darwall, W. Global Swimways for the conservation of migratory freshwater fishes. Front. Ecol. Environ. 20(10), 573–580. https://doi.org/10.1002/fee.2550 (2022).
18. Stoffers, T., Buijse, A. D., Poos, J. J., Verreth, J. A., & Nagelkerke, L. A. Ontogenetic shifts by juvenile fishes highlight the need for habitat heterogeneity and connectivity in river restoration. Limnol. Oceanogr. 70, 732–748. https://doi.org/10.1002/lno.12797 (2025).
19. Auerswald K., Moyle P., Seibert S.P., & Geist J. HESS Opinions: Socio-economic and ecological trade-offs of flood management - benefits of a transdisciplinary approach. Hydrol. Earth Syst. Sci. 23, 1035–1044. https://doi.org/10.5194/egusphere-2024-1702 (2019).

20. He, F., Zarfl, C., Tockner, K., Olden, J. D., Campos, Z., Muniz, F., ... & Jähnig, S. C. Hydropower impacts on riverine biodiversity. Nat. Rev. Earth Environ. 5(11), 755–772. https://doi.org/10.1038/s43017-024-00596-0 (2024).
21. Deinet, S., Flint, R., Puleston, H., Baratech, A., Royte, J., Thieme, M. L., Nagy, S., Hogan, Z. S., Januchowski-Hartley, S. & Wanningen, H. The Living Planet Index (LPI) for migratory freshwater fish 2024 update - Technical Report. World Fish Migration Foundation, The Netherlands. http://icsfarchives.net/id/eprint/20318 (2024).
22. Belletti, B., Garcia de Leaniz, C., Jones, J., Bizzi, S., Börger, L., Segura, G., ... & Zalewski, M. More than one million barriers fragment Europe's rivers. Nature 588(7838), 436–441. https://doi.org/10.1038/s41586-020-3005-2 (2020).
23. Hein, T., Schwarz, U., Habersack, H., Nichersu, I., Preiner, S., Willby, N., & Weigelhofer, G. Current status and restoration options for floodplains along the Danube River. Sci. Total Environ. 543, 778–790. https://doi.org/10.1016/j.scitotenv.2015.09.073 (2016).
24. European Commission. State of the European Waters – The EU Water Framework Directive. Publications Office of the European Union. Retrieved from https://ec.europa.eu/environment/water/water-framework/index_en.html (2021).
25. Suding, K. N. Toward an era of restoration in ecology: Successes, failures, and opportunities ahead. Annu. Rev. Ecol. Syst. 42(1), 465–487. https://doi.org/10.1146/annurev-ecolsys-102710-145115 (2011).
26. European Commission. Proposal for a regulation of the European parliament and of the council on nature restoration. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022PC0304 (2024).
27. Stoffers, T., Altermatt, F., Baldan, D., Bilous, O., Borgwardt, F., Buijse, A. D., ... & Hein, T. Reviving Europe's rivers: Seven challenges in the implementation of the Nature Restoration Law to restore free-flowing rivers. WIREs Water 11(3), e1717. https://doi.org/10.1002/wat2.1717 (2024).
28. Franklin, P. A., Bašić, T., Davison, P. I., Dunkley, K., Ellis, J., Gangal, M., ... & Gutowsky, L. F. G. Aquatic connectivity: challenges and solutions in a changing climate. J. Fish Biol. 105(2), 392–411. https://doi.org/10.1111/jfb.15727 (2024).
29. IPBES Summary for Policymakers of the Thematic Assessment Report on the Underlying Causes of Biodiversity Loss and the Determinants of Transformative Change and Options for Achieving the 2050 Vision for Biodiversity of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. O'Brien, K., Garibaldi, L., Agrawal, A., Bennett, E., Biggs, O., Calderón Contreras, R., Carr, E., Frantzeskaki, N., Gosnell, H., Gurung, J., Lambertucci, S., Leventon, J., Liao, C., Reyes García, V., Shannon, L., Villasante, S., Wickson, F., Zinngrebe, Y., & Perianin, L. (eds.). IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.11382230 (2024).
30. Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Agard, J., Arneth, A., Balvanera, P., Brauman, K. A., Butchart, S. H. M., Chan, K. M. A., Garibaldi, L. A., Ichii, K., Liu, J., Subramanian, S. M., Midgley, G. F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., … & Zayas, C. N. Pervasive human-driven decline of life on Earth points to the need for transformative change. Science 366(6471), eaax3100. https://doi.org/10.1126/science.aax3100 (2019).
31. Kuemmerlen, M., Reichert, P., Siber, R., & Schuwirth, N. Ecological assessment of river networks: From reach to catchment scale. Sci. Total Environ. 650, 1613-1627. https://doi.org/10.1016/j.scitotenv.2018.09.019 (2019).
32. Hein, T., Hauer, C., Schmid, M., Stöglehner, G., Stumpp, C., Ertl, T., ... & Wang, C. The coupled socio-ecohydrological evolution of river systems: Towards an integrative perspective of river systems in the 21st century. Sci. Total Environ. 801, 149619. https://doi.org/10.1016/j.scitotenv.2021.149619 (2021).
33. Hermoso, V., Carvalho, S., Giakoumi, S., Goldsborough, D., Katsanevakis, S., Leontiou, S., Markantonatou, V., Rumes, B., Vogiatzakis, I., & Yates, K. The EU Biodiversity Strategy for 2030: Opportunities and challenges on the path towards biodiversity recovery. Environ. Sci. Policy 127, 263–271. https://doi.org/10.1016/j.envsci.2021.10.028 (2022).
34. Farwig N., Sprenger P., Baur B., Böhning-Gaese K., Brandt A., Eisenhauer N., Ellwanger G., Hochkirch A., Karamanlidis A., Mehring M., Pusch M., Rehling F., Sommerwerk N., Spatz T., Svenning J.C., Tischew S., Tockner K., Tscharntke T., Vadrot A., Taffner J., Fuerst C., Jähnig S.C., & Mosbrugger V. Identifying major factors for success and failure of conservation programs in Europe. J. Environ. Manag. , 1–19. https://doi.org/10.1007/s00267-024-02086-x (2024).
35. Nagel, C., Pander, J., Droll, J., Loy, G., Grüner, B., Wesemann, J., & Geist, J. Fish and chips: Conservation of freshwater fish populations through an integrative multi-stakeholder approach. J. Appl. Ecol. 00, 1–9. https://doi.org/10.1111/1365-2664.70004 (2025).

