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Moving towards Europe-wide freshwater restoration through model-based integration of policy objectives

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HIGHLIGHTS

- Integrating HD and WFD data and indicators for pan-EU freshwater screening.
- Framework to identify where, when and which restoration meets policy targets.
- Bayesian network approach for data-driven decisions under WFD, HD and NRR.
- Continental-scale zoning for freshwater conservation, restoration and mitigation.
- Uncertainty-aware data tool to maximize ecological impact of restoration.

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ABSTRACT

In Europe, ecological restoration efforts remain restricted and fragmented, with limited success and coordination across policies. The newly adopted Nature Restoration Regulation aims to address these challenges by setting ambitious, legally binding restoration targets. For freshwater ecosystems, its success depends on better integration of existing legislative frameworks, particularly the Habitats Directive (HD) and the Water Framework Directive (WFD). We present a novel European-scale modeling framework that for the first time, combines HD and WFD-related indicators, and applies specific Bayesian Network features, to achieve: i) a Europe-wide status prediction to identify areas with potential for restoration, conservation or mitigation measures, including spatially explicit information on uncertainty and data gaps, and ii) spatially explicit restoration targets, such as lateral and longitudinal connectivity improvements, derived through backward inference. Model validation demonstrated acceptable performance for six of twelve HD groups, including Bogs, Mires, Fens, as well as Amphibia, Fish and Plants, while sensitivity analysis indicated that taxon-specific responses were primarily driven by pressures from hydrology, morphology, and organic pollution. We provide a large-scale data-driven tool to maximize the ecological impact of restoration efforts across Europe, support efficient resource use, and help policymakers to direct efforts where they are most likely to succeed.

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1. Introduction

Freshwater ecosystems are among the most species-rich ecosystems, but at the same time, they are also among the most endangered (Sayer et al., 2025). Humans are highly dependent on the ecological integrity of freshwater systems for a wide range of functions and services (Lynch et al., 2023). At the same time, anthropogenic pressures such as pollution, hydrological modifications, and morphological degradation exert ongoing impacts on these systems (Lemm et al., 2021; Reid et al., 2019). The condition of European freshwater systems is particularly concerning, with recent pan-European assessments revealing widespread ecological degradation across species, habitats, and ecosystems, underscoring an urgent need for large-scale restoration (Duarte et al., 2023).

Ecosystem restoration, including freshwater, is prioritized in major international frameworks such as the UN Decade on Ecosystem Restoration (United Nations, 2019 A/RES/73/284) or the European Green Deal (European Commission, 2019, COM/2019/640), with considerable potential to enhance the provision of essential ecosystem services (Duarte et al., 2023). However, progress is hindered primarily due to funding limitations, competing land-use interests, and often a general lack of political interest (Cortina-Segarra et al., 2021; Reid et al., 2019). In the freshwater domain, implementation is complicated by the distinct yet complementary regulatory frameworks of the Habitats Directive (HD, 92/43/EEC), which is legally binding and site-based with a primary focus on the conservation of protected habitats and species, and the Water Framework Directive (WFD, 2000/60/EC), which is oriented towards ecological functioning on a basin-scale, aiming to achieve good ecological status (or potential) of all water bodies. Their integration remains inconsistent due to institutional fragmentation and divergent legal objectives and incentive structures (Bouwma et al., 2018; Janauer, Albrecht and Stratmann, 2015; Rouillard et al., 2018). Nevertheless, coordinated implementation has been achieved in several river basin management plans and Natura 2000 sites, demonstrating that integration is feasible when conservation objectives are systematically embedded within data-driven water management planning (Janauer et al., 2015; Solheim et al., 2015). Persistent constraints are primarily associated with fragmented EU restoration funding mechanisms and sectoral budget allocations, which impede strategic coordination at broader spatial scales (Cortina-Segarra et al., 2021). Furthermore, systematic large-scale restoration and conservation planning is frequently lacking, as restoration efforts are typically designed at local scales or focused on individual protected areas, whereas species and habitats are distributed supra-regionally or across even broader spatial extents (Battisti and Fanelli, 2015). Strategies for the designation of conservation and restoration areas and their subsequent management are slow, heterogeneous and insufficiently coordinated (Battisti and Fanelli, 2015; Hermoso et al., 2022).

To counteract the ongoing loss of biodiversity, the European Commission recently intensified its efforts to restore ecosystems by adopting the Nature Restoration Regulation (NRR, 2024), thereby reaffirming its commitment to large-scale ecological restoration at the landscape level in aquatic and terrestrial areas. The NRR builds extensively on existing European legislation, incorporating experiences from previous directives. In the context of freshwater ecosystems, two key legal bases are the HD and the WFD (Hering et al., 2023). The general restoration objectives set out in Article 4 of the NRR are based on the HD and cover a wide range of species and habitats listed in the HD that depend on freshwater systems, with progressive targets set for 2030, 2040 and 2050. Meanwhile, the specific objectives for restoring rivers and floodplains set out in Article 9, which are related to hydromorphological aspects of the WFD, emphasize connectivity restoration of rivers in all dimensions. These include the removal or mitigation of longitudinal and lateral barriers in rivers and floodplains, to restore 25,000 km of free-flowing river stretches and reconnect rivers to their floodplains (Hering et al., 2023). Climate change mitigation is a further important context where wetlands and peatlands restoration, rewetting and restoring connectivity is explicitly mentioned as a joint contribution alongside high biodiversity. Particularly in urban and agricultural areas, the restoration and conservation of wetlands can yield additional co-benefits, such as flood mitigation, recreational opportunities, and improved water filtration (NRR, 2024). Although the objectives of the HD and the WFD are often seen as complementary and various efforts have been made to integrate the two, coordination remains limited and potential conflicts between the two frameworks persist (Evers and Nyberg, 2013). Furthermore, both directives remain far from achieving their stated objectives. Better coordination of these directives is therefore a crucial prerequisite for the effective implementation of the NRR, particularly when identifying areas of high relevance for restoration (Hering et al., 2023).

Predictive modeling is an important tool for restoration and conservation planning as it forecasts ecosystem responses, guiding effective and efficient interventions (Guisan, Thuiller and Zimmermann, 2017). The HD and WFD offer complementary information supporting this goal. More specifically, the WFD provides data on the ecological status of freshwater habitats across all MS, along with extensive data on anthropogenic alterations (i.e. pressures). This enables the investigation of the influence of environmental drivers on ecological conditions. In contrast, the HD provides a harmonized, albeit relatively coarse-grained dataset on the distribution and conservation status of all species and habitats that are listed in the annexes of this directive. This includes assessments of the overall condition of natural habitats and species in terms of their distribution, structure, function, and prospects for long-term survival (Hering et al., 2023). Taken together, the datasets from both directives facilitate the identification of potential causal links between environmental pressures and the status of species and habitats and offer a valuable basis for prioritizing areas with the highest potential for ecological restoration.

