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Trends and purposes of European river monitoring and restoration

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ABSTRACT

This study provides the first geospatial analysis of the trends and uptake of European river monitoring and restoration. European monitoring targets rivers draining agricultural and urban land, which leads to geospatial biases due to the co-occurrence with soils, topography, and river orders. Most notably, intermittent rivers and ephemeral streams are underrepresented due to lower monitoring intensities in Southern Europe, headwaters, and catchments with steeper slopes or less arable soils. Improving monitoring efforts in these ecosystems can advance our scientific understanding of complex linkages between ecological quality outcomes and specific stressors. Large differences were found in the spatial coverage of river monitoring and chemical status reporting between European river regions, which highlights comparability issues with the outcomes of Water Framework Directive river quality status due to the 'one-out-all-out' principle. Chemical status monitoring is also less frequent in agricultural catchments, which leads to a knowledge gap on the impacts of priority substances, such as pesticides, on agricultural rivers. These uncertainties around the actual quality of rivers are propagated to the prioritisation, design and purposes of river restoration. River restoration coverage is distinctively higher in Western Europe and larger urban rivers, compared to lower incidences in headwaters draining agricultural or (semi-)natural catchments. Across most regions and geospatial factors, biodiversity conservation was the major purpose for river restoration. Agricultural headwaters and intermittent rivers are low-hanging fruits for future river restoration, wherein socio-economic drivers of river restoration can be leveraged to achieve parallel goals of biodiversity and water resource management.

1. Introduction

The combination of multiple biogeochemical, biological, and geomorphological stressors has a profound negative impact on the habitat quality, biodiversity, and service provision of European river ecosystems (Lemm et al., 2021). Industrial and urban pollution from point sources introduce a wide range of harmful substances and emerging contaminants (Houtman, 2010; van Wezel et al., 2018; Whelan et al., 2022). Land use change and increased soil runoff lead to higher inputs of nutrients, sediment and associated diffuse pollutants in rivers (Jones et al., 2012; Sherriff et al., 2019; Wohl, 2015). In particular, pesticide and nutrient losses from agricultural soils to river networks impact aquatic ecosystems negatively through direct toxicity, eutrophication and algal blooms (Andersen et al., 2017; de Souza et al., 2020; Ulén et al., 2007). Moreover, the increasing dispersal of invasive fauna and flora cause a range of adverse impacts on native aquatic biodiversity through competition or predation, structural damage to aquatic habitats, and loss of genetic integrity (Boon et al., 2020). River systems have also been physically altered through the systematic straightening, deepening, and embanking of rivers, with negative consequences for habitat diversity and flood regulation (Alaoui et al., 2018; Blann et al., 2009; Brown et al., 2018). Harvesting and damming of rivers for irrigation, energy, industrial, and household purposes have further altered their discharge generation and hydrological connectivity (Biemans et al., 2011; Gerten et al., 2008; Vicente-Serrano et al., 2019). Moreover, climate change will likely exacerbate existing water quantity

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and quality pressures by altering the magnitude, frequency and dynamics of rainfall, temperature, runoff, and pollutant transport (Bieroza et al., 2024; O'Briain, 2019; Payne et al., 2020; Stewart-Koster et al., 2024).

To address the current and future challenges in European water management, the Water Framework Directive (WFD) was initiated to provide a framework for the protection and sustainable management of European water bodies, including rivers (European Parliament and Council, 2000). The combined assessment of ecological and chemical status applies a one-out-all-out principle, which selects the worst outcomes from all assessed quality elements. This is used as conservative management tool to identify water bodies with environmental problems that require management intervention. The European State of the Environment (SoE) Monitoring was installed to provide high-level, pan-European assessments of water quality and quantity, focussed on environmental trend analysis rather than regulatory compliance reporting (European Parliament and Council, 2003). Although the ecological status is not a continuous scale for quantifying environmental quality, the resulting cross-continental assessment of water bodies is often used to compare their status between regions (Bouleau and Pont, 2015; Voulvoulis et al., 2017). To date, the majority of European rivers do not reach the WFD target of good ecological status, wherein bad and poor status persists particularly in temperate lowland agricultural catchments (Kristensen et al., 2018). Although previous analyses of WFD results have identified agricultural and urban land uses as dominant predictors of ecological status, a substantial unexplained variation remains both within and between different regions (Lemm et al., 2021; Schürings et al., 2024). This is because different river systems have unique environmental dynamics and pollutant processing capacities, which prevent the disentangling of local land use pressures from upstream contribution and fluvial geomorphology (Stubbington et al., 2022). River systems with high pollutant loading from the land but low residence times can cause large downstream problems, while not necessarily displaying poor ecological status themselves. Conversely, lowland rivers with fine-textured beds have higher nutrient concentrations and lower diversity of aquatic taxa used as biological quality elements, regardless of current local land use pressures (Bol et al., 2018; Bracken et al., 2015; Elosegi, Díez and Mutz, 2010). In addition, regional differences in ecological status can also result from differences in the intensity and implementation of the WFD monitoring (Birk et al., 2012; Boeuf and Fritsch, 2016; Erba et al., 2022; Pardo et al., 2012). Due to the one-out-all-out principle, regions with higher monitoring efforts will have reduced probabilities of achieving good ecological status. Another example of a comparability issue is the definition of where rivers begin, wherein headwaters are sometimes excluded from monitoring and reporting by environmental agencies due to their intermittent activity and legislative uncertainty (Baattrup-Pedersen et al., 2018; Bieroza et al., 2024; Brinkerhoff et al., 2024). Thus, when assessing outcomes of ecological status between regions, it is critical to account for the differences in monitoring intensities and respective degree of land use and geospatial bias.

While water quality and biodiversity in European rivers have partly recovered from the 1990s due to stricter emission regulations, this recovery has slowed down since the 2010s (Haase et al., 2023; Qu et al., 2023; Whelan et al., 2022). Legacy pollutants, accumulated in soils, groundwater and rivers, continue to negatively impact river water quality, which implies that reductions in pollutant inputs alone will not necessarily lead to improvements in water quality and ecological status (Basu et al., 2022; Bieroza et al., 2019; Wasson et al., 2010; Wohl, 2015). Thus, to accomplish further improvements in ecological status of rivers and European Green Deal goals, further actions such as river restoration are necessary (Bieroza, Bol and Glendell, 2021). Here, river restoration refers to a large variety of ecological, physical, and hydromorphological management practices aimed at restoring the biodiversity and ecosystem functioning of the river system (Flávio et al., 2017; Smith et al., 2014; Wohl et al., 2015). Evaluations of previous restoration efforts have shown that despite large investments, river restoration activities do not consistently lead to tangible improvements in water quality and water resource management (Bol et al., 2018; Destouni et al., 2017; Jähnig et al., 2011). This can be attributed to environmental variability, upstream pollutant pressures, land use and pollution legacies in shaping contemporary water quality responses in rivers. Basing river restoration on ecological status without considering aforementioned factors can lead to unrealistic expectations (Baattrup-Pedersen et al., 2018; Brown et al., 2018; Mellander et al., 2018; Wiering et al., 2020) or inappropriate placement and design of river restoration projects (Djodjic et al., 2022; Hallberg et al., 2024).