36. Hering, D., Schürings, C., Wenskus, F., Blackstock, K., Borja, A., Birk, S., Bullock, C., Carvalho, L., Dagher-Kharrat, M.B., Lakner, S., Lovrić, N., McGuinness, S., Nabuurs, G.-J., Sánchez-Arcilla, A., Settele, J., & Pe'er G. Securing success for the Nature Restoration Law. Science 382, 1248–1250. https://doi.org/10.1126/science.adk1658 (2023).
37. Bengston, D. N. Horizon scanning for environmental foresight: A review of issues and approaches. General Technical Report NRS-121, U.S. Department of Agriculture, Forest Service, Northern Research Station. https://doi.org/10.2737/NRS-GTR-121 (2013).
38. Wintle, B. C., Kennicutt II, M. C. & Sutherland, W. J. Scanning horizons in research, policy and practice. In: Sutherland, W. J., Brotherton, P. N. M., Davies, Z. G., Ockendon, N., Pettorelli, N. & Vickery, J.A., eds. Conserv. Res. Policy Pract.. Ecological Reviews. Cambridge University Press, 29–47. https://library.oapen.org/bitstream/handle/20.500.12657/93203/obp.0360.pdf?sequence=1#page=268 (2020).
39. Sutherland, W. J., Bennett, C., Brotherton, P. N., Butchart, S. H., Butterworth, H. M., Clarke, S. J., … & Thornton, A. A horizon scan of global biological conservation issues for 2024. Trends Ecol. Evol. 39(1), 89–100. https://doi.org/10.1016/j.tree.2023.11.001 (2024).
40. Cooke, S. J., Danylchuk, A. J., Kaiser, M. J., & Rudd, M. A. Is there a need for a "100 questions exercise" to enhance fisheries and aquatic conservation, policy, management and research? Lessons from a global 100 questions exercise on conservation of biodiversity. J. Fish. Biol. 76(9), 2261–2286. https://doi.org/10.1111/j.1095-8649.2010.02666.x (2010).
41. Dey, C. J., Rego, A. I., Midwood, J. D., & Koops, M. A. A review and meta-analysis of collaborative research prioritization studies in ecology, biodiversity conservation and environmental science. Proc. R. Soc. B 287(1923), 20200012. https://doi.org/10.1098/rspb.2020.0012 (2020).
42. Martin, T. G., Burgman, M. A., Fidler, F., Kuhnert, P. M., Low-Choy, S. A. M., McBride, M., & Mengersen, K. Eliciting expert knowledge in conservation science. Conserv. Biol. 26(1), 29–38. https://doi.org/10.1111/j.1523-1739.2011.01806.x (2012).
43. Mukherjee, N., Hugé, J., Sutherland, W. J., McNeill, J., Van Opstal, M., Dahdouh-Guebas, F., & Koedam, N. The Delphi technique in ecology and biological conservation: Applications and guidelines. Methods Ecol. Evol. 6(9), 1097–1109. https://doi.org/10.1111/2041-210X.12387 (2015).
44. European Commission. Directorate-General for Environment, Biodiversity Strategy for 2030 – Barrier Removal for River Restoration. Publications Office of the European Union. https://data.europa.eu/doi/10.2779/181512 (2022).
45. Harper, M., Mejbel, H. S., Longert, D., Abell, R., Beard, T. D., Bennett, J. R., Carlson, S. M., Darwall, W., Dell, A., & Domisch, S. Twenty-five essential research questions to inform the protection and restoration of freshwater biodiversity. Aquat. Conserv. 31(9), 2632–2653. https://doi.org/10.1002/aqc.3634 (2021).
46. Van Rees, C. B., Waylen, K. A., Schmidt-Kloiber, A., Thackeray, S. J., Kalinkat, G., Martens, K., ... & Jähnig, S. C. Safeguarding freshwater life beyond 2020: Recommendations for the new global biodiversity framework from the European experience. Conserv. Lett. 14(1), e12771. https://doi.org/10.1111/conl.12771 (2021).
47. Fischer, A. R., Tobi, H., & Ronteltap, A. When natural met social: a review of collaboration between the natural and social sciences. Interdiscip. Sci. Rev. 36(4), 341–358. https://doi.org/10.1179/030801811X13160755918688 (2011).
48. Barthel, R., & Seidl, R. Interdisciplinary collaboration between natural and social sciences–status and trends exemplified in groundwater research. PloS One 12(1), e0170754. https://doi.org/10.1371/journal.pone.0170754 (2017).
49. Bennett, N. J., Roth, R., Klain, S. C., Chan, K., Christie, P., Clark, D. A., ... & Wyborn, C. Conservation social science: Understanding and integrating human dimensions to improve conservation. Biol. Conserv. 205, 93–108. https://doi.org/10.1016/j.biocon.2016.10.006 (2017).
50. Sadler, G. R., Lee, H. C., Lim, R. S. H., & Fullerton, J. Recruitment of hard-to-reach population subgroups via adaptations of the snowball sampling strategy. Nurs. Health Sci. 12(3), 369–374. https://doi.org/10.1111/j.1442-2018.2010.00541.x (2010).
51. Greenacre, M. Correspondence analysis in practice. chapman and hall/crc. https://doi.org/10.1201/9781315369983 (2017).
52. R Core Team. R: A language and environment for statistical computing (version 4.4.2). (2024).
53. Barouillet, C., González-Trujillo, J. D., Geist, J., Gíslason, G. M., Grossart, H. P., Irvine, K., ... & Boon, P. J. Freshwater conservation: Lost in limnology?. Aquat. Conserv. 34(1), e4049. https://doi.org/10.1002/aqc.4049 (2024).