To achieve this, our analysis uses a model-based framework that aligns with policy objectives, prioritizing restoration actions supporting the new NRR (Fig. 1). We apply a Bayesian Network (BN) approach to model the status of multiple freshwater-related species and habitat groups from the HD and combine these with WFD-related data on ecological status and anthropogenic-related pressures, i.e., hydrological, morphological alteration and organic pollution as predictors. Leveraging the potential of BNs, we apply status prediction, uncertainty quantification and backward inference to identify and prioritize areas across Europe that i) exhibit joint restoration potential, ii) are supported by sufficient knowledge and certainty, or iii) require further monitoring and research. We define potential restoration targets in terms of lateral or longitudinal reconnection of rivers or both, aligning the results with NRR targets. This study provides the first Europe-wide, policy-aligned predictive tool to prioritize freshwater restoration and directly supports EU policy objectives by directing restoration resources where success is most likely.

2. Material and methods

2.1. Study area and data basis

The study area encompassed all regions in Europe for which data from Article 17 reporting under the HD were available, including all MS as well as the United Kingdom. The analysis was based on a newly developed spatial database of River Restoration Units (R2U, Duarte et al., 2025). This database was designed to support large-scale river restoration planning by enabling the integration of heterogeneous datasets from multiple sources with varying spatial resolutions, while maintaining the nested hierarchy of rivers. In the present study, it was employed to integrate and analyze data from both WFD and HD.

2.2. Indicators

The monitoring and reporting of hydro-morphological pressures

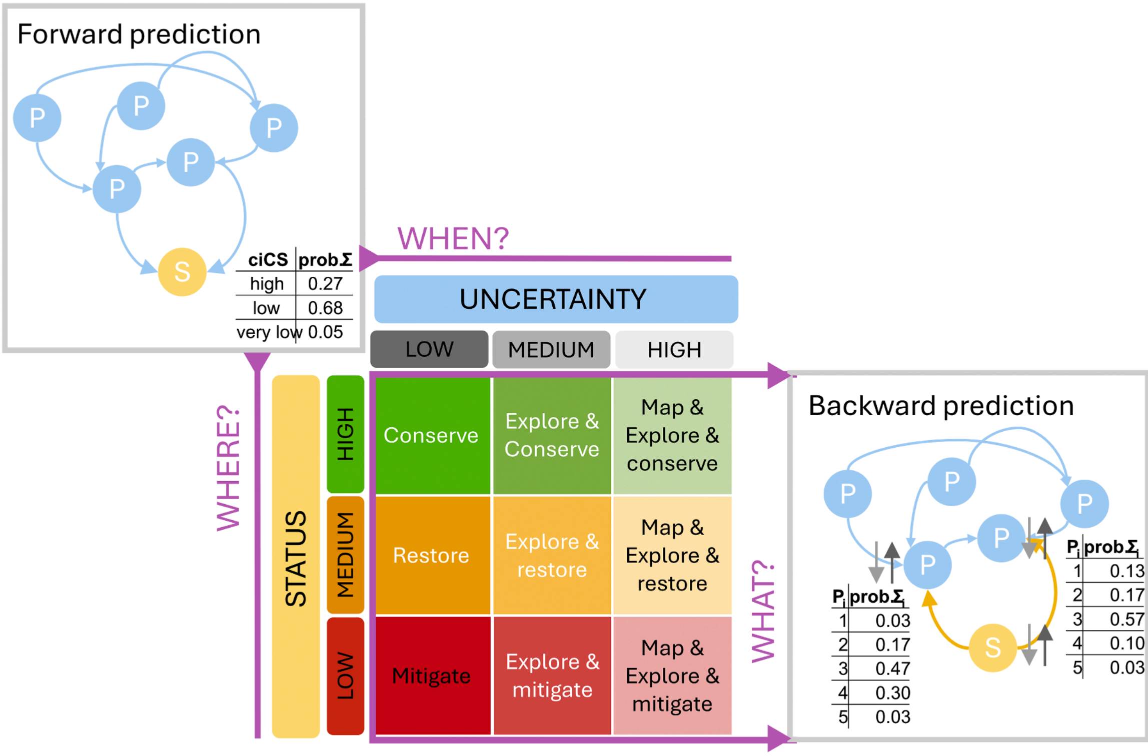


Fig. 1. The conceptual framework for streamlining planning across the main EU directives for freshwater systems using a spatio-temporal prioritization for conservation and restoration. Based on the developed and validated Bayesian network models (see methods), status is predicted in a forward step, showing deviation from high status driven by human alterations. River Restoration Units (R2U) with low pressure values and no deviation from high status are defined as conservation areas, while those with relatively low levels of human alteration and minor deviations (one class) from high status are identified as potential restoration areas. Model uncertainty provides spatially explicit insight into predictive ability and reflects concordance between pressure and status variables across the HD and WFD. Thus, areas with low uncertainty indicate zones potentially ready for implementing restoration measures, whereas areas with high uncertainty or data gaps from HD reporting require immediately intensified monitoring and research to meet timely concordance with the NRR. In a secondary backward prediction step, R2U are prioritized for specific types of restoration, namely, hydrological restoration (i.e., longitudinal connectivity) and/or morphological restoration (i.e., lateral connectivity) as well as reducing pollution.

under the WFD are very heterogeneous across the MS (Santos, Vidal, Gonçalves, Castro and Pereira, 2021). Therefore, we used pressure indicators that are based on a continent-wide modeling approach from Vigiak et al. (2021, see Supplementary Table S1). Probabilities for the ecological status and the pressures were modeled with multiple logistic regressions based on European databases (see Vigiak et al., 2021, for details). Due to the mentioned heterogeneous reporting and lack of harmonization, hydrological and morphological alteration was difficult to predict in the models leading to uncertainties in the model outcomes. Nevertheless, those outcomes are predicted solely based on best available quantitative water pressure indicators homogeneously provided on the continental scale (Vigiak et al., 2021) and therefore provide a quantitative representation of hydromorphological alteration assessed under WFD across Europe. We used morphological alteration, mainly sensitive to the share of artificial and agricultural area in the catchment, as well as net water abstraction (Vigiak et al., 2021) as indicators of lateral connectivity alteration. Hydrological alteration, sensitive to net water abstraction combined with mean annual rainfall, floodplain areas with natural land cover and dam-free length of the river sections (Vigiak et al., 2021), is used as a proxy for longitudinal connectivity alteration. Additionally, we included organic pollution, mainly sensitive to nitrogen load due to agriculture as well as point sources. To test for concordance between HD and WFD status and account for the uncertainties associated with the hydromorphological pressure indicators we further included modeled WFD status into the models, which was predicted with good model performance. Modeled risk of failing the good ecological status is mainly sensitive to agricultural and artificial areas in the catchment, nitrogen point sources and natural floodplain area (Vigiak et al., 2021). The probability of occurrence of morphological alteration, hydrological alteration, organic pollution, as well as the risk of failing good ecological status, were discretized into 5 equally distributed classes (0–20, 20–40, 40–60, 60–80 and 80–100 % probability) before using them in the BN modeling approach.