As we approach the end of the third river basin management cycle of WFD and start of the European Green Deal, there is thus a need to investigate the regional and geospatial distribution of monitoring and restoration used for water management strategies across European rivers. The main objective of this study was therefore to explore regional, environmental, and land use-associated biases of the current implementation of European river monitoring and restoration. Herein, we aimed to answer the following questions:

1) Are there significant regional differences in the coverage of monitoring and restoration?

2) Do geospatial biases in land use, hydrology, and geomorphology influence the comparability of ecological status assessments?

3) What is the distribution of ecological and chemical status reporting in rivers?

4) What are the major purposes for river restoration?

5) What are the gaps for supporting future river management strategies?

To answer these questions, we leveraged recent progress and availability of pan-European datasets of river networks, land use, elevation, and soil classes. Water quality monitoring and river restoration of all European rivers were quantified based on the i) WFD and SoE monitoring points reported to the Water Information System for Europe (WISE), ii) RESTORE river dataset for river restoration activities, and iii) Global Runoff Data Centre (GRDC) dataset for hydrological gauging. These databases were integrated into the novel Geospatial European River Monitoring and Restoration Dataset (GERD) that provides standardised geospatial information on land use, geomorphology, and hydrology for each of the monitored or restored river sections (Wynants et al., 2024). This open-access dataset can be utilised as a novel tool for evaluating regional differences, bias, and data comparability within European river monitoring and restoration.

2. Materials and methods

2.1. Geospatial data gathering and processing

A 10 m resolution Digital Elevation Map was collected from the EU-DEM10 project (Copernicus Land Monitoring Service, 2016). Pan-European data on the river networks and their drainage basins was collected from the validated EU-Hydro River Network Database split in 35 river regions that cover EU member and partner states (Copernicus Land Monitoring Service, 2020b). This spatial dataset contains vectorised river network files with Strahler order and associated headwater catchments (average 21.3 km^2) that were calculated from the EU-DEM flow accumulation. Each headwater catchment is thus connected to a specific river section and constitutes their direct hydrological drainage area with exclusion of drainage catchment upstream of confluences. However, river sections from this database do not necessarily correspond with WFD river water body classification. Land cover information was obtained from the 100 m resolution Corine dataset (Copernicus Land Monitoring Service, 2020a), which provides a pan-European Land Cover inventory for 44 thematic classes for the 2018 reference year. A soil map for Europe was gathered from the harmonised European Soil Database (European Soil Data Centre, 2004), which includes soil types according to the World Reference Base soil classification system.

European surface water bodies were collected from the European Environment Agency geospatial data catalogue (European Environment Agency, 2020, 2023a, b).

Monitoring points reported to the WFD and SoE (hereafter only referred to as WFD) in 2010, 2016, and 2022 by the EU member and partner countries were also gathered from the European Environment Agency geospatial data catalogue (European Environment Agency, 2020, 2023a, b). The WFD monitoring point dataset contains information on the two main assessment types in rivers: ecological status, which is based on biological, hydromorphological, and physico-chemical indicators; and chemical status, which are measurements of priority substances and hazardous pollutants against environmental quality standards. A pan-European dataset on river restoration was obtained from the RESTORE Project, which is based on voluntary case reporting (River Restoration Centre, 2023). The RESTORE database held, at the time of download, over 1400 restoration sites covering most of the study area and contains information on the purposes for restoration (Economic benefits, Fisheries, Flood management, Habitat and Biodiversity, Hydropower, Hydromorphology, Social benefits, and Water quality). European hydrological river gauging station information was obtained from the GRDC, containing river discharge measurements over the entire world (Global Runoff Data Centre, 2024).

All processing of the geospatial data was done in ArcMap 10.8.1. The 44 Corine land cover classes were reclassified to four main land use types: urban, agriculture, (semi-)natural, and water. All WFD monitoring points for groundwater, and points that were located within 100 m of lakes, artificial water bodies, transitional and coastal water were removed so that only river monitoring points were retained. Lakes and artificial water bodies were also omitted from the river and basin network. Spot checks of sites with quantitative and chemical trend status were performed to validate that they were river sites. For each headwater catchment, the total areas, percentages, and majority of each land use type were calculated. The average slope per catchment was calculated from the EU-DEM. The catchments were dissolved with soil type as a majority statistic, yielding the dominant soil type per catchment. Subsequently, the geospatial information was transferred to the river sections located within each catchment using intersect analysis. The resulting river network dataset (Wynants et al., 2024) contains sectioned information on Strahler order, dominant land use, average slope, dominant soil type, and river length. Finally, the WFD monitoring points, RESTORE points, GRDC points were linked with the geospatial data from the nearest river section using the 'Spatial Join' tool.

2.2. Data analyses

All data analysis was performed in R 4.1.3 (R Core Team, 2022). The average slope was classified in five slope classes: 'Flat' = 0°- 4°, 'Gentle' = 4°- 9°, 'Moderate' = 9°- 15°, 'Steep' > 15°- 30°, and 'Very Steep' > 30°. Only the major soil groups of the World Reference Base were retained for further analysis. Catchments dominated by urban land use that were not assigned a soil type due to gaps in the soil maps, were given 'Urban soils' as classification. The cumulative total European river length was calculated per category (dominant land use type, Strahler order, slope class, and soil type). Likewise, the cumulative WFD monitored, GRDC gauged, and restored river length was calculated per category, wherein the reported point values were assumed to cover the entire reach (river order within a catchment). Subsequently, the proportion of monitored, gauged and restored river length against total river length was calculated per category. Differences in types of WFD monitoring and river restoration were calculated and visualised with respectively bar plots and radar plots per category. For each category, the number of sites with specific restoration purposes was calculated, after which the proportion was calculated against the total amount of restoration cases. These proportions were subsequently converted to coordinates to plot as a radar using 'ggplot2' adapted from the 'ggradar' function (Bion, 2023). As opposed to categorical analysis, the continuous impact of land use cover on probabilities of monitoring and restoration presence was inferred using binomial regressions in the "Generalized Linear Models" function from R stats (R Core Team, 2022). Given the presence of reported chemical trend and quantitative status in rivers, the former was assumed to be misattributed from chemical status and the latter from ecological status. We transferred those points to the appropriate assessment type for further analysis, although the small amount (<100) does not influence the outcomes.

Independence of the categorical variables (dominant Land use, Strahler order, Slope Class, and Soil type) was investigated using Chi-square tests. Strength and direction of correlation was calculated on three different levels: 1) unranked on major variables (dominant land use, slope class, Strahler, soil type), 2) by classifying proportions of each land use type into factor ranks and comparing with other variables, and 3) by comparing all individual factor levels of each variable. These were calculated and with the basic 'stats' package using respectively 1) Cramér's V, 2) Polychoric relationship, and 3) Pearson correlation on dummy variables (categorical variables are one-hot encoded to binary levels), and subsequently plotted on correlation matrices. Multivariate interactions were visualised using Multiple Correspondence Analysis using the "FactoMineR" and "factoextra" packages (Husson et al., 2023; Kassambra and Mundt, 2020).