54. Ostrom, E. Governing the commons: The evolution of institutions for collective action. Cambridge university press. (1990).
55. Ostrom, E. A general framework for analyzing sustainability of social-ecological systems. Science, 325(5939), 419-422. https://doi.org/10.1126/science.1172133 (2009).
56. Geist, J. Integrative freshwater ecology and biodiversity conservation. Ecol. Indic. 11, 1507–1516 https://doi.org/10.1016/j.ecolind.2011.04.002 (2011).
57. Palmer, M., & Ruhi, A. Linkages between flow regime, biota, and ecosystem processes: Implications for river restoration. Science 365(6459), https://doi.org/10.1126/science.aaw2087 (2019).
58. Palmer, M. A., Hondula, K. L., & Koch, B. J. Ecological restoration of streams and rivers: shifting strategies and shifting goals. Annu. Rev. Ecol. Syst. 45(1), 247–269. https://doi.org/10.1146/annurev-ecolsys-120213-091935 (2014).
59. Holm, P., Goodsite, M. E., Cloetingh, S., Agnoletti, M., Moldan, B., Lang, D. J., ... & Zondervan, R. Collaboration between the natural, social and human sciences in global change research. Environ. Sci. Policy 28, 25–35. https://doi.org/10.1016/j.envsci.2012.11.010 (2013).
60. de Leaniz, C. G., C. G., & O'Hanley, J. R. Operational methods for prioritizing the removal of river barriers: Synthesis and guidance. Sci. Total Environ. 848, 157471. https://doi.org/10.1016/j.scitotenv.2022.157471 (2022).
61. Darre, M. E., Constantinides, P., Domisch, S., Floury, M., Hermoso, V., Ørsted, M., & Langhans S.D. Evaluating the readiness for river barrier removal: A scoping review under the EU nature restoration law, Sci. Total Environ. 959, 178180, ISSN 0048-9697. https://doi.org/10.1016/j.scitotenv.2024.178180 (2024).
62. Jumani, S., Andrews, L., Grantham, T. E., McKay, S. K., Duda, J., & Howard, J. A decision-support framework for dam removal planning and its application in northern California. Environ. Challenges 12, 100731. https://doi.org/10.1016/j.envc.2023.100731 (2023).
63. Alp, M., Arnaud, F., Barthélémy, C., Bernez, I., Clemens, A., Cottet, M., ... & Lamouroux, N. Restaurer la continuité écologique des cours d'eau: que sait-on et comment passer collectivement à l'action?. VertigO 24(2). https://doi.org/10.4000/12ppa (2024).
64. Mouchlianitis, F.A. Dam Removal Progress 2024. Dam Removal Europe. https://damremoval.eu/wp-content/uploads/2025/05/Mouchlianitis-F.A.-2025.-Dam-Removal-Progress-2024.pdf (2025).
65. MERLIN project. Mainstreaming Ecological Restoration of freshwater-related ecosystems in a Landscape context: INnovation, upscaling and transformation (Horizon 2020). Project website: https://projectmerlin.eu (accessed 7 February 2026).
66. O'Brien, K. Global environmental change II: From adaptation to deliberate transformation. Prog. Hum. Geogr. 36(5), 667–676. https://doi.org/10.1177/0309132511425767 (2012)
67. Feola, G. Societal transformation in response to global environmental change: A review of emerging concepts. Ambio 44(5), 376–390. https://doi.org/10.1007/s13280-014-0582-z (2015).
68. Flávio, H., Ferreira, P., Formigo, N., & Svendsen, J. C. Reconciling agriculture and stream restoration in Europe: A review relating to the EU Water Framework Directive. Sci. Total Environ. 596, 378–395. https://doi.org/10.1016/j.scitotenv.2017.04.057 (2017).
69. Vári, Á., Podschun, S. A., Erős, T., Hein, T., Pataki, B., Iojă, I.-C., Adamescu, C. M., Gerhardt, A., Gruber, T., & Dedić, A. Freshwater systems and ecosystem services: Challenges and chances for cross-fertilization of disciplines. Ambio 51(1), 135–151. https://doi.org/10.1007/s13280-021-01556-4 (2022).
70. Panagiotou, A., Zogaris, S., Dimitriou, E., Mentzafou, A. & Tsihrintzis, V.A. Anthropogenic barriers to longitudinal river connectivity in Greece: A review. Ecohydrol. Hydrobiol. 22(2), 295–309. https://doi.org/10.1016/j.ecohyd.2021.10.003 (2022).
71. European Commission. Second Flood Hazard and Risk Maps and Second Flood Risk Management Plans. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52025SC0034 (2025).
72. Cid, N., Erős, T., Heino, J., Singer, G., Jähnig, S., Cañedo-Argüelles, M., Bonada, N., Sarremejane, R., Mykrä, H., & Sandin, L. et al. From meta-system theory to the sustainable management of rivers in the Anthropocene. Front. Ecol. Environ. 20(1), 49–57. https://doi.org/10.1002/fee.2417 (2022).
73. Poff, N. L., & Zimmerman, J. K. Ecological responses to altered flow regimes: A literature review to inform the science and management of environmental flows. Freshw. Biol. 55(1), 194–205. https://doi.org/10.1111/j.1365-2427.2009.02272.x (2010).
74. Gounand, I., Little, C. J., Harvey, E., & Altermatt, F. Cross-ecosystem carbon flows connecting ecosystems worldwide. Nat. Commun., 9(1), 4825. https://doi.org/10.1038/s41467-018-07238-2 (2018).
75. Geist, J. & Hawkins, S.J. Habitat recovery and restoration in aquatic ecosystems: Current progress and future challenges. Aquat. Conserv. 26, 942–962. https://doi.org/10.1002/aqc.2702 (2016).

76. Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Jäger, J., ... & Mitchell, R. B. Knowledge systems for sustainable development. Proc. Natl. Acad. Sci. U.S.A. 100(14), 8086–8091. https://doi.org/10.1073/pnas.1231332100 (2003).
77. Pahl-Wostl, C. A conceptual framework for analyzing adaptive capacity and multi-level learning processes in resource governance regimes. Glob. Environ. Change 19(3), 354–365. https://doi.org/10.1016/j.gloenvcha.2009.06.001 (2009).
78. Erős, T., Hermoso, V., & Langhans, S. D. Leading the path toward sustainable freshwater management: Reconciling challenges and opportunities in historical, hybrid, and novel ecosystem types. WIREs Water 10(3), e1645. https://doi.org/10.1002/wat2.1645 (2023).
79. Reed, M. S. Stakeholder participation for environmental management: a literature review. Biol. Conserv. 141(10), 2417–2431. https://doi.org/10.1016/j.biocon.2008.07.014 (2008).
80. Roux, D. J., Rogers, K. H., Biggs, H. C., Ashton, P. J., & Sergeant, A. Bridging the science–management divide: Moving from unidirectional knowledge transfer to knowledge interfacing and sharing. Ecol. Soc. 11(1), 4. https://www.jstor.org/stable/26267817 (2006).
81. Cook, C. N., Mascia, M. B., Schwartz, M. W., Possingham, H. P., & Fuller, R. A. Achieving conservation science that bridges the knowledge–action boundary. Conserv. Biol. 27(4), 669–678. https://doi.org/10.1111/cobi.12050 (2013).
82. Taylor, A., Pretorius, L., McClure, A., Iipinge, K. N., Mwalukanga, B., & Mamombe, R. Embedded researchers as transdisciplinary boundary spanners strengthening urban climate resilience. Environ. Sci. Policy 126, 204–212. https://doi.org/10.1016/j.envsci.2021.10.002 (2021).
83. Hermoso, V. Freshwater ecosystems could become the biggest losers of the Paris Agreement. Glob. Chang. Biol. 23(9), 3433–3436. https://doi.org/10.1111/gcb.13655 (2017).
84. Geist, J. Green or red: Challenges for fish and freshwater biodiversity conservation related to hydropower. Aquat. Conserv. 31(7), 1551–1558. https://doi.org/10.1002/aqc.3597 (2021).
85. Rinaldi, A.cBiodiversity 2030: a road paved with good intentions: The new EU Commission's biodiversity Strategy risks to remain an empty husk without proper implementation. EMBO reports 22(6), e53130. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8183400/pdf/EMBR-22-e53130.pdf (2021)
86. Lynch, A. J., Elliott, V., Phang, S. C., Claussen, J. E., Harrison, I., Murchie, K. J., Steel, E. A., & Stokes, G. L. Inland fish and fisheries integral to achieving the Sustainable Development Goals. Nat. Sustain. 3(8), 579–587. https://doi.org/10.1038/s41893-020-0517-6 (2020).
87. Perry, D., Harrison, I., Fernandes, S., Burnham, S., & Nichols, A. Global analysis of durable policies for free-flowing river protections. Sustainability 13(4), 2347. https://doi.org/10.3390/su13042347 (2021).
88. Ostrom, E. Polycentric systems for coping with collective action and global environmental change. Global Environmental Change 20, 550–557. https://doi.org/10.1016/j.gloenvcha.2010.07.004 (2010)
89. Bernhardt, E. S., Palmer, M. A., Allan, J. D., Alexander, G., Barnas, K., Brooks, S., ... & Sudduth, E. Synthesizing US river restoration efforts. Science 308(5722), 636–637. https://doi.org/10.1126/science.1109769 (2005)
90. Pander, J., & Geist, J. Ecological indicators for stream restoration success. Ecological indicators, 30, 106-118. https://doi.org/10.1016/j.ecolind.2013.01.039 (2013)
91. Stoffers, T. Data from: Removing barriers: a collaborative research agenda for restoring free-flowing rivers. 4TU.ResearchData Repository. https://doi.org/10.4121/36b75ce9-3a6d-4076-9f33-3c53e9f74df5 (2026).