Then, we determined freshwater and wetland related species and habitats of the HD using the IUCN database following the approach of Carrao et al. (2020a; 2020b) differentiating between five habitat groups; i.e. i) Freshwater, ii) Forests, iii) Grasslands, iv) Wet Heath and v) Bogs, Mires and Fens habitats (BMF); and eight species groups; i.e. i) Mammals, ii) Reptiles, iii) Amphibia, iv) Fish, v) Insects, vi) Molluscs, vii) Vascular and viii) Non-Vascular (nV) Plants (for details see Duarte et al., 2023, for data see Supplementary Table S1). The HD status for freshwater-related habitats and species was calculated as a composite indicator of conservation status (ciCS) based on the HD article 17 database (for details see Duarte et al., 2023), based on conservation status (Favorable, Unfavorable-Inadequate, Unfavorable-Bad). The ciCS aggregated the individual conservation status of multiple habitats or species coexisting in the same unit into one categorical value of conservation status (Carrao et al., 2020a, 2020b). The method established 15 possible categorical values and aggregated them into three value groups, indicating the conservation status: Very Low, Low and High. HD reporting is subject to national differences in data quality, knowledge, monitoring effort, and interpretation (Ellwanger et al., 2018), therefore, an explicit treatment of prediction uncertainty is required (see chapter 2.3).

2.3. Modeling and predictive framework

Our analysis followed a stepwise approach, combining discrete Bayesian Network (BN) modeling with spatial prioritization to support restoration and conservation planning under the HD, WFD, and NRR. The approach was based on a fully data-driven framework using the R package "bnlearn" (Scutari, 2010) and consisted of two steps detailed in chapters 2.3.1–2.3.5 (data sources and analysis code in the supplementary material):

a. **Model development, validation and concordance check:** The structure of the BN models was learned from the data, ensuring that all associations were empirically supported. Models were tested using cross-validation and sensitivity analyses. Only models that had acceptable performance were used for prediction. Further, we performed a concordance analysis to identify and quantify the relationships between multiple WFD indicators and the conservation status (ciCS) of different freshwater-related species and habitat groups. Only models with a reasonable relationship between the indicators were used for the prediction.
b. **Predictive Zoning** (Fig. 1): The calibrated models were then used for **forward prediction** to estimate ciCS values based on WFD-related indicators across the European river network. We interpreted areas with a dominant predicted ciCS value of "High" as conservation areas as many habitats and species are already under favorable conditions; thus, the main objective in this region is conservational management. A ciCS value of "Low" was interpreted as areas that hold potential for large scale restoration, particularly focusing on improving lateral and longitudinal connectivity in rivers. Accordingly, ciCS values of "Very Low" were interpreted as mitigation areas, where the status of habitats and species is highly degraded and management interventions are required in rivers and wetlands to maintain and enhance ecosystem functioning, for example in relation to climate change mitigation, flood mitigation, and biodiversity conservation.

As BNs inherently account for uncertainty (Uusitalo, 2007), we spatially delineated zones where conservation status could be predicted with high certainty, and in turn to identify areas where predictions are more uncertain. We used this information to prioritize zones that are suitable for immediate restoration or mitigation measures, as well as to identify areas where limited data availability highlights the need for urgent, targeted data collection and more extensive planning efforts.

Backward Inference was used to identify R2U where the restoration of hydromorphological features—specifically, longitudinal and lateral connectivity—would yield the highest ecological benefit. These features were proxied by morphological and hydrological alteration indicators, respectively. The analysis also accounted for pollution pressures to identify areas for restoration based on multiple interacting stressors.

The approach integrated the perspective of different environmental policies (i.e. WFD, HD, NRR) to provide a spatially explicit framework for restoration planning that is consistent with the policy targets and accounts for both current knowledge and uncertainty (Fig. 1). Summarizing, uncertainty in model predictions was quantified using multiple complementary approaches: i) bootstrapping to identify robust network structures, accounting for structural uncertainty, ii) multiple cross-validation runs to assess predictive performance and uncertainty, and iii) the standard deviation of the conditional probabilities of the outcome variable (ciCS) in the final model as a descriptive measure of output uncertainty. Together, these measures provide a robust estimate of confidence in predicted ciCS outcomes for prioritizing restoration and conservation efforts.

2.3.1. Bayesian network models

We used a bootstrapping approach (Friedman, Goldszmidt and Wyner, 1999) to estimate the importance of the possible links in the BNs and calculated a certainty value for: i) nodes, i.e., variables; and ii) arcs, i.e., conditional probability and causality relationships between variables. Therefore, we used a Bayesian Dirichlet equivalent score (BDe) with a uniform prior distribution (Heckerman, Geiger and Chickering, 1995) in a hill-climbing search with random restarts. 200 non-parametric bootstraps were conducted using the "*boot.strength*" function from the package "bnlearn" (Scutari, 2010) for R, which calculates the probability of each arc in the network based on its empirical frequency over a set of networks learned from bootstrap samples. Model averaging was used to build the WFD-HD BN containing only the relevant arcs appearing in at least the half of all bootstrap samples using the "*averaged.network*" function. The direction of arcs was set to go from WFD to HD indicators, reflecting the prediction goal. Derived networks were fitted based on the data using the function "*bn.fit*" of the same package.

2.3.2. Validation

Models were validated using 10-fold cross validation with 100 repeats based on scores specific to ordinal data. We used the "*cv.bn*" function of "*bnlearn*" for cross-validation and Cohen‘s Kappa weighted for ordinal data and Kendall's coefficient of concordance (W), two different coefficients of concordance for unbalanced ordinal data using the "*kendall*" and "*kappa2*" functions of the "irr" package (Gamer, Lemon and Sing, 2012) in R. Further we used the area under the ROC curve (AUC), directly implemented in "bnlearn", a metric usable for multiclass target variables. Only indicators with acceptable performance were used further for the predictive step. Landis and Koch (1977) propose the following threshold scheme for Cohen‘s Kappa also applied by Vigiak et al. (2021), whereby a value < 0 indicates no agreement, 0–0.20 small, 0.21–0.40 fair, 0.41–0.60 moderate, 0.61–0.80 substantial, and > 0.81 almost perfect agreement. Using Cohen's interpretation guidelines (Cohen, 1960) a threshold scheme can be set for Kendall's W, whereby a value between 0.1–$<$0.3 indicates small, 0.3–$<$0.5 moderate and $\geq$0.5 large agreement. AUC ranges between 0.5 indicating a model not performing better than random, and 1 indicating perfect discrimination (Ben-David et al., 2008).

Further sensitivity analysis based on mutual information was conducted to identify which of the WFD-related indicators have the most impact on the outcome of the respective HD indicator, using the "*mutual_info*" function of the "bnmonitor" package (Albrecht, Nicholson and Whittle, 2014).

2.3.3. Concordance check

Conditional probabilities of the HD indicators, calculated in the BN models based on WFD status risk as well as hydrological and morphological alteration indicators, were examined to assess the direction and strength of the relationships. Only HD indicators whose dependencies were ecologically consistent, i.e., showing an improvement in HD status corresponding to a decrease in WFD-related risk or alteration, were retained for the predictive step. Models failing this concordance check across any variable were discarded from the analyses. Such evaluation of directionality and strength is recommended as good practice in Bayesian Network modelling of environmental systems (Chen and Pollino, 2012).

2.3.4. Forward prediction

In the Forward Prediction step, BNs were used to predict the status class as well as the conditional probabilities for each status class for all R2U and groups. To summarize the status prediction over all selected groups, the mode was calculated per R2U, to count for the majority vote across all groups. To express the uncertainty per R2U and group, the standard deviation of conditional probabilities was calculated. It has a value of 0 for equally distributed conditional probabilities, indicating the highest level of uncertainty, and a maximum value of 0.58 for perfect discrimination, where one status class is predicted with a probability of one and the two others with a probability of 0, representing the highest level of certainty. Finally, uncertainty values were averaged across all selected groups, and the median across all R2U was used to split them into two groups: one with low uncertainty and one with high uncertainty. The highest uncertainty level was given to areas where the status of more than half of the groups had not been reported, so where knowledge gaps or reporting gaps prevail.