3. Results

3.1. Regional coverage of WFD monitoring, GRDC gauging, and river restoration

There are strong regional variations in monitoring and restoration coverage and purposes between the different river regions of Europe, with overall higher coverage in northwestern Europe (Fig. 1; Table S1). Among reported WFD assessment types, chemical status showed the highest variation between river regions (Table S2). In all regions, ecological status was the dominant type of WFD monitoring points. Biodiversity is the most important driver for restoration cases reported to RESTORE.

WFD monitoring is distinctively highest in the Skjern (for corresponding countries see Table S1), where 84 % of river sections are covered. High WFD coverages are also found in the Rhine (51 %) and Shannon (46 %) basins. Low WFD monitoring coverages (<5 %) are found in the Hondo, Iceland, Tana, Tweed, and Vorma river regions. GRDC hydrological gauging coverage typically covers less than 5 % of river sections, except for the Nemunas (9.6 %), Rhine (9.0 %) and Thames (8.2 %) regions. The Scandinavian and Irish river regions have lower incidence (<10 %) of chemical status reporting compared to ecological status. In contrast, the Hondo, Neva, Rhone, and Tirso rivers have higher relative importance of chemical status (> 75 %) reporting. Even though chemical trend and quantitative status assessment should be confined to groundwater bodies according to the WFD (European Parliament and Council, 2000), results show significant amount of river sites that received these types of status. The Garonne, Rhone, and Vistula have received significant amounts reports of chemical trend monitoring (> 25 %). Notable quantitative status reporting of rivers was only found in Iberian and Italian river basins, albeit still very low ranging between 1.2 % and 2.2 %.

River restoration coverage was by far greatest in the Thames, where roughly 10 % of river length was reported to have undergone restoration. River restoration coverage in other regions typically covered less than 1 % of the river lengths, except for the Ebro (1.8 %), Rhine (2.2 %), Seine (2.0 %) and Tweed (1.9 %). Distinct differences were also found in dominant purposes of river restoration between the river basins (Table S3), although no clear regional trends stand out. River basins in northern Europe are more often restored for hydropower purposes, while fisheries is particularly important in the British Isles, Northern Europe, and the Baltic states. Social purposes for river restoration are more common in Southern Europe and the British Isles.

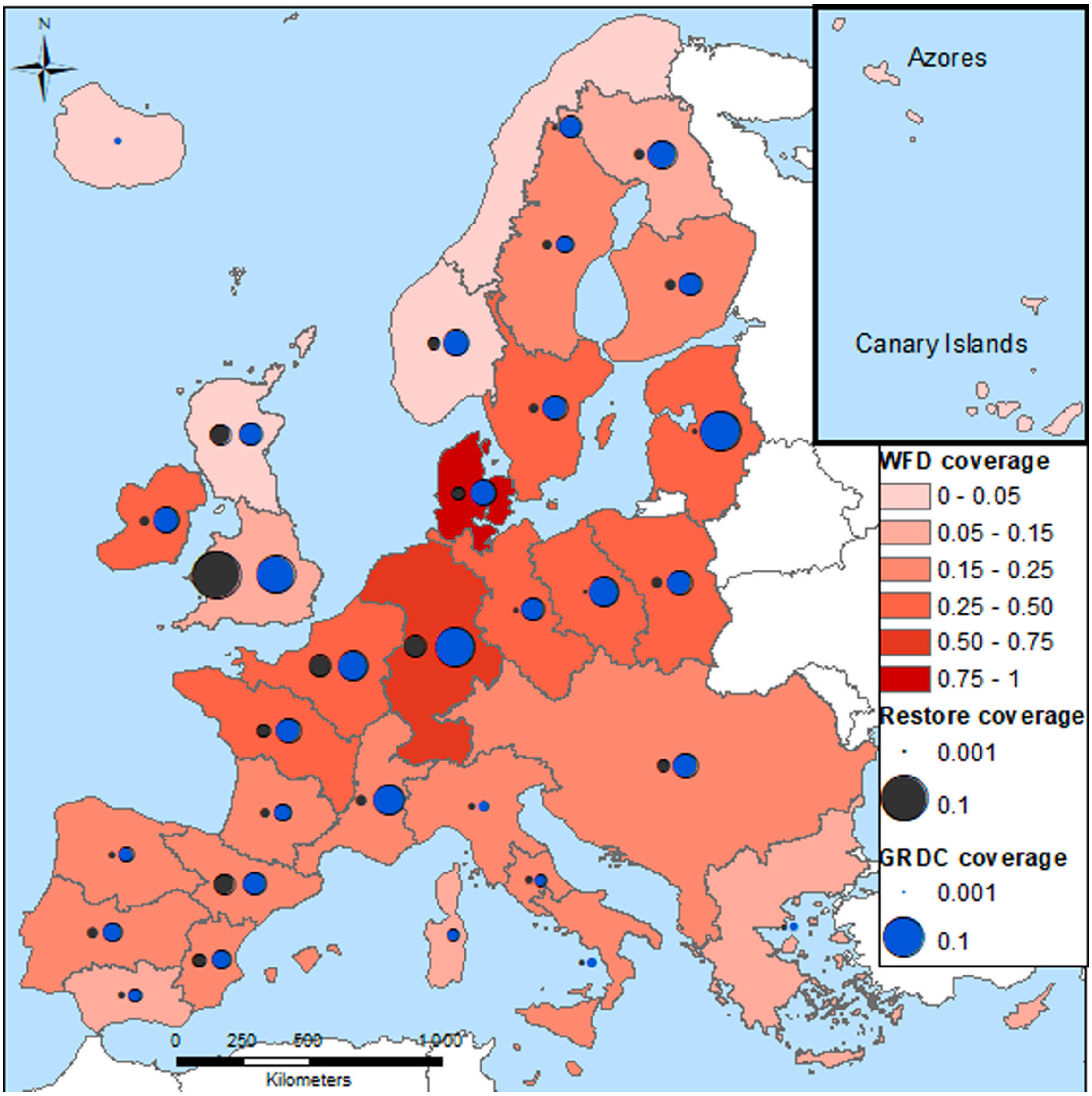

Fig. 1. Coverage maps of the study area showing the European river basin regions and their total proportion of river length 1) monitored for Water Framework Directive (red colour), 2) Restored (black points), and 3) gauged for hydrology (blue points), compared against the total regions' river length.