Figure captions

Figure 1. Outline of the multi-step approach used to develop the research agenda for restoring free-flowing rivers. The process began with an online scoping survey followed by an expert workshop to refine the identified topics and categorize them into natural and social science disciplines. A subsequent ranking survey prioritized the topics using weighted measures.

Figure 2. Overview of the 27 research priority topics identified for restoring free-flowing rivers. The topics were derived from 425 unique submissions provided by 237 respondents in the initial step of our scoping study. Circle size indicates the relative frequency with which elements contributing to each topic were mentioned, with larger circles reflecting above-average

representation. Topics are organized along a conceptual gradient from social science-oriented themes (lavender) to natural science-oriented themes (turquoise), with integrative or cross-cutting topics shown in grey. Topics that ranked into the top 10 (see Fig. 3) are highlighted with yellow borders. More details on the topics can be found in Supplementary Materials 3 and 8.

Figure 3. Final ranking of the 27 research priorities for restoring free-flowing rivers, arranged from highest rank (top) to lowest (bottom). The bar charts on the right show how many times each topic was originally mentioned in the scoping survey (see also Fig. 1). Grey bars denote social science topics, while black bars represent natural science topics. The dots on the left indicate the spatial scales (local, regional, national, and global) assigned to each topic based on its scope, potential impact, and capacity to influence policies or ecosystems. Light grey dots indicate the probable spatial scale of action for each topic, while dark grey dots denote the scale most frequently assigned by the author group (see Suppl. Mat. 4 for further details).

Figure 4. Results of the correspondence analysis of 75 research priority lists, indicating how topics cluster in CA space and how different respondent groups are distributed across these dimensions. The first two CA axes explain a total of 22.1% of the inertia (Axis 1: 12.4%, Axis 2: 9.7%). (A) shows the 27 research topics (labeled by short descriptions found in Suppl. Mat. 8), with social science topics in grey triangles and natural science topics in black circles. (B-D) plot respondent scores (indicated by topic numbers) over the same CA space (social science topics: triangles, natural science: circles), grouped by discipline, profession, and country, respectively, with convex hulls outlining each group. For the country plot (panel D), only countries with at least five respondents are highlighted with distinct colors and convex hulls. Countries with fewer than five respondents are combined into an "other countries" group, with their CA positions displayed as grey dots.

Tables and captions

Table 1. Final ranking of the top 10 research priorities for restoring European free-flowing rivers.
Each topic is listed with its final rank, the change in rank compared to the initial mention-based ranking, a short description and topic number (as used in Fig. 4), a detailed description, its position in the correspondence analysis space (see Fig. 4), and the number of times it was ranked first and included in the top 10 by respondents (see Supplementary Material 5). In the "Rank change" column, the number indicates how many positions a topic moved between the initial and final rankings, and the arrow indicates the direction of change (up arrow = higher rank; down arrow = lower rank).

Rank	Rank change	Short (+ topic no.)	Topic	Detailed description	Clustering position in CA space	Times ranked #1	Times included in top 10
1	2 ↑	Ecological responses (7)	Enhancing riverine biodiversity and ecosystem functioning	This research investigates how restoring free-flowing rivers impacts biodiversity and ecosystem functioning, focusing on river reconnection, natural flow regimes, and the restoration of key species and habitats. It explores how restored flows influence biodiversity, species distributions, ecosystem processes, and their long-term benefits in Key Biodiversity Areas.	Centrally positioned with the natural science topics *species-specific responses (topic no 13)*, *connectivity and species migration (16)*, and *monitoring and baseline efforts (11)*.	14	44
2	1 ↓	Prioritization strategies (27)	Developing prioritization strategies for targeted restoration	This research prioritizes river restoration based on ecological, social, and economic factors. It aims to identify key areas for restoring free-flowing rivers, using criteria like biodiversity, cost-efficiency, feasibility, and ecosystem connectivity. It also explores how to prioritize rivers based on size, water quality, and	Central, adjacent to the natural science topics *climate change adaptation (14)*, *hydropower impacts (17)*, *drought and flood resilience (1)*, and *connectivity and species migration (16)*.	9	46