2.3.5. Backward prediction

Backward Prediction was performed, creating a hypothetical "restoration scenario" or "full compliance scenario" where all R2U in which HD species and habitats were reported to have a high ciCS value across all models with reliable model performance. Then, conditional probabilities were calculated for each WFD indicator separately, keeping all other WFD indicators constant. The probabilities were then expressed as the improvement of pressure values compared to the backward prediction based on the *status quo* for each ciCS summarized in an index (Funk et al., 2019). It highlights the WFD indicators that have a quantitative impact on the HD ciCS status in the model per R2U, therefore it is possible to screen for R2U that would have the potential to benefit from restoration activities that address the impacts of a certain pressure. For index formula and more detailed descriptions, see the supplementary.

3. Results

3.1. Model validation and concordance between Habitats Directive and Water Framework Directive

Model validation results showed that six out of twelve models had acceptable model performance (>0.2 for Cohen's Kappa and >0.4 for Kendall W and >0.6 for AUC): Bogs, Mires and Fens (BMF) habitats, freshwater habitats and grassland habitats, as well as the species groups amphibia, fish and plants. The remaining six models showed low validation scores (Table 1) and low sensitivity to the WFD indicators (Table 2).

Table 1
Model validation results, weighted Cohen's Kappa, Kendall's W as well as AUC (expressed as mean and standard deviation over 100 10-fold cross-validation runs), as well as coverage across Europe in percentage. Habitats Directive groups with acceptable results (see methods section for thresholds) are marked in bold. BMF: Bogs, Mires and Fens; Plants (nV): non-vascular plants.

Habitats Directive group	coverage	Cohen's Kappa	Kendall W	AUC
BMF Habitat	**100**	**0.23 (0.01)**	**0.46 (0.005)**	**0.71 (0.001)**
Freshwater	**100**	**0.23 (0.01)**	**0.48 (0.004)**	**0.66 (0.001)**
Grassland	**100**	**0.31 (0.01)**	**0.47 (0.006)**	**0.72 (0.001)**
Forest	100	0.01 (0.004)	0.20 (0.002)	0.61 (0.001)
Plants (nV)	62	0.17 (0.01)	0.45 (0.007)	0.59 (0.002)
Plants	**77**	**0.23 (0.002)**	**0.40 (0.006)**	**0.60 (0.001)**
Molluscs	62	0 (0)	0.21 (0.01)	0.56 (0.002)
Fish	**88**	**0.30 (0.01)**	**0.53 (0.005)**	**0.65 (0.001)**
Insects	77	0.12 (0.01)	0.41 (0.008)	0.62 (0.001)
Amphibia	**92**	**0.29 (0.008)**	**0.53 (0.004)**	**0.67 (0.0007)**
Reptiles	38	0 (0)	0.20 (0.002)	0.58 (0.002)
Mammals	92	0.08 (0.009)	0.39 (0.004)	0.57 (0.002)

Table 2
Sensitivity analysis results expressed as mutual information for the respective target node (Habitats Directive group) of all other nodes (Status WFD = risk of failing Water Framework Directive status, hydrological and morphological alteration and organic pollution indicators). Only values for Habitats Directive groups showing acceptable results in the validation step (Table 1) are shown here.

	Morphology	Hydrology	organic Pollution	Status WFD
BMF Habitat	0.06	0.01	0.07	0.06
Freshwater	0.06	0.02	0.03	0.03
Plants	0.03	0.00	0.03	0.05
Fish	0.05	0.05	0.02	0.02
Amphibia	0.09	0.03	0.05	0.07

The conditional probabilities of BNs linking ciCS and the WFD status risk indicator (Fig. 2) showed a reasonable relationship, indicating an overall concordance between the HD ciCS status and the WFD status risk for two habitat groups, BMF and Freshwater, as well as the three species groups Amphibia, Fish and Plants. In contrast, Grasslands exhibited a negative dependency. Similarly, conditional probabilities of the ciCS, conditioned equally on WFD indicators for hydrological and morphological alteration, showed a clear positive relationship between the HD ciCS status and the WFD pressure indicators (Fig. 2) for the same groups. This suggests that regions exhibiting a high conservation status under the HD also displayed a low risk of failing the good ecological status according to the WFD and that this pattern was consistently reflected in the corresponding WFD pressure indicators. Therefore, the five groups with acceptable model performance as well as reasonable dependency on the WFD pressure indicators (i.e., BMF, Freshwater, Amphibia, Fish and Plants) were included in the subsequent predictive steps, while the Grassland model was omitted.

Among the five selected models, Fish were most strongly influenced by the WFD pressure indicator hydrology (Table 2). For BMF and Freshwater habitats, Amphibia, and Fish, the pressure indicator morphology was relevant, while the WFD status indicator was relevant for Plants, BMF habitat, and Amphibia. The pressure indicator of organic pollution showed the highest relevance for BMF (see also Figure S1).

3.2. Forward prediction – status and uncertainty

The model predictions for the five selected groups are summarized in Fig. 3, which shows the dominant status class (ciCS class) across all groups calculated as the mode, as well as the model uncertainty (see maps per group in the supplementary material, Figures S2–S6). Overall, the medium status class "Low" was dominant across many regions, highlighting areas where species habitat did not reach the good conservation status but restoration might have a high potential to improve to good condition the considered indicator groups. The ciCS status class "Very Low" highlights areas with worst conservation status across the modeled organism groups and was concentrated in southern parts of Europe and urban and agriculturally dominated areas. Finally, the ciCS status "High" was mainly found in northern regions. Uncertainty, i.e., standard deviation of predicted ciCS probabilities averaged over the selected models, is ranging from 0.03, indicating nearly equal distribution of probabilities, to 0.51, indicating nearly perfect discrimination. In general, uncertainty was lowest in the least impacted systems, i.e., in R2U with high HD status (Fig. 3), which are primarily found in the Nordic region. For other HD species groups, especially Fish, uncertainty was also low in heavily impacted habitats, i.e., in areas with very low status.