3.2. *Distribution of monitored and restored rivers across geospatial classes*

Of the 2.3×10^6 km of total European river length, an estimated 23 % (5.1×10^5 km) is monitored and reported to the WFD, 3.4 % % (7.8×10^4 km) is gauged according to the GRDC, and 0.9 % (2.0×10^4 km) has been subject to river restoration as reported in RESTORE (Table S4). However, these proportions vary strongly with the dominant land use, soil type, slope class, and Strahler order (Fig. 2). Urban and agricultural rivers are more intensively monitored, and urban rivers have distinctively higher proportions of GRDC gauging and restoration. The highest coverage in monitoring, gauging, and restoration were found in large rivers (6th to 8th order), in flat catchments, and productive soils.

Within agriculturally dominated rivers, 30 % are WFD monitored, 4.2 % are hydrologically gauged, and 1.3 % underwent river restoration (Table S4). In (semi-)natural rivers, 17 %, 2.7 %, and 0.5 % are respectively WFD monitored, GRDC gauged, and restored. Approximately 30 % of urban dominated rivers are WFD monitored, while the proportions of GRDC gauging and restoration are distinctively higher than the other land use types with 6.4 % and 4.9 % respectively. There's a strong positive relationship between agricultural land cover and chemical status monitoring ($p < 2e^{-16}$), weak positive with ecological status ($p = 6.48e^{-06}$), and non-significant for GRDC ($p = 0.10$) and RESTORE ($p = 0.36$) points (Figure S3). The relationships between urban land cover and ecological status, chemical status, GRDC monitoring, and RESTORE points is constant ($p = 0.11$), strongly positive ($p < 2e^{-16}$), positive ($p = 3.12e^{-13}$), and positive ($p = 4.3e^{-09}$) respectively. The relationship with natural land cover is weakly negative for ecological status ($p = 9.63e^{-06}$), GRDC monitoring ($p = 0.04$), and RESTORE ($p = 6.98e^{-3}$), but strongly negative for chemical status ($p < 2e^{-16}$). The WFD monitoring coverage increases strongly from 8.2 % of 1st order rivers to ca. 81 % of 6th and 7th order rivers, but subsequently decreases to 74 % in the 8th order and 49 % of 9th order rivers (Fig. 2B; Table S5). The hydrological gauging coverage in 1st and 2nd order headwaters is below 1 %, but subsequently increases from 5 % in 3rd order to 50 % in 7th order rivers, after which it decreases again to 36 % and 24 % in 8th and 9th orders respectively. The river restoration coverage increases exponentially from 1st order (0.3 %) to 8th order (23 %), followed by a slight decrease to the 9th order (16.1 %). The monitoring and restoration coverage corresponds

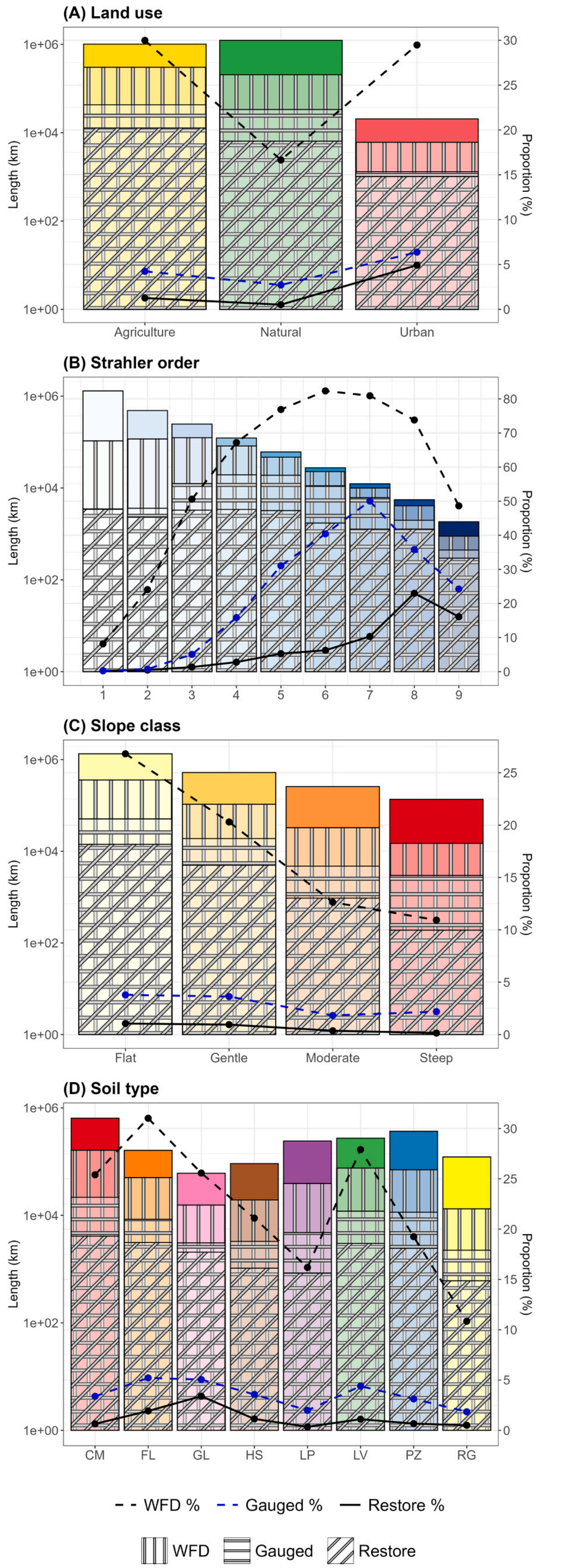

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Fig. 2. The cumulative total river lengths (full columns) with length of WFD (vertical lines), hydrological gauged (horizontal lines), and restored (diagonal lines), shown on left y axis (note log scale).The proportion of total stream length (%) of WFD (black dashed lines), hydrological gauged (blue dashed lines), and restored (black full lines), shown on right y axis. Rivers lengths are grouped by dominant land use, Strahler order, slope class, and dominant soil type (Cambisols, Fluvisols, Gleysols, Histosols, Leptosols, Luvisols, Podzols, and Regosols).

negatively with the slope steepness class, decreasing from 27 % to 11 % for WFD monitoring and from 1.1 % to 0.1 % for restoration (Fig. 2C; Table S6). The hydrological gauging coverage is around 3.7 % for flat and gentle sloped rivers and around 2 % for moderately and steeply sloped rivers. The greatest decline in both monitoring and restoration coverage is thus observed between gentle and moderately sloped river catchments. The monitoring and restoration coverage strongly varies with the dominant soil type (Fig. 2D). Roughly 30 % of Fluvisol and Luvisol dominated rivers are monitored, 25 % of Cambisols and Gleysols, 20 % of Histosols and Podzols, 16 % of Leptosols, and 11 % of Regosol dominated catchments. The distribution of hydrological gauging is similar, albeit with lower coverage and differences. The coverage of river restoration was most noteworthy in Gleysol (3.4 %) and Fluvisol (1.9 %) dominated rivers (Table S7).