				vulnerability while balancing ecological goals with development needs.			
3	11 ↑	Defining standards (15)	Establishing restoration standards for free-flowing rivers	This research establishes clear definitions and restoration standards, targets and criteria for free-flowing rivers, focusing on setting biodiversity and ecosystem targets.	Central with the natural science topics *monitoring and baseline (11)* and *habitat availability (9)*.	8	33
4	0	Community and stakeholder involvement (26)	Engaging communities and stakeholders	This research investigates how to involve communities, stakeholders, and cultural perspectives in free-flowing river restoration projects. It focuses on integrating local knowledge, overcoming socio-political barriers, and fostering public engagement.	Centrally located within the social science cluster, grouping with *stakeholder cooperation (21)*, *financing and viability (20)*, and *cross-boundary governance (23)*.	4	33
5	3 ↓	Public awareness and communication (24)	Enhancing public awareness and communication strategies	This research focuses on communicating the benefits (and risks) of restoring free-flowing rivers and addressing public concerns. It emphasizes how restoration supports climate change mitigation, recreational opportunities, and community well-being. It also explores best practices for engaging local communities, policymakers, and dam owners to build support for restoration efforts.	Located in the center of the CA space between social and natural science topics; surrounded by the social science topics *stakeholder cooperation (21)*, *community and stakeholder involvement* (26) and the natural science topic *hydropower impacts (17)*.	4	35
6	0	Connectivity and species migration (16)	Improving species migration through connectivity restoration	This research focuses on restoring river connectivity (longitudinal and lateral) through barrier removal and floodplain reconnection to facilitate movement for a diverse array of species, including migratory fishes, invertebrates, insects, macrophytes, riparian plants, and amphibians. It addresses the impacts of river infrastructure on species dispersal and emphasizes improving fish passage efficiency across natural and artificial barriers to enhance migration and aquatic biodiversity.	Centrally positioned, encircled by the natural science topics *ecological responses and biodiversity (7)*, *drought and flood resilience (1)*, *species-specific responses (13)*, *hydropower impacts (17)* and the social science topic *prioritization strategies (27)*.	1	33
7	15 ↑	Financing and viability (20)	Securing long-term financial sustainability	This research develops financing strategies for long-term river restoration projects, including green finance and corporate investments. It focuses on ensuring the economic sustainability of large-scale river restoration efforts and creating models for securing financial support over the long term.	At the periphery of the social science cluster, adjacent to the topics *economic challenges (19)*, *cross-boundary governance (23)*, *community and stakeholder involvement (26)*, and the natural science topic *innovative technical solutions (18)*.	8	31
8	0	Drought and flood resilience (1)	Enhancing resilience to droughts and floods through restoration	This research investigates whether and to which extent restoring free-flowing rivers enhances resilience to droughts and floods while improving water availability. It focuses on using natural river dynamics to mitigate water scarcity and manage flood risks.	Centrally placed at the intersection of natural and social science clusters; surrounded by the natural science topics *hydropower impacts (17)*, *connectivity and species migration (16)* and the social science topic *prioritization strategies (27)*.	1	38
9	9 ↑	Stakeholder cooperation (21)	Improving governance and stakeholder collaboration	This research focuses on improving governance frameworks by involving stakeholders and fostering cross-sectoral collaboration. It focuses on inclusive governance and collaboration across different sectors, which are key to achieving balanced restoration of free-flowing rivers that meet ecological and community needs.	Positioned at the edge of the social science cluster, clustered with *community and stakeholder involvement (26)*, *public awareness and communication (24)*, *cross-boundary governance (23)*, and *societal and cultural impacts (25)*.	4	33
10	3 ↑	Climate change adaptation (14)	Enhancing climate resilience and biodiversity in rivers	This research explores how restoring free-flowing rivers enhances resilience to climate change, focusing on long-term water security, reducing climate-related risks, and supporting biodiversity adaptation. Examining species responses and ecological health ensures restoration strategies incorporate climate adaptation for resilient ecosystems and communities.	On the outer edge of CA space, surrounded by the social science topics *prioritization strategies (27)*, *science-policy and legal frameworks (22)* and the natural science topics *connectivity and species migration (16)*, *drought and flood resilience (1)*.	3	33

Table 2. Alignment of the top 10 research priorities with European policy frameworks and monitoring indicators. The table links each priority to relevant articles within the NRR, WFD, Habitats Directive, and BDS2030, and shows how these priorities can be operationalized through policy levers and indicative indicators for monitoring within National Restoration Plans and River Basin Management Plans. Abbreviations: NRR, Nature Restoration Regulation; WFD, Water Framework Directive; BDS2030, EU Biodiversity Strategy for 2030; RBMPs, River Basin Management Plans; NRPs, National Restoration Plans; CIS, Common Implementation Strategy; JRC, Joint Research Centre; PES, payment for ecosystem services.

Rank	Research priority	Key EU policy link	Relevant policy lever or program	Indicative indicator(s)
1	Enhancing riverine biodiversity and ecosystem functioning	NRR Art. 4 & Art. 9; WFD Art. 4(1)(a)(ii–iii) (ecological status incl. hydromorphology); Habitats Directive Art. 1(e) & Art. 6 (maintaining/restoring favorable conservation status); EU BDS2030 Target A2	Integration of freshwater habitat restoration targets into NRPs and River Basin Management Plans (RBMPs); updates to Natura 2000 site management plans	River length reconnected (km); percentage of water bodies at good ecological status; progress toward favorable conservation status
2	Developing prioritization strategies for targeted restoration	NRR Art. 15(3); WFD Art. 11 (Programme of Measures) & Art. 13–15 (RBMP cycle)	Barrier and floodplain prioritization frameworks linked to Natura 2000 requirements and species distribution data; incorporation into Programmes of Measures under the WFD	Number of basins with prioritization maps; implementation rate of multi-criteria decision analysis tools
3	Establishing restoration standards	NRR Art. 12; WFD Art. 1/(8) & Annex V (classification of ecological status); Habitats Directive monitoring under Art. 17	Updates to Common Implementation Strategy (CIS) guidance documents; development of EU-wide restoration standards through the Joint Research Centre (JRC)	Adoption of harmonized monitoring indicators; availability of before-and-after ecological datasets
4	Engaging communities and stakeholders	NRR Art. 15(3)(w); WFD Art. 14 (public participation); Habitats Directive Art. 6(1) (stakeholder-involved site management); BDS2030 Target C	Co-design platforms for restoration planning; community stewardship models; stakeholder-involved Natura 2000 site management procedures	Number of stakeholder partnerships; percentage of restoration projects developed through co-design
5	Enhancing public awareness and communication	NRR Art. 19; WFD Art. 14; BDS2030 Target C	National communication and outreach strategies; knowledge-exchange platforms at EU and Member State levels	Public support indicators; number of engagement initiatives
6	Improving species migration through connectivity restoration	NRR Art. 9(1–4); WFD Art. 4(1)(a)(ii–iii); Habitats Directive Art. 6(3–4) (assessing barrier removal & mitigation inside Natura 2000)	Barrier-removal programs; nature-like bypass channel implementation; adaptive fish-passage design guidelines	Number of artificial barriers removed; fish-passage efficiency; species recolonization patterns (e.g., via environmental DNA or telemetry)
7	Securing long-term financial sustainability	NRR Art. 15(3)(u); EU Green Deal / InvestEU	Long-term stewardship contracts; blended public–private financing mechanisms; payment-for-ecosystem-services (PES) schemes	Total euros secured beyond construction phases; proportion of projects with long-term (10+ year) maintenance plans
8	Enhancing resilience to droughts and floods	NRR Art. 9(3); WFD Art. 4(1)(a)(ii/iii) (hydromorphology) and Art. 11 (resilience); Habitats Directive Art. 10 (ecological connectivity networks); EU Climate Adaptation Strategy; Floods Directive 2007/60/EC	Floodplain reconnection programs; wetland restoration initiatives; nature-based solutions under the EU Climate Adaptation Strategy and Floods Directive	Floodplain area restored (hectares); water-retention capacity; reduction in peak-flow magnitude
9	Improving governance and stakeholder collaboration	NRR Art. 15(3)(t,w); WFD Art. 3 (River Basin District co-ordination); BDS2030 Target D	Establishment or strengthening of River Basin Organizations; inter-agency coordination agreements; cross-border basin collaboration platforms	Number of multi-level governance bodies; diversity and inclusion of stakeholder representation
10	Enhancing climate resilience and biodiversity in rivers	NRR Art. 15(3)(t); WFD Art. 13–15 (adaptive RBMP updates); Habitats Directive Art. 1(e) (climate-compatible favourable conservation status); EU Climate Adaptation Strategy	Climate-informed planning in RBMPs; development of basin-scale ecological corridors; implementation of climate-adaptive restoration measures	Percentage of restoration projects using climate-scenario planning; reduction in ecosystem vulnerability to climate hazards