Fig. 4 integrates the information from the maps in Fig. 3, illustrating the distribution of promising areas for restoration, conservation and mitigation, including the temporal framework based on uncertainty presented in Fig. 1. Based on the status prediction, areas identified for restoration (Fig. 4, predicted ciCS class "Low") and for conservation and

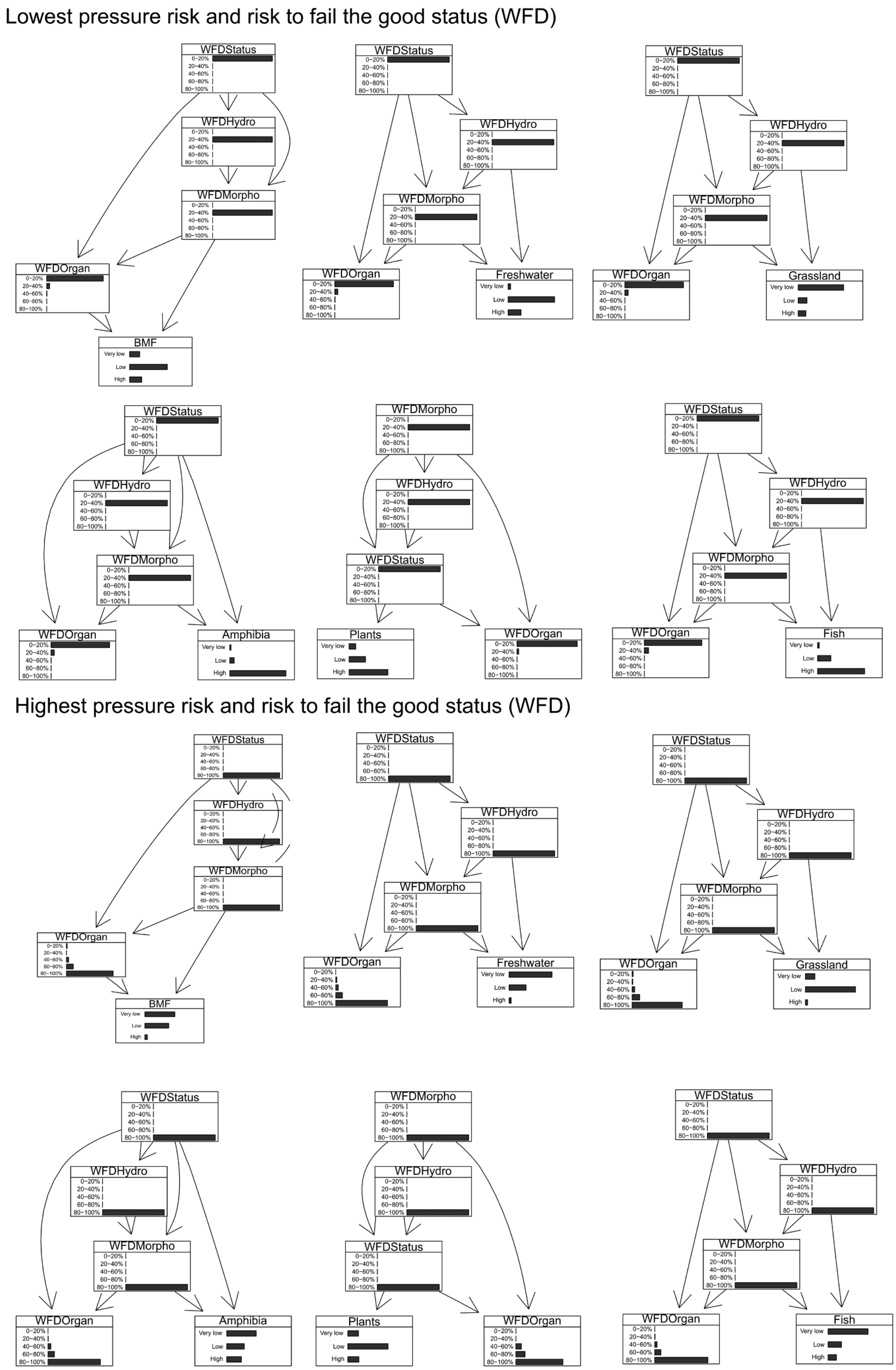


Fig. 2. Concordance check: Best and worth case scenario i.e., conditional probabilities of Habitats Directive ciCS status classes conditioned on Water Framework Directive (WFD) status and WFD Hydrology and Morphology pressures risk indicators (Vigiak et al., 2021) highest and lowest levels, respectively. Represented are only the Bayesian Network models of the indicator groups with acceptable model performance. For full results across all possible levels see Supplementary Figure S1.

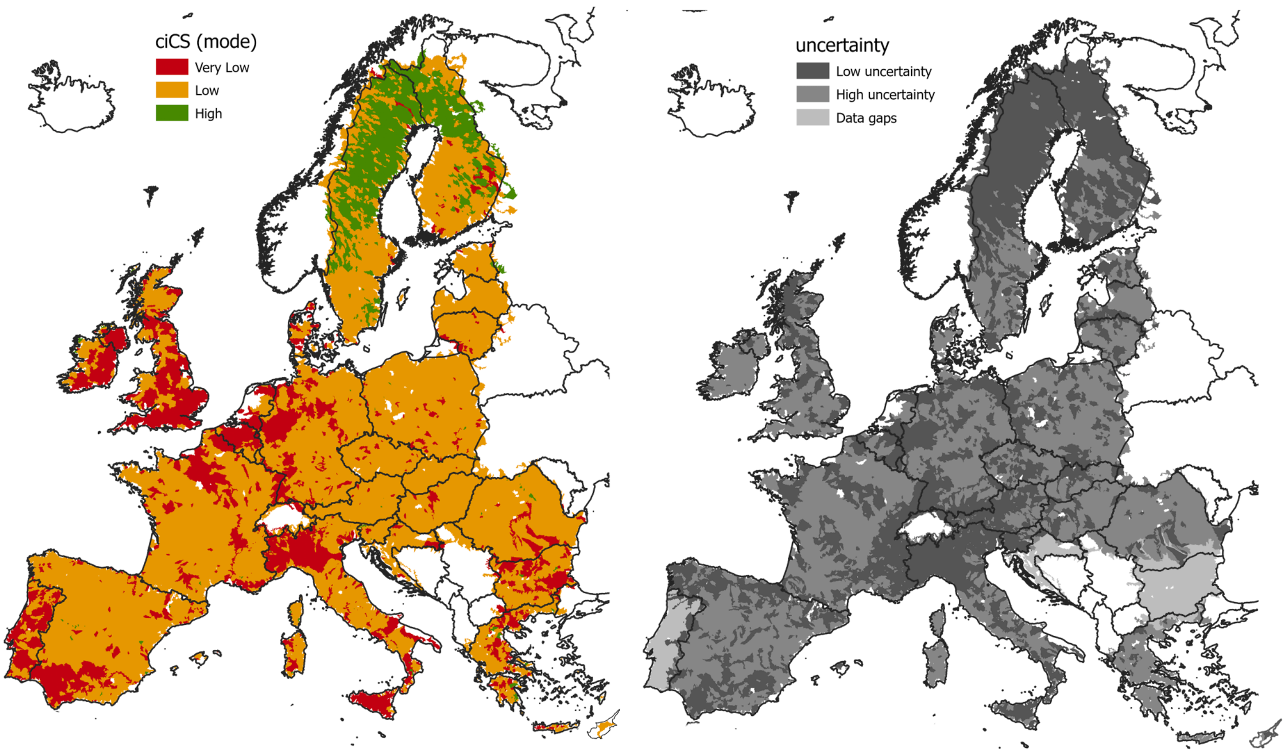


Fig. 3. Basic model output for the spatio-temporal prioritization based on the forward predictive step. Left map: Dominant predicted Habitats Directive (HD) ciCS status class (mode of ciCS prediction across all acceptable and reasonable models). Right map: Areas with data gaps (areas with missing reporting) respectively high or low uncertainty in the models (standard deviation of conditional probabilities split at the median across all acceptable models) indicating spatially low and high local concordance between the Water Framework Directive (WFD) and HD related indicators.

mitigation (Fig. 4, predicted ciCS classes “High” and “Very Low” respectively) are highlighted. Potential restoration sites were widely distributed across all ecoregions and countries, indicating good possibilities to implement measures in all regions of Europe. Temporal prioritization, informed by uncertainty and reporting gaps, categorized sites into those with low uncertainty, ready for immediate restoration; those with high uncertainty, which require more time and effort; and areas with prevalent HD reporting gaps that require time and immediate intense effort in mapping, increased monitoring effort and pressure indicator development and harmonization. Sites suitable for immediate restoration are broadly distributed across regions and countries. Few countries showed clear reporting gaps, including Croatia and Bulgaria, which are among the most recent EU members. The R2U prioritized for conservation (Fig. 4) were widely predicted with high certainty and mainly found in northern and boreal regions. Areas with worst ciCS status were also often predicted with high certainty except where data gaps were prevailing (Fig. 4)

3.3. Backward prediction

Cross-validation results from multiple 10-fold backward predictions (Supplementary Table S2) indicated that all models performed well, ranging from good predictive accuracy to excellent (0.41–0.87 for Cohen’s Kappa and 0.53–0.9 for Kendall W).