None of the geospatial variables were independent as shown by all p-values of the correlation tests being below 0.001. When comparing unranked variables, the strongest correlation was found between slope and land use (Cramér's V= 0.30, $p < 0.001$), explained by a positive correlation between (semi-)natural land use and slope class (Polychor = 0.65, $p < 0.001$), and a negative correlation between slope class and agricultural land use (Polychor= −0.50, $p < 0.001$) and urban land use (Polychor = −0.32, $p < 0.001$) (Figure S1). There was also a significant relationship between unranked soil type and land use (Cramér's V = 0.26, $p < 0.001$). Most notably, agricultural land use correlated to Fluvisols ($r = 0.13$, $p < 0.001$) and Luvisols ($r = 0.19$, $p < 0.001$), while (semi-)natural land use correlated to Leptosols ($r = 0.16$, $p < 0.001$) and Podzols ($r = 0.24$, $p < 0.001$). The relationship between Strahler and land use was weak, but still significant (Cramér's V = 0.03, $p < 0.001$). Most notably, urban land use correlated to higher Strahler order (Polychor = 0.13, $p < 0.001$). These general trends are also reflected in the MCA biplot (Figure S2), although there remains 80 % of unexplained variance. The MCA revealed some additional trends, for example that headwaters (Strahler 1–2) take a central place on the MCA indicating their ubiquitous place in the landscape.

3.3. The types of European river monitoring

Determination of ecological status reporting was the most common reporting type for the WFD dataset, regardless of geospatial factors (Fig. 3; Table S8). The percentage of ecological status monitoring was slightly higher in agricultural rivers (76 %) compared to semi-natural (72 %) and urban rivers (73 %). Chemical status reporting is more common in urban rivers (38 %) compared to agricultural and semi-natural rivers (ca. 25 % in both). With regards to river lengths, ecological status negatively corresponded to the Strahler order decreasing from 77 % of Strahler 1–2–64 % of Strahler 5–9. The opposite was observed for chemical status monitoring, which increases from 21 % in Strahler 1–2–51 % in Strahler 7–9. Concerning slope, rivers draining flat catchments were more frequently monitored for ecological status (77 %) and less frequent in moderately sloped rivers (62 %). Chemical status was monitored relatively equally in flat to moderate slope classes (ca. 25 %). Among the dominant soil types, ecological status monitoring was the most prevalent purpose in monitoring of Histosol-dominated rivers (82 %) and the lowest in Regosols (64 %). Chemical status monitoring was highest in Fluvisol dominated rivers (34 %) and Histosols (32 %), and lowest in Podzols and Regosols (Table S8).

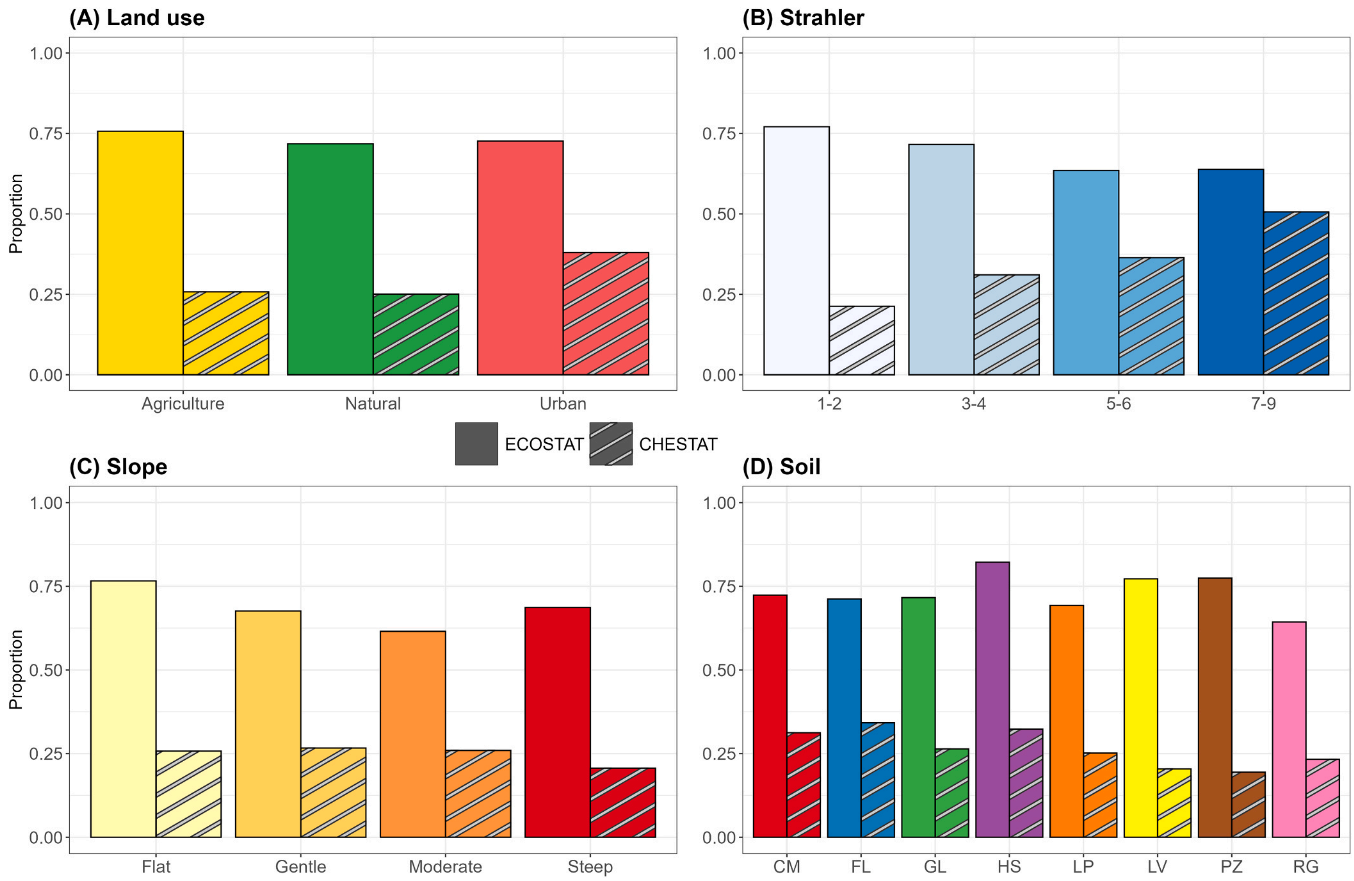

Fig. 3. The proportional differences in river WFD assessment type: ecological status (ECOSTAT) and chemical status (CHESTAT) across geospatial variables. The Strahler numbers relate to the river orders. The soil types are cambisol (CM), fluvisol (FL), gleysol (GL), histosol (HS), leptosol (LP), luvisol (LV), podzol (PZ), regosol (RG).

3.4. The purposes of European river restoration

Biodiversity conservation was the most common purpose for river restoration as reported to RESTORE in Europe (85 % of sites), regardless of dominant land use, Strahler order, slope, or soil type. Except for biodiversity, the purpose for river restoration strongly varied with the dominant land use type (Fig. 4A; Table S9). Strong variations in river restoration purposes were also observed between Strahler order (Fig. 4B), slope class (Fig. 4 C), and dominant soil type (Fig. 4D). The purposes of hydromorphology, water quality, social benefits, fisheries, and flood risk mitigation were reported in around 30 % of restoration cases. Economic benefits and hydropower were reported the least (11 % and 5 % respectively).