Competing interest statement

The authors declare no competing interests.

Author contributions

T.S., K.E.M.V., Si.S., and S.C.J. contributed equally to the conceptualization, methodology, validation, and data curation of the study. T.S. led the formal analysis, investigation, software development, visualization, and preparation of the original manuscript draft, and coordinated the review and editing of the manuscript. K.E.M.V., Si.S., and S.C.J. contributed equally to the preparation of the original draft and to the review and editing of the manuscript.

Conceptualization of the research agenda was further supported by P.C.G., M.C., T.E., J.Ge., M.K., So.S., and R.v.T., who also contributed to the preparation of the original draft and to the review and editing of the manuscript.

All remaining authors (M.A., D.Ba., S.Bi., O.Bi., F.Bo., M.Br., A.D.B., V.C., M.E.D., J.E., P.F., T.F., K.G.L., J.Gr., D.Gu., F.H., T.H., Z.S.H., L.L.H., P.M., I.M., S.Mo., C.L.M., L.A.J.N., J.Nä., P.d.R.O., J.Pa., P.Pe., M.Pf., S.L.R., J.L.R., T.D.R., A.Sc., A.S.K., S.Schm., M.Sch., G.A.S., A.T., K.T.T., J.To., M.Ts., J.v.R., P.V., F.W., B.W., C.W., C.X., T.A.W., and S.Z.) contributed to the preparation of the original draft and to the review and editing of the manuscript.

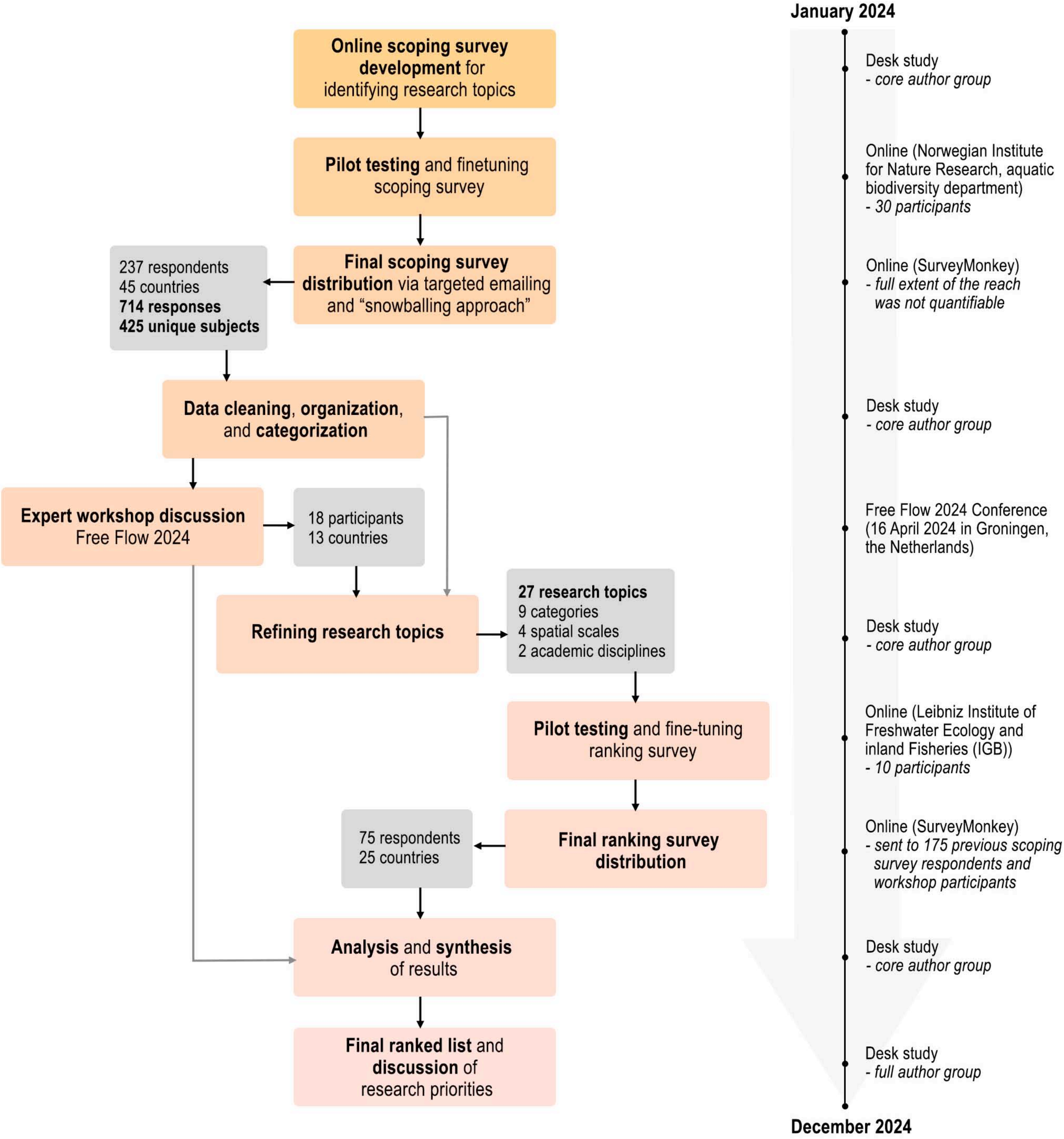
Acknowledgements

The work leading to this publication was supported by project BioAgora (European Union Horizon Europe Research and Innovation Programme grant agreement No. 101059438). S.C.J., P.M., T.H. consider this a contribution to the project DANUBE4ALL (European Union Horizon Europe Research and Innovation Programme grant agreement No. 101093985) and S.C.J. to the Collaborative Research Centre 1439/2 RESIST (Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) grant number 426547801). The financial support by the Austrian Federal Ministry for Digital and Economic Affairs, the National Foundation for Research, Technology and Development, and the Christian Doppler Research Association is gratefully acknowledged by O.B., F.B., T.H. and P.M. MB was funded through BiodivRestore ERA-NET Cofund (GA N°101003777) and the Federal Ministry of Education and Research Germany (16LW0174K). Survey tools were made available via the international non-profit organization Alternet Europe. This article is a contribution of the Alliance for Freshwater Life (www.allianceforfreshwaterlife.org).