Backward prediction identified priority R2U for hydrological and morphological restoration, as well as pollution (Fig. 5), indicated by three selected HD groups with high indication potential for these three pressures. HD groups predicted to benefit most from the restoration of longitudinal connectivity (hydrological restoration) include fish and freshwater habitats. While fish indicate the importance of hydrological pressures widely in mountainous and southern areas, for freshwater habitats, hydrological pressures are most important for restoration in the most southern regions, northern regions, as well as intense agricultural and urbanized areas in the lowlands. Morphological as well as pollution pressures were mainly prioritized in lowland regions, whereas peatland habitats (i.e., BMF) are more impacted by pollution and freshwaters as well as fish by morphological alteration. Consequently, restoration of lateral connectivity (morphological restoration) is expected to directly benefit BMF habitats, fish, and freshwater habitats as well as amphibians in many R2U. Detailed results for each group are provided in Supplementary Figures S2–S6. In many areas, uncertainty from the models and data doesn’t allow for determining the underlying pressures with high accuracy, these areas are marked in light grey in Fig. 5.

4. Discussion

Our analyses provide evidence of a good concordance between the Water Framework Directive (WFD) and the Habitats Directive (HD) indicators in freshwater environments, indicated for areas where models predict with high certainty. Building on this concordance, we conducted the first Europe-wide prioritization of restoration and conservation targets for freshwater ecosystems, incorporating specific restoration objectives, such as lateral and longitudinal connectivity, that are highly relevant to the new NRR. Nonetheless for many areas and HD groups it is highlighted that there is strong need to improve the harmonization between the WFD and HD indicators to obtain a final integrated image of conservation needs.

4.1. Advantages of Bayesian networks as a tool for prioritization

We selected BN over other modeling methods as they are well-known tools for management applications (Barton et al., 2012), they support decision-making across policy contexts (Moe, Carriger and Glendell, 2021) and offer several advantages compared to other widely used predictive modeling approaches: BNs allow the integration of

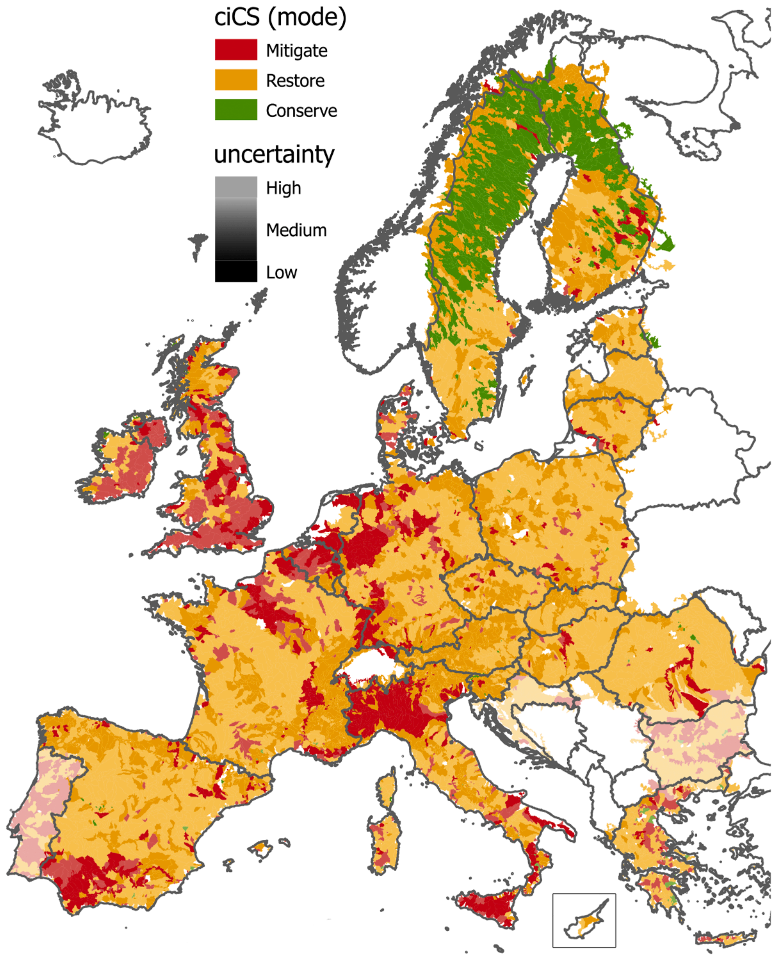


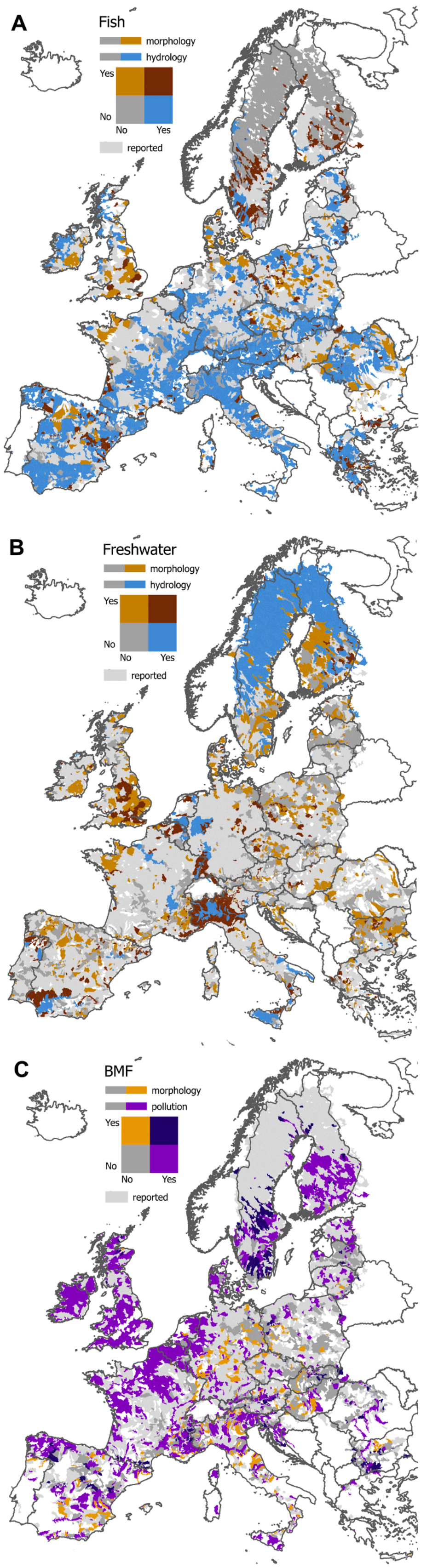
Fig. 4. Spatiotemporal prioritization for conservation, restoration and mitigation, following the framework in Fig. 1, combining information from Fig. 3. Color coding indicates dominant predicted Habitats Directive (HD) ciCS status class “High”, “Low” and “Very low”, used as an indicator to identify areas for conservation, restoration, and mitigation measures, respectively. Transparency indicates level of uncertainty in the models and data gaps. Areas with low uncertainty might be ready for immediate management action whereas areas with high uncertainty and especially data gaps require immediately intensified effort to assess pressure and HD status of species and habitats (see Fig. 1 for a more detailed description).