Flood management and social benefits were more common in urban rivers (45 % and 55 % respectively), compared to agricultural (29 % for both) and (semi-)natural rivers (24 % and 15 % respectively). Water quality was the second most important reason for restoration in agricultural rivers (34 %), but less so for (semi-)natural (25 %) and urban rivers (16 %). Hydromorphology was found to be an important factor for restoration of (semi-)natural rivers (45 %) and agricultural rivers (34 %), but less for urban rivers (19 %). Economic purpose for river restoration was most common in urban rivers (16 %), compared to agricultural (10 %) and (semi-)natural rivers (8 %). Hydropower purpose was only considerable in (semi-)natural rivers (16 %). Across Strahler orders, biodiversity conservation was more frequently reported in lower order rivers, decreasing from ca. 85 % in Strahler 1–4–68 % in Strahler 7–9 (Fig. 4B). While fisheries and flood management were often indicated as a reason for restoration in rivers with Strahler order 1–6 (ca. 34 % and 30 % respectively), they were less important in Strahler 7–9 (5 % and 17 % respectively). The importance of social benefits as a reason for restoration negatively relates with Strahler order, decreasing from 32 % in Strahler 1–2–15 % in Strahler 7–9. Water quality as a purpose for river restoration is more frequently reported in Strahler 1–4 (ca. 30 %), compared to Strahler 5–6 (11 %) and Strahler 7–9 (21 %). Biodiversity conservation and flood management were major purposes in all slope classes, but of lower importance in moderately sloped rivers (75 % and 22 % respectively). The importance of fisheries, social benefits, and water quality as purposes for river restoration were negatively related with the slope class of the river, decreasing from 32 % to 10 %, 32–10 %, and from 30 % to 20 % respectively. Conversely, hydropower and hydromorphology were positively related with the slope class, increasing from 3 % to 20 % and from 32 % to 90 % respectively. Economic benefits were most important in moderately sloped rivers (18 %), compared to 10 % of flat and gentle sloped rivers and 0 % of steep sloped rivers. Restoration for biodiversity purposes ranged from 75 % in Regosols to 92 % for Leptosols. Hydropower and hydromorphology were found to be relatively important in Podzols (14 % and 45 % respectively) and Regosols (21 % and 45 % respectively). The importance of fisheries, flood risk management, and social benefits as purposes for river restoration was relatively high in Gleysols (41 %, 38 %, and 40 % respectively). Levosol rivers were commonly restored for the purpose of fisheries (38 %) and social benefits (35 %). Hydromorphology and flood risk management are important reasons for river restoration in Leptosols (54 % and 40 % respectively). Histosol dominated rivers were commonly restored for the purpose of water quality improvement (46 %), economic reasons (16 %), and hydromorphology (48 %).

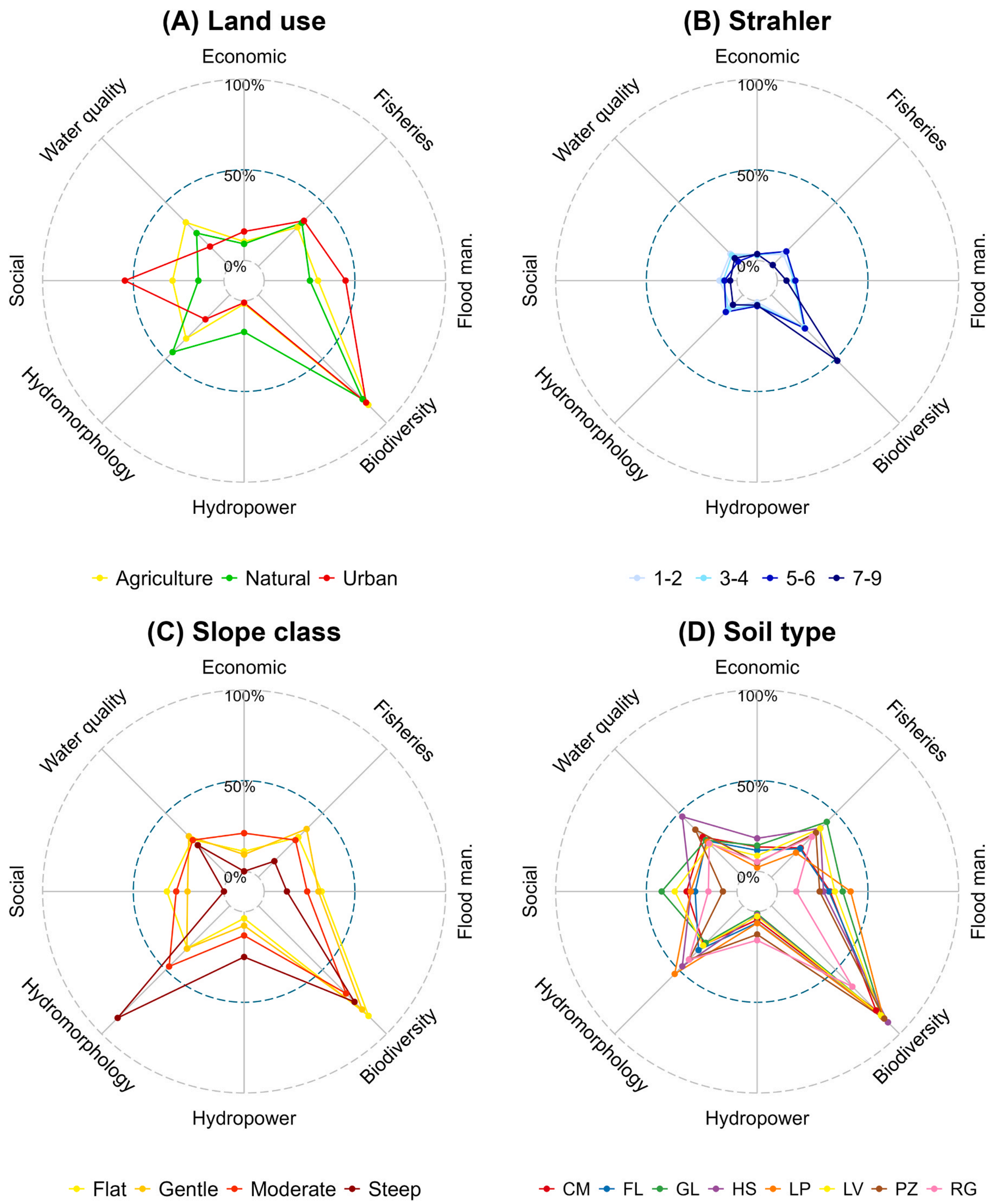

Fig. 4. Radar plots showing the differences in purpose for river restoration depending on the geospatial environment. The Strahler numbers relate to the river orders. The soil types are cambisol (CM), fluvisol (FL), gleysol (GL), histosol (HS), leptosol (LP), luvisol (LV), podzol (PZ), regosol (RG).

