



FUTURELAKES

For Nature, Climate and People

A methodological framework for prioritising and upscaling lake restoration in Europe

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1 PU = Public
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Summary

Lakes are vital freshwater ecosystems that support biodiversity, regulate climate, and provide essential services to society. However, many lakes across Europe are under pressure from pollution, habitat degradation, climate change, and competing land uses. To address these challenges, FutureLakes proposes a methodological framework to prioritise lakes for restoration. This framework consists of a two-layer approach: firstly, for identifying lakes with the greatest need for restoration to support achievement of EU Water Framework Directive (WFD) and EU Biodiversity Strategy policy goals, and secondly, to weight these priorities in relation to additional benefits to society.

The prioritisation framework is designed to support strategic decision-making on restoration priorities, at a regional, national or European-scale, by identifying lakes that can deliver the highest ecological and societal returns. The overarching goal of this framework is to improve WFD ecological status and freshwater biodiversity across the European Union, by identifying lakes that can deliver the greatest ecological gains while also contributing to wider environmental and societal objectives. The framework is developed to directly support key EU policy objectives, particularly the requirement for EU Member States to develop National Restoration Plans under the new EU Nature Restoration Regulation.

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Abbreviations

WFD.....	Water Framework Directive
RBMP	River Basin Management Plans
UWWTD.....	Urban Wastewater Treatment Directive
HD.....	Habitat Directive
BD.....	Birds Directive
WWQA.....	World Water Quality Alliance
NRR.....	Nature Restoration Regulation
NbS.....	Nature-based Solutions
BQEs.....	Biological Quality Elements
MCDA	Multi-Criteria Decision Analysis
GHG.....	Green House Gas
EEA.....	European Environmental Agency
SEDI.....	Socio-economic Deprivation Index
nEQR.....	Normalized ecological quality ratio
PFAS.....	per- and polyfluoroalkyl substances
C3S.....	Copernicus Climate Change Service
P.....	Phosphorus

1 Introduction

This report introduces a preliminary FutureLakes Prioritisation Framework for Upscaling Lake Restoration and the aligned European Lakes Data Portal (eLakes Portal), designed following stakeholder consultation, to support national authorities in identifying and selecting lakes for restoration based on a combination of ecological and socio-economic criteria. The report provides a summary of the stakeholder consultation process completed and uses the key guiding principles produced from this process to develop the Prioritisation Framework and Approach. It includes examples of prioritising restoration efforts to achieve improved water quality, biodiversity, and climate regulation. The report provides general guidance on how to utilise the eLakes Portal to explore policy relevant prioritisation cases and provides guidance on moving forward following prioritisation to build site specific management plans framed within an adaptive management approach.

1.1 The Baseline Status on European Lake Restoration

Lakes are vital freshwater ecosystems that support biodiversity, regulate climate, and provide essential services to society (WWQA, 2024). However, many lakes across Europe are under pressure from pollution, habitat degradation, climate change, and competing land uses. Implementation of European water policies, specifically the EU Water Framework Directive (WFD), River Basin Management Plans (RBMPs) and supporting directives (e.g. Urban Wastewater Treatment Directive (UWWTD), Nitrates Directive, Bathing & Drinking Water Directives) have aimed to achieve WFD Good Ecological Status in all European lakes >0.5 km² area. The WFD and daughter directives have resulted in thousands of measures implemented across Europe to reduce pollution and restore lakes. However, despite reductions in nutrient concentrations, largely due to the UWWTD, many lakes in Europe have not seen improvements to Good Ecological Status. Analysis of WFD data does indicate that improvements are most visible in lakes that were at Poor or Bad Ecological Status (Figure 1), but there has been little overall change in the proportion of sites in Good or High Status, indicating no change of sites improving from Moderate to Good or High Status, and for lake macrophytes, one of the WFD Biodiversity Quality Elements, some indications of deterioration of sites in Moderate Status (Figure 1). This highlights a clear priority to target restoration measures in lakes in Moderate or Worse Status.