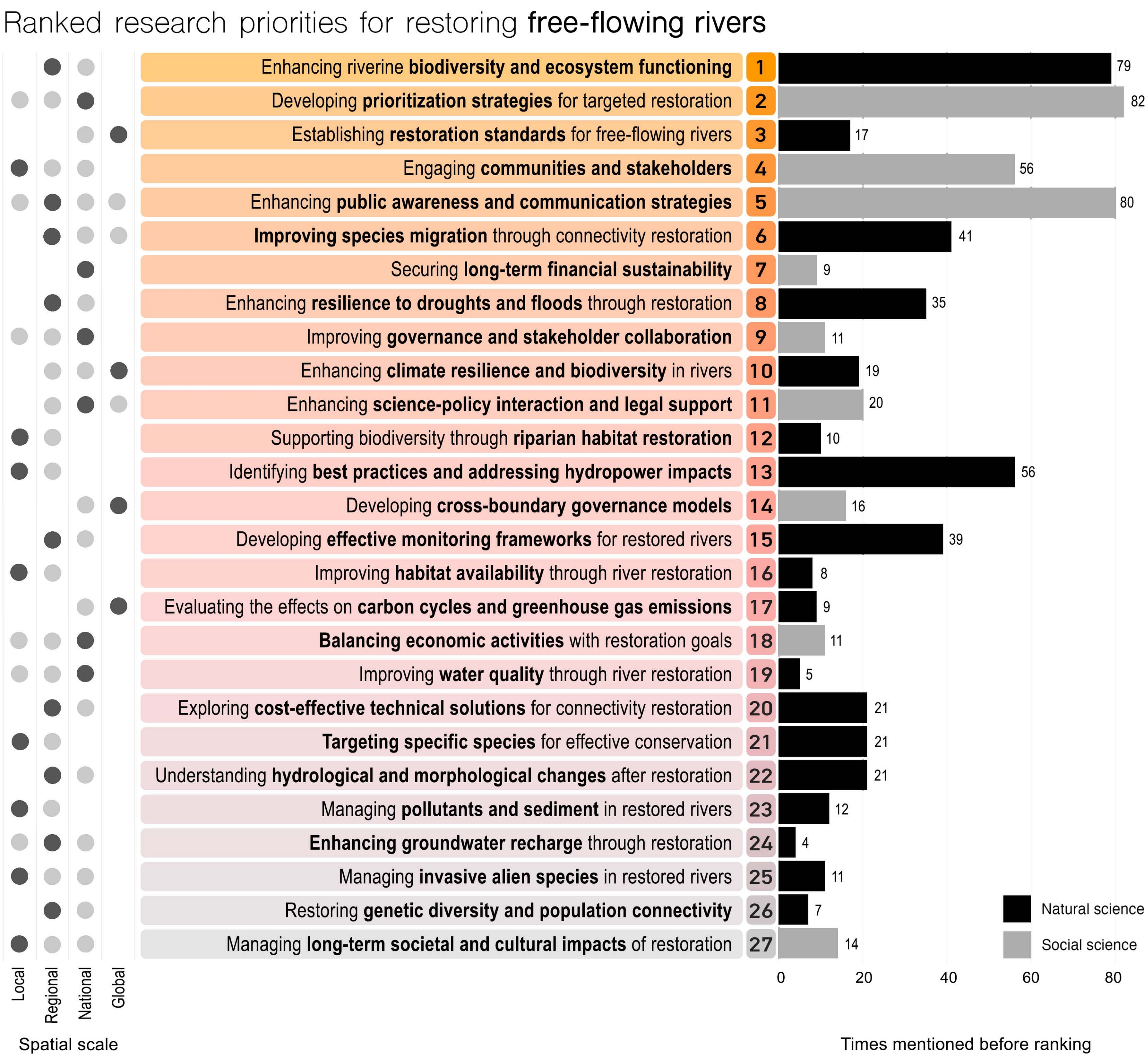
Editorial summary:
Experts from 45 countries find that implementation and coordination, not ecological knowledge, form the main barrier to restoring free-flowing rivers, according to a study using a modified Delphi process to identify and rank research priorities for river restoration