4. Discussion

4.1. Limitations and reporting biases

Management practices and land use intensities have a wide variation of impacts on river systems, which are not necessarily reflected by the dominant or the percentage agricultural and urban land cover alone. Future improvements to the dataset could be made by adding ordinal land use pressure scores based on management factors and land cover (Schürings et al., 2024; Wasson et al., 2010). The lack of specific quality elements (biological, hydromorphological, and physico-chemical) reporting in monitoring points of WISE also impede evaluation of the used tools within WFD.

The reported coverage of WFD monitoring in the Danube is impacted by the Balkan countries that are not participating in the WFD. Likewise, the upper Rhine and Elbe is located in Switzerland, which, while not reporting to WFD, collaborates with EU members on programmes for cross-sectoral water management. The UK's recent ceasing of reporting to the WFD will likely also underestimate monitoring coverage in the Shannon, Thames, and Tweed River regions (De Vito et al., 2020). Although there are many overlaps in monitoring sites reported to WFD and SoE, the SoE is voluntary and does not require status assessment.

There are thus likely additional independent efforts in river water quality and quantity monitoring in participating countries that are not included in this analysis. Likewise, the GRDC and RESTORE datasets are solely dependent on voluntary reporting by scientists and practitioners, and are thus more likely to be impacted by reporting biases. For example, the higher restoration coverage found in the UK may be due to the RESTORE dataset being managed by the UK-based River Restoration Centre, which has a larger outreach and better overview of river restoration cases in their region. The lack of a centrally managed reporting framework and a European database on river restoration remains a gap in European water policy, which could be solved by implementing unified reporting of river restoration cases within the WFD. This would also allow researchers and managers to better connect environmental quality monitoring with river restoration and thereby evaluate its success. Moreover, reporting bias in river restoration can also occur across other geospatial domains, since river restoration implemented by large state projects, nature conservation, or public services, is more likely to be reported compared to restoration by private landholders (Kondolf et al., 2007). This study also only investigated the spatial distribution of reported river restoration regardless of their size, but does not assess the total invested resources and impact. The regional and geospatial trends of the hydrological gauging and restoration intensities reported here should thus be interpreted within this context, and are possibly underestimations of total coverage. Finally, the regional analysis is based on the major European basins as river regions, which in some cases include disparate policy zones and socio-economic conditions. The large size of some regions might also hide important local differences in monitoring and restoration, one example being the greater implementation of river restoration in Southeast England within the Thames region. Since this dataset is published open access (Wynants et al., 2024), we invite researchers to further build on our spatial analyses on locally relevant scales.

4.2. Regional trends and biases in monitoring and restoration intensities

The overall monitoring and gauging coverage of rivers is the highest in Western and Northern Europe. WFD monitoring is particularly high in the Skjern and Rhine River regions (Fig. 1; Table S1). These correspond to western Germany, the Netherlands, and Denmark, which are also the areas with high proportions of rivers in poor ecological status (Kristensen et al., 2018). There are also large differences in the frequency of chemical status monitoring between different regions (Table S7), although these do not reflect industrial and urban land use. The found quantitative status (Italy and Spain) and chemical trend status (France and Poland) reporting highlights discrepancies in the WFD reporting, since these parameters are normally reserved for groundwater (European Parliament and Council, 2000). This is potentially a result from i) misattributions when transferring national river and SoE monitoring points, and 2) wrong WFD classifications when assessing hydrological elements or high-frequency physico-chemical elements.

Lower monitoring, gauging and restoration frequencies in the northernmost regions are likely due to lower population and environmental pressures, while correspondingly low frequencies in Southern Europe could be explained by river variability and socio-economic conditions (Berbel and Expósito, 2018; Bouleau and Pont, 2015; Voulvoulis et al., 2017). It can be argued that the higher percentage of rivers with good ecological status in these less monitored regions (Kristensen et al., 2018) reduces the need for higher coverage of monitoring and river restoration. However, it is important to consider that this may also be a result of insufficient sampling effort and that a higher monitoring intensity in western Europe increases the likelihood of not reaching good ecological status following the one-out-all-out approach. Thus, poor water quality, changing discharge regimes, and high pollutant loads could be masked by low monitoring coverage and intensity. In particular, the higher prevalence of intermittent rivers in Southern Europe complicates monitoring and evaluation (Stubbington et al., 2018). These differences in WFD coverage and implementation hinders comparison, wherein regions with higher spatial and temporal monitoring resolutions are thus likely to yield lower proportions of rivers in good ecological status (Voulvoulis et al., 2017). There is thus a need to increase the incidence of temporally-relevant gauging and pollutant monitoring, particularly in flashy rivers in Southern Europe (Bieroza et al., 2023). In the context of climate change, increased incidence of extreme weather will likely impact hydrology, water quality and ecological status of European rivers, regardless of the current anthropogenic impacts (Jacob et al., 2020; Miao et al., 2023; Payne et al., 2020). We therefore recommend that WFD and SoE river monitoring should increase its coverage and frequency in the river regions that are most sensitive to climate change. Herein, the GRDC offers an already substantial network of hydrological monitoring, which can be used for comparison against antecedent conditions. The coverage of reported river restoration is only substantial in Western Europe, in particular England and Wales. Although we acknowledge the likely underreporting in RESTORE, the overall low coverage of river restoration in European river regions highlights the remaining challenge to reach ambitions of the WFD and European Green Deal, considering that the majority of the river basin districts have over 50 % of rivers that do not reach good ecological status (Kristensen et al., 2018).

4.3. Land use trends in monitoring and restoration

Higher river monitoring coverages are observed in agricultural and urban rivers, indicating a general focus on areas with higher expected anthropogenic impacts. While the WFD monitoring intensities are similar in agricultural and urban rivers, their purposes differ slightly, with a stronger focus on chemical status in urban rivers and ecological status in agricultural rivers (Fig. 3, Figure S3). This can be partly explained by the presence of larger rivers in urban areas, wherein priority substances are more conservative and are therefore mostly monitored at the downstream end of river basins. It could also reflect a stronger focus on priority substances and their impacts on human health in urban areas as opposed to a focus on diffuse pollution and hydromorphological impacts in agricultural areas (Lintern et al., 2020). The low incidence of chemical status monitoring in agricultural rivers (7.7 % of all agricultural streams) remains problematic since it overlooks the transport and fate of legacy priority pollutants, such as banned pesticides (de Souza et al., 2020). In addition, there might be agriculturally-relevant emergent pollutants, such as PFAS, pharmaceuticals, and other pesticides added the to the WFD Priority Substance List that are neglected with the present monitoring efforts.