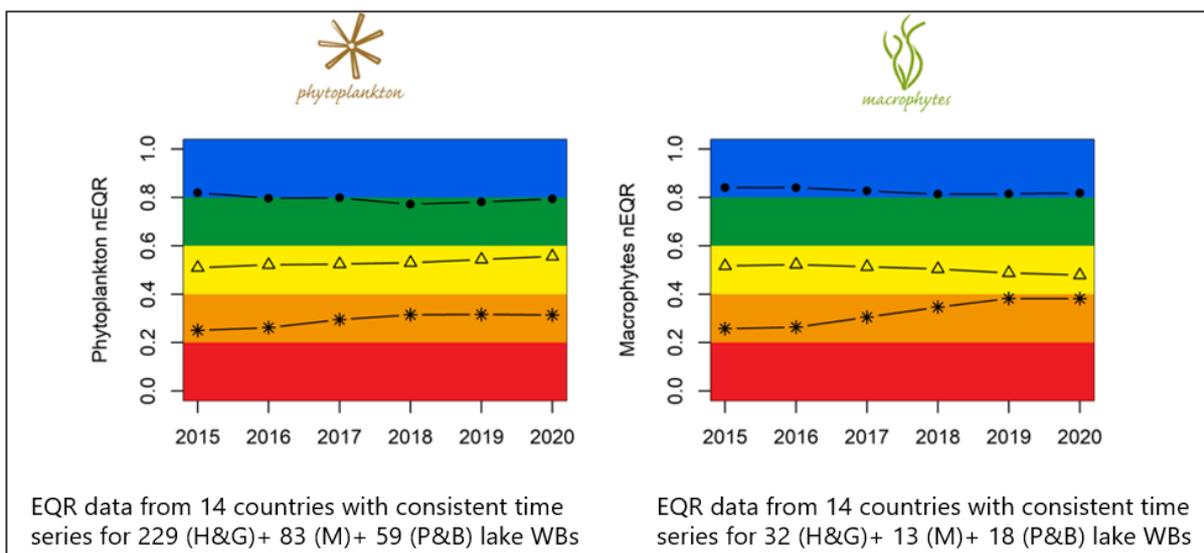


Figure 1: Change in ecological status (nEQR) of Biological Quality Elements in European lakes during the 2nd RBM cycle for (a) phytoplankton and (b) macrophytes (Internal NIVA analysis of EEA State of Environment data). Lakes having Good or Better Status in 2015 (upper line, filled circles), Moderate Status in 2015 (middle line, open triangles) and Poor or Bad Status in 2015 (lower line, stars). Each line represents the same water bodies from 2015-2020. Data from 371 lakes (11 countries) for phytoplankton and 63 lakes (6 countries) for macrophytes.

The condition of Habitats Directive priority lake habitats has not been collated, but provisional analysis shows that across all biogeographical regions, favourable condition is rare (typically <20%), unfavourable-bad condition dominates for two lake habitat types and unfavourable-inadequate (inadequate data) for others (EEA BISE database). This picture is reinforced where data are reported at the country level (e.g. in Poland 69% of priority lake habitats were considered unfavourable). Priority species are not assigned to particular habitats and it is currently impossible to query Article 17 reporting for lake-specific species. FutureLakes will aim to establish a list of lake-dependent species to allow more specific analysis of freshwater biodiversity status and trends. Furthermore, the adoption of the EU Nature Restoration Regulation (NRR) in August 2024 introduces an additional policy driver, reinforcing commitments to restore freshwater habitats across Member States. This is the first EU-wide legislation focused on restoring degraded ecosystems and is time-bound, legally binding targets to restore all degraded ecosystems by 2050. The NRR sets legally binding targets for member states to restore at least 20% of the EU’s land and sea areas by 2030, and all ecosystems in need of restoration by 2050. Among its specific targets are freshwater ecosystems, including rivers, lakes, and wetlands, which are critical for biodiversity, climate resilience, and societal well-being. To meet these targets, member states are required to develop National Restoration Plans, using a uniform format that allows for comparability and transparency across the EU. However, with thousands of lakes across Europe varying in ecological status and socio-economic importance, a systematic prioritisation framework is essential to guide decision-making and optimise restoration outcomes.

1.2 The FutureLakes Prioritisation Framework Objective and Approach

Here, we describe the FutureLakes Prioritisation Framework, which employs a two-layer approach for identifying lakes with the greatest potential to contribute to (1) improved WFD ecological status and biodiversity (Habitats & Birds Directive targets) and (2) additional benefits to society (ecosystem services). The Prioritisation Framework is designed to support strategic decision-making; the overarching goal of this framework is to support the recovery of ecosystems across the European Union by identifying lakes that can deliver the greatest ecological gains while also contributing to wider environmental and social benefits directly supporting key EU policy objectives (Table 1). By linking restoration priorities to these objectives, the framework provides a pathway for large-scale, transformative action that strengthens ecological networks, safeguards species, and enhances resilience to climate change.