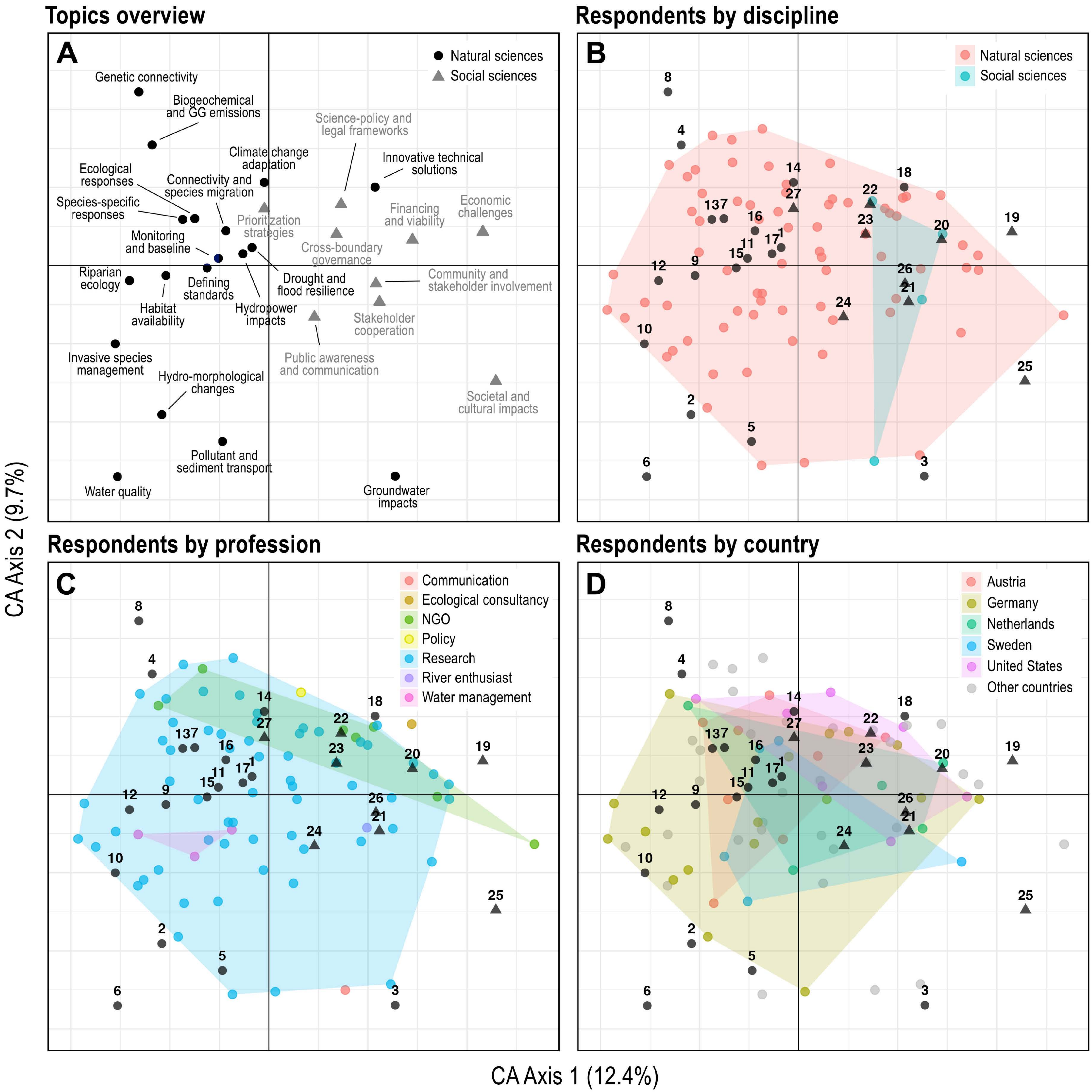
Peer review information:

Communications Earth and Environment thanks Jeffrey Duda and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Letícia Santos de Lima and Yann Benetreau. A peer review file is available.


January 2024
Online scoping survey development for identifying research topics
Pilot testing and finetuning scoping survey
Final scoping survey distribution via targeted emailing and "snowballing approach"
237 respondents
45 countries
714 responses
425 unique subjects
Data cleaning, organization, and categorization
Expert workshop discussion Free Flow 2024
18 participants
13 countries
Refining research topics
27 research topics
9 categories
4 spatial scales
2 academic disciplines
Pilot testing and fine-tuning ranking survey
Final ranking survey distribution
75 respondents
25 countries
Analysis and synthesis of results
Final ranked list and discussion of research priorities
Desk study
- core author group
Online (Norwegian Institute for Nature Research, aquatic biodiversity department)
- 30 participants
Online (SurveyMonkey)
- full extent of the reach was not quantifiable
Desk study
- core author group
Free Flow 2024 Conference (16 April 2024 in Groningen, the Netherlands)
Desk study
- core author group
Online (Leibniz Institute of Freshwater Ecology and inland Fisheries (IGB))
- 10 participants
Online (SurveyMonkey)
- sent to 175 previous scoping survey respondents and workshop participants
Desk study
- core author group
Desk study
- full author group
December 2024


Financing
and viability
Cross-boundary
governance
Economic
challenges
Science-policy
and legal frameworks
Public awareness
and communication
Social
Science
Societal and
cultural impacts
Stakeholder
cooperation
Community
and stakeholder
involvement
Prioritization
strategies
Defining
standards
Innovative
technical solutions
Climate change
adaptation
Monitoring
and baseline
Water quality
Pollutant and
sediment transport
Invasive species
management
Genetic
connectivity
Riparian
ecology
Hydropower
impacts
Species-specific
responses
Ecological
responses
Hydromorphological
changes
Connectivity and
species migration
Habitat
availability
Natural
Science
Drought and
flood resilience
Biogeochemical
and GG
emissions
Groundwater
impacts


Ranked research priorities for restoring free-flowing rivers
Enhancing riverine biodiversity and ecosystem functioning 1 79
Developing prioritization strategies for targeted restoration 2 82
Establishing restoration standards for free-flowing rivers 3 17
Engaging communities and stakeholders 4 56
Enhancing public awareness and communication strategies 5 80
Improving species migration through connectivity restoration 6 41
Securing long-term financial sustainability 7 9
Enhancing resilience to droughts and floods through restoration 8 35
Improving governance and stakeholder collaboration 9 11
Enhancing climate resilience and biodiversity in rivers 10 19
Enhancing science-policy interaction and legal support 11 20
Supporting biodiversity through riparian habitat restoration 12 10
Identifying best practices and addressing hydropower impacts 13 56
Developing cross-boundary governance models 14 16
Developing effective monitoring frameworks for restored rivers 15 39
Improving habitat availability through river restoration 16 8
Evaluating the effects on carbon cycles and greenhouse gas emissions 17 9
Balancing economic activities with restoration goals 18 11
Improving water quality through river restoration 19 5
Exploring cost-effective technical solutions for connectivity restoration 20 21
Targeting specific species for effective conservation 21 21
Understanding hydrological and morphological changes after restoration 22 21
Managing pollutants and sediment in restored rivers 23 12
Enhancing groundwater recharge through restoration 24 4
Managing invasive alien species in restored rivers 25 11
Restoring genetic diversity and population connectivity 26 7
Managing long-term societal and cultural impacts of restoration 27 14
Natural science
Social science
0 20 40 60 80
Local
Regional
National
Global
Spatial scale
Times mentioned before ranking



Topics overview
A
Natural sciences
Social sciences
Genetic connectivity
Biogeochemical and GG emissions
Science-policy and legal frameworks
Climate change adaptation
Innovative technical solutions
Ecological responses
Connectivity and species migration
Species-specific responses
Prioritization strategies
Financing and viability
Economic challenges
Monitoring and baseline
Cross-boundary governance
Riparian ecology
Defining standards
Drought and flood resilience
Community and stakeholder involvement
Habitat availability
Hydropower impacts
Stakeholder cooperation
Invasive species management
Public awareness and communication
Hydro-morphological changes
Societal and cultural impacts
Pollutant and sediment transport
Water quality
Groundwater impacts
Respondents by discipline
B
Natural sciences
Social sciences
Respondents by profession
C
Communication
Ecological consultancy
NGO
Policy
Research
River enthusiast
Water management
Respondents by country
D
Austria
Germany
Netherlands
Sweden
United States
Other countries
CA Axis 2 (9.7%)
CA Axis 1 (12.4%)