heterogeneous and discrete data types (Barton et al., 2012; Moe et al., 2021), such as status classes, which is particularly relevant for our approach. Unlike methods such as Generalized Linear Models (GLMs) or Random Forests, BNs explicitly account for multiple sources of uncertainty in model predictions (Moe et al., 2021; Uusitalo, 2007). In our approach, this includes structural uncertainty, predictive uncertainty and spatially explicit representation of output uncertainty. This specifically enabled us to identify R2U in which higher uncertainty indicates areas where further research on the impacts of anthropogenic alterations and conservation status is most needed. Another key advantage of BNs is their ability to perform backward inference (Albrecht et al., 2014; Uusitalo, 2007), which allowed us to highlight the alteration types most relevant to each R2U, guiding targeted restoration efforts in those areas. More recently, Glendell, Moe and Negri (2025) and Elliott, Graham, Franklin and Larned (2024) highlighted the importance of transparent model evaluation, ecological plausibility checks and clear communication of uncertainty when using BNs for predictive ecological assessment. Consistent with these recommendations, we implemented a concordance check to ensure that the learned dependencies were ecologically meaningful. We used the variability in conditional probabilities to communicate prediction confidence. These features position our approach in line with current best practice in the application of BNs to environmental risk assessment and restoration planning.

The BN framework provides a powerful tool for European-scale restoration and conservation planning by enabling data integration across countries and large river systems, thereby supporting pan-European comparability and alignment between WFD and HD reporting (Birk et al., 2012; Vigiak et al., 2021). However, structural biases in input data, such as differences in monitoring intensity and/or frequency, national reporting practices, and indicator definitions, as well as simplifications of complex and context-dependent ecological responses can influence model predictions (Birk et al., 2012; Moe et al., 2021; Uusitalo, 2007). While aggregation provides important advantages for large-scale assessments and policy guidance, it smooths local heterogeneity and may obscure fine-scale ecological processes or region-specific stressors. Consequently, model outputs should be interpreted as probabilistic indicators of restoration and conservation potential with operational application requiring targeted local validation and higher-resolution data where available (Thuiller, Guéguen, Renaud, Karger and Zimmermann, 2019; Uusitalo, 2007).

4.2. Concordance between habitats directive and water framework directive

Our analyses showed a reasonable overall concordance between the HD ciCS and the WFD status risk indicator as well as the anthropogenic alteration indicator related to WFD. The best-performing models showed sensitivity to the WFD alteration indicators, especially hydrology and



(caption on next column)

Fig. 5. Results of the backward inference step in the BN approach (Fig. 1). Dominant pressures identified for A) Fish, B) Freshwater habitats, and C) Bogs, Mires and Fens (BMF). In the maps, River Restoration Units (R2U) are highlighted that were prioritized for hydrological restoration, morphological restoration or pollution restoration. Only R2Us for which the model certainly allowed accurate predictions are displayed. R2Us with high uncertainty are marked in light grey and R2U with already low pressure and a relatively high status class, for which no relevant pressure could be identified, are marked in dark grey.

morphology, indicating the importance of hydro-morphological pressures for different freshwater-related taxa and habitats. This demonstrates the high relevance of using these datasets as a foundation for the NRR. It also highlights the need to enhance monitoring and assessment efforts and to achieve better harmonization of these datasets across MS.

In general, the strict freshwater-related HD groups, including fish, amphibians, freshwater and BMF habitats, showed better model performance and better concordance with WFD data. For example, fish protected under the HD include typical river species as well as floodplain species that are sensitive to both morphological and hydrological pressures (Funk et al., 2019), which is well reflected in our model results. Also, for amphibians, the modeling approach found a reasonable dependency between anthropogenic alterations and conservation status. Amphibians, that are mainly dependent on terrestrial habitats and more isolated waterbodies in the floodplain, are particularly reliant on lateral connectivity (Funk et al., 2019) and were, as expected, most impacted by morphological alterations. For freshwater habitat types of the HD our models showed the strongest effects of morphological alteration. This habitat type comprises lakes and wetlands with diverse macrophyte assemblages as well as fast-flowing rivers with their associated riparian vegetation and is frequently threatened by the loss of lateral connectivity and floodplain areas (Keruzoré, Willby and Gilvear, 2013). In contrast, hydrological alterations, e.g., longitudinal fragmentation due to artificial barriers, only influence specific macrophyte communities, thus being context dependent (Jones, Consuegra, Börger, Jones and de Leaniz, 2020). Models for peatland habitats (i.e., BMF) showed strong sensitivity to pollution, consistent with their well-known vulnerability to various pollutants including nutrient enrichments, toxic pollutants or acidification/alkalinization (Grootjans, van Diggelen, Joosten and Smolders, 2012). BMF habitats, mostly situated in floodplains, are specifically threatened by habitat loss due to agricultural encroachment or urban development (Grootjans et al., 2012), a finding supported by our results, which showed strong sensitivity of BMF to morphological alteration. Conversely, more terrestrial groups, including alluvial forest habitats, reptiles or mammals, exhibited poor concordance. Notably, grasslands showed an inverse relationship. This might reflect the influence of other management factors, such as forestry practices (Borrass, 2014), hunting regulations (Epstein, Christiernsson, López-Bao and Chapron, 2019), or agricultural management like hay meadow management (Muller, 2002). It may also result from larger reporting gaps in more complex groups like insects, reptiles, or molluscs (EEA, 2020). These reporting gaps highlight the need for additional monitoring efforts to acquire sufficient, reliable data for effective management and restoration (EEA, 2020). In summary, the moderate to low performance of several HD groups reflects weaker links to freshwater systems per se and thus to freshwater pressures as well as reporting gaps; these groups were therefore excluded from the prioritization, and the results should be interpreted as applying specifically to strictly freshwater-dependent habitats and species.