The main purpose of river restoration, as recorded in RESTORE, is habitat restoration & biodiversity conservation, regardless of the dominant land use (Fig. 4). This indicates that river restoration is mostly used as a tool for biodiversity conservation, and less for socio-economic and water resources benefits. Illustrative is the relative lower uptake of hydrological gauging and river restoration activities in agricultural rivers, even though these are highly impacted by hydromorphological changes, hydrological variability, and diffuse pollution. The restoration purpose of improving water quality is more frequent in agricultural rivers compared to the other land uses, although the difference is small. The higher hydrological gauging and restoration activity in rivers draining urban catchment suggests a greater interest in hydrology and river restoration in urban areas. Cross-referencing these findings with differences in the restoration purposes, this seems to be mainly driven by a need for flood mitigation and social benefits in urban areas. Economic motives for restoration are also more prevalent in urban rivers, which might relate to high costs of urban flooding, the need to keep rivers navigable for shipping, or to promote tourism (Kenney et al., 2012). Surprisingly, water quality is a less important purpose for restoration in urban rivers. One explanation could be that the reduction of pollution from industrial and sewage point sources (e.g. emission caps and water treatment plants) have reduced the emphasis on water quality improvement with river restoration. Given the large pools of historical pollutants and continuing issues with raw sewage releases and emerging contaminants, restoration of urban rivers will also increasingly need to focus on water quality improvement (Guimarães et al., 2021). Overall, these findings indicate that there is a large untapped potential for river restoration in agricultural and urban rivers, especially in context of achieving some of the goals of the WFD and European Green Deal (Bieroza et al., 2021).

4.4. Geophysical trends in river monitoring and restoration

Headwaters were found to have overall lower coverage of monitoring, gauging, and restoration intensities, which is likely linked to their high number, intermittent nature, and legislative uncertainty (Baattrup-Pedersen et al., 2018; Bieroza et al., 2024). The higher prevalence of chemical status monitoring in higher order rivers is likely partly due to the co-occurrence of large rivers with urban areas and the need to monitor the confluence of upstream pollution. No obvious trends in restoration purposes were found between river orders, except for the lower importance of fisheries and flood management in the largest rivers. The distinctively lower incidence of water quality as a restoration purpose in 5th and 6th order rivers is also noteworthy and could be due to co-occurrence with urban areas.

There was a greater coverage of monitoring and restoration in rivers draining lower-sloped catchments with arable soil types, which reflect suitability for agriculture, higher population densities and anthropogenic activities in these areas. However, given the higher vulnerability to soil erosion in catchments with steeper slopes and weakly developed or degraded soils (Panagos et al., 2015), and their lower pollutant retention capacities (Haygarth et al., 2005), these results highlight potential caveats in attributing the sources of sediments and associated pollutants. The difference in purposes for river monitoring and restoration between slope classes and soil types reflect the co-occurrence with land uses and the associated water management and socio-economic needs. The distinctively higher restoration activities in Gleysol dominated rivers might be explained by the geographical focus and/or the reporting bias of river restoration towards northwestern Europe, where these soils are more common. Moreover, agriculture in Gleysol areas has historically been subjected to productivity increases through ditching, channel deepening, and rectification, which are obvious priorities for restoration (Flávio et al., 2017).

5. Conclusion: implications for European river monitoring and management strategies

In this pan-European assessment, we found distinct regional and geospatial trends in river monitoring and restoration, with higher proportional coverages in Western Europe and urban areas. Four major types of geospatial biases in European river monitoring and restoration were identified: Southern European rivers, headwaters, and rivers draining sloped catchments with less arable soils. The common factor in these river types is their intermittent and ephemeral nature, complicating monitoring and comparison with reference conditions (Brinkerhoff et al., 2024; Datry et al., 2014; Stubbington et al., 2018). Further, the inclusion of chemical status monitoring was highly variable between river regions and land use types. These findings thus highlight the need for a more comprehensive inclusion of intermittent rivers and ephemeral streams to capture their inherent spatial and temporal variability, explore their role as important ecological habitats, and link stressors with ecological quality (Bieroza et al., 2024; Costigan et al., 2016; Harvey and Kampf, 2024; Pastor et al., 2022), which can be supported by recent progress in high-frequency monitoring techniques (Bieroza et al., 2023). With regards to quantitative monitoring, we further suggest to integrate existing databases of river discharge monitoring from the GRDC hydrological monitoring.

Considering the importance of geospatial factors in regulating runoff and pollutant transport, the identified gaps in monitoring coverage hinder regional comparability in environmental quality and the disentangling of natural and anthropogenic stressors (Brown et al., 2018; Stubbington et al., 2022). In its current form, the WFD is not suitable for identifying and managing the actual sources and dynamics of diffuse and legacy pollutants in river basins. Disentangling the drivers of river water quality will require us to take a river network approach and complement the ecological status with interactions of upstream pollutant contribution, connectivity, and retention (Bracken et al., 2015; Lemm et al., 2021; Stubbington et al., 2022). We therefore urge practitioners to design monitoring and restoration strategies in the context of the mobilisation-transport-deposition continuum (Haygarth et al., 2005; Wall et al., 2011). For example, rivers with good ecological status and low water and pollutant retention capacities can still be valid targets for restoration to tackle downstream water quality and quantity problems (Bracken et al., 2015; Elosegi et al., 2010). To support these shifts, the WFD should aim to include mandatory reporting of monitoring frequency of each included quality element. Moreover, the WISE database should include different quality elements assessed per monitoring site, which would allow for exploration of their distribution and influence on total quality outcomes in the one-out-all-out model.

In accordance with WFD monitoring, the river restoration assessment based on the RESTORE dataset revealed higher uptake of restoration activities in Western Europe, larger rivers, and urban rivers. The overall low coverage of river restoration highlight the challenges ahead to achieve the ambitions of the European Green Deal and increase resilience to climate change impacts. The first step would be to implement systematic reporting of river restoration activities to the WFD, which will allow for a more comprehensive evaluation of their success in improving local ecosystem quality and regulating water and pollutant fluxes (Flávio et al., 2017). Biodiversity conservation is currently the most common purpose for river restoration, wherein other purposes show a large variation between different regions. Lessons from river regions with high river restoration uptake show that social and economic drivers of river restoration can be leveraged to achieve parallel goals of environmental quality and resource management. Future river restoration and management will thus need to refrain from blanket targets of ecological status and instead design river basin management plans on upstream fluxes, localised stressors and vulnerabilities, and economic feasibility (Berbel and Expósito, 2018; Bouleau and Pont, 2015; European Parliament and Council, 2000). This will require the integration of science-based ecological targets with socio-economic demands, while being resilient to projected climatic extremes (Bieroza et al., 2024; Wohl et al., 2015). As shown in this study, opportunities exist in currently neglected river types, particularly through restoration and monitoring of agricultural headwaters, intermittent rivers and ephemeral streams.

CRediT authorship contribution statement

Magdalena Bieroza: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Laura-Ainhoa Prischl:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **John Livsey:** Writing – review & editing, Conceptualization. **Maarten Wynants:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lukas Hallberg:** Writing – review & editing, Visualization, Validation, Conceptualization.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2025.104130.

Data availability

All data is been made available open access on a data repository that has been referenced in the manuscript and attach file step.

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