4.3. Forward prediction – status and uncertainty

Our approach enables prediction of the status of HD groups and, accordingly, the identification of promising areas for restoration (Fig. 1). The “Low” ciCS status class, most relevant for restoration, was the most dominant across Europe. In contrast, the “High” ciCS class was primarily found in the northern parts of Europe, while the worst status class, “Very Low,” was mainly located in highly urbanized and agricultural areas. This was already shown in the pan-European model for the WFD indicators (Vigiak et al., 2021), where freshwater systems having a high probability of failing the good ecological status were found to be mainly located in heavily urbanized and industrial floodplain areas, whereas freshwater habitats having a very low probability of failing the good ecological status were situated in less altered northern parts of Europe and also mountainous areas. The same pattern is revealed for several of the HD groups analyzed in our study, having “very bad” or “high” ciCS, respectively. Concordance between HD and WFD assessments was highest in areas with consistently high ciCS, suggesting these areas should be prioritized for strict conservation, potentially through the designation of additional Natura 2000 sites. High concordance was also found for some areas with bad conditions especially, in urban areas or intensely used agricultural areas. This pattern was also found in other modelling approaches for example in expert elicitation, where experts were able to predict outcomes with lowest uncertainty in extreme cases, while the intermediate cases were more difficult to predict (Mzyece et al., 2024).

Moreover, our approach highlights where low uncertainty in model predictions and therefore high concordance of HD and WFD related indicators, marks feasible conditions for initiating management action. For identified areas with dominant lower distance to good conservation status these areas are ready to screen for relevant rivers for lateral and longitudinal connectivity restoration. For areas with high distance, “Very low” ciCS often found in urban and agricultural areas, mitigating the negative impact on biodiversity is of high priority in the NRR and restoration and conservation of wetlands can yield co-benefits, such as climate change and flood mitigation, recreational opportunities, and improved water filtration (NRR, 2024).

On the one hand, our models highlight areas where a high uncertainty due to a lack of concordance between the HD and WFD related indicators indicates a lack of knowledge and data. Important indicators of anthropogenic alterations are not yet available on a European scale, in relation to morphological alteration, especially consistent information on lateral damming (Vigiak et al., 2021). In terms of hydro-morphological alteration, this includes the lack of data for the often very high density of small barriers and other engineering structures that are currently unaccounted for at the European scale (Vigiak et al., 2021). These structures can exert substantial impacts on freshwater habitats, with their effects often remaining undetected or unattributed (Belletti et al., 2020). These areas might be under higher risk to fail the timely implementation of measures, to avoid this immediate effort is required to get more accurate information on hydro-morphological pressures and status of habitat and species. Likewise, spatially explicit, high-resolution predictions of phosphorus concentrations in freshwater systems at the European scale are still lacking, which hampers effective management and risk assessment for phosphorus-induced eutrophication and habitat degradation (Grizzetti et al., 2022). For many HD habitats and species, data availability remains limited and significant knowledge gaps persist (EEA, 2020). Our approach explicitly identifies areas with notable reporting gaps, such as in newer EU member states like Bulgaria, Portugal or Croatia, which require enhanced and potentially more harmonized monitoring efforts and reporting (Ellwanger et al., 2018). This also means that compliance with the NRR will require more time and effort, and therefore process must start immediately. For those regions, model results should be interpreted with particular caution and require targeted local validation and supplementary data collection (Birk et al., 2012; Vigiak et al., 2021). Such areas should therefore not be regarded as having low restoration relevance, but rather as priority regions for enhanced monitoring and the improvement of local knowledge.

4.4. Backward prediction

A clear pattern can also be seen regarding restoration targets related to the NRR, particularly the restoration of lateral and longitudinal connectivity (see Fig. 1). In many low-elevation areas, the restoration of lateral connectivity, indicated by morphological alteration, is most promising for improving the status of multiple HD groups representing different river types (Ellwanger et al., 2018). In contrast, in other zones, such as southern regions, hydrological pressures are often more relevant for restoration purposes, where water abstraction is a key issue due to overall water scarcity (Vigiak et al., 2021). In these areas, measures to mitigate impacts in wetlands are a particularly urgent goal, as biodiversity is under severe threat, as indicated by the ciCS status often classified as “very low” in our models, e.g. in large parts of Portugal, Italy or Spain. NRR has a strong focus on these wetlands due to their joint high importance for climate change mitigation (NRR, 2024). In mountainous areas, hydrology and longitudinal connectivity are often key issues due to the intense use of hydropower (Ellwanger et al., 2018) and other barriers especially a key threat for fish (Heckerman et al., 1995). These pressures are frequently combined with significant loss of lateral connectivity in urban and agricultural areas, which are typically concentrated along narrow river valleys (Wasson et al., 2010), reducing space for natural river dynamics. Significantly improving this lateral and longitudinal connectivity and thus fostering riverine biodiversity is a key targeted in Article 9 of the NRR. While backward inference allows identification of the pressures most strongly associated with restoration potential, these results remain context-dependent and rely on the validity of pressure proxies. Therefore, priorities should be interpreted cautiously (Moe et al., 2021).

5. Conclusion

In summary, our approach demonstrates the following:

- A generally strong concordance was observed between multiple indicators used in the Habitats Directive (HD) assessments and Water Framework Directive (WFD) indicators of anthropogenic pressures and risks of failing to achieve good ecological status. This finding underscores the value of these datasets for management under the NRR, while also highlighting the need to further improve, supplement, and intensify and harmonize existing assessments. The proposed framework is flexible and can be re-applied as higher-resolution or more comprehensive data become available.
- At the European scale, it enables the zoning of areas with high certainty of restoration and mitigation potential. Future work should validate the identified freshwater priority restoration areas at regional to local scales by comparing them with existing European restoration projects and incorporating local stakeholder knowledge. These insights can then be used to guide recommendations for new restoration initiatives, including the identification of sites for large-scale restoration of longitudinal and lateral river connectivity, wetland restoration with joint biodiversity and climate mitigation benefits, and targeted small-scale measures in urban and agricultural landscapes that deliver multiple ecosystem services.
- The identification of areas characterized by high uncertainty, data deficiencies, and reporting gaps is critical, as these limitations require urgent action to ensure timely compliance with the NRR. Specifically, targeted research efforts, enhanced biodiversity monitoring, and improved quantification of pressure indicators are essential to support effective freshwater management, conservation, and restoration.
- European-scale zoning of pressures relevant for HD restoration provides additional decision support. These pressures are mapped at the drainage basin level and include both protected and non-protected areas. Different HD groups are affected by distinct pressure profiles, implying that restoration and mitigation measures must be

tailored accordingly and implemented in alignment with the objectives of the NRR.

Data statement

No new data were generated in this study. All data analyzed are from previously published sources. Publicly available datasets are cited and linked where possible. A small subset of datasets is available only from the corresponding authors of the original studies; details are provided in the Supplementary Materials.

CRediT authorship contribution statement

Andrea Funk: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Gonçalo Duarte:** Writing – review & editing, Validation, Investigation, Data curation, Conceptualization. **Paulo Branco:** Writing – review & editing, Validation, Investigation, Data curation, Conceptualization. **Thomas Hein:** Writing – review & editing, Validation, Conceptualization. **Astrid Schmidt-Kloiber:** Writing – review & editing, Project administration, Conceptualization. **Tamara Leite:** Writing – review & editing, Investigation, Data curation. **Angeliki Peponi:** Writing – review & editing, Investigation, Data curation. **Maria Teresa Ferreira:** Writing – review & editing, Validation, Conceptualization. **Sebastian Birk:** Writing – review & editing, Conceptualization. **Annette Baattrup-Pedersen:** Writing – review & editing, Project administration, Conceptualization. **Florian Borgwardt:** Writing – review & editing, Visualization, Validation, Project administration, Methodology, 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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2026.125426.

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