Table 1. Key EU policies and how the framework contributes to their success

EU Policy	Key Framework Contributions
EU Biodiversity Strategy 2030	Contributes to reversing biodiversity loss and restoring degraded ecosystems by prioritising degraded lakes within Natura-2000 sites.
EU Nature Restoration Regulation	Aligns with legally binding targets for restoring freshwater ecosystems, ensuring compliance and accelerating progress toward ecological recovery.
Water Framework Directive	Helps achieve Good Ecological Status for surface waters by targeting lakes with the greatest potential to achieve good ecological status.
Habitats & Birds Directive(s)	Helps identify lakes that support Annex-listed species or habitats and where restoration can contribute to Directive targets on species and habitat condition
EU Climate Adaptation Strategy	Promotes EU climate strategy through selecting lakes where restoration can lead to the largest reductions in GHG emissions.
European Green Deal	Integrates biodiversity restoration with climate and pollution goals, delivering co-benefits for societal health, economy, and sustainability.

Traditionally, lake management has often relied on reactive monitoring, where restoration efforts are started only after ecological degradation becomes severe or legally non-compliant. Our Prioritisation Framework enables a shift toward proactive and strategic planning, by identifying lakes at risk before critical thresholds are crossed and aligning restoration actions with long-term ecological and policy goals. By integrating predictive indicators on ecosystem degradation, climate regulation and socio-economic context, the following framework supports forward-looking decision-making that anticipates degradation, rather than merely responding to it, and allows for combining multiple objectives into one framework-ultimately fostering more resilient freshwater systems and communities and a more efficient use of resources.

While the main aim of the Prioritisation Framework is improving biodiversity and achieving WFD good ecological status, the Framework takes a broad, integrated approach compared to species-specific or habitat-focused prioritisation methods. Our method combines biodiversity priorities with societal co-benefits, including pollution reduction, greenhouse gas mitigation, and socio-economic needs. This dual-layer approach allows for restoration planning that not only supports ecological integrity but also delivers benefits for communities and climate resilience. Additionally, this Framework can help member states meet reporting obligations under EU Nature Restoration Regulation by providing a transparent, data-driven prioritisation process. It supports harmonized monitoring and reporting for biodiversity and ecosystem restoration targets, ensuring consistency with EU-level indicators and compliance requirements.

1.3 Stakeholder consultations on the Prioritisation Framework

Stakeholder consultations were held over a 12-month period from October 2024 to October 2025. This included a mix of in-person and virtual discussions with representatives from the wider FutureLakes Project (e.g., WP engagement at project meetings), and from the other ‘Mission Lakes’ projects including:

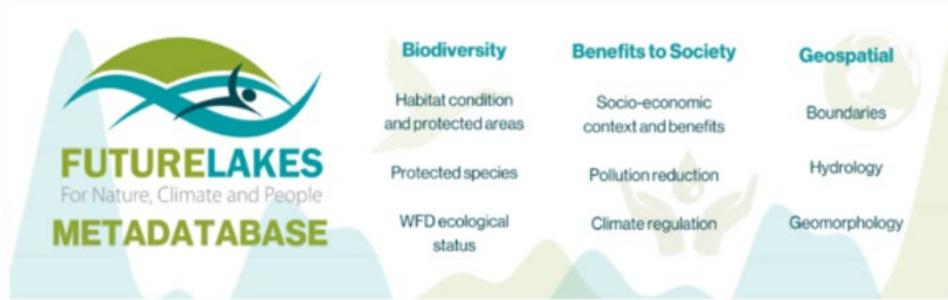
- Members of the FutureLakes Steering Committee who also represent end-users of the Framework
- Representatives from lake and regional management boards and national knowledge exchange networks (e.g. the Broads Authority and Living Lakes Network, UK)
- Leading NGOs focussed on lake restoration (e.g. Wetlands International)
- Experts in implementing European Commission policies and directives and experts in data science (e.g., European Commission; European Environment Agency; DG Environment, and the EC Joint Research Centre).

Stakeholder consultations focussed on a range of topics including framework design and utility in comparison to other systems, defining the end-user community, scoping the policy landscape, and exploring data availability and framework application process.

1.4 Overview of eLakes Data Portal

Alongside the EU prioritisation framework, FutureLakes is developing the eLakes Data Portal (Figure 2). This metadatabase ([eLakes Data Portal](#)) is a centralised platform designed to provide comprehensive datasets required for implementing the Prioritisation Framework at multiple spatial scales. It serves as an open-access resource that consolidates ecological, hydrological, and socio-economic data, including WFD status, Habitats and Birds Directive (HD/BD) assessments, Natura 2000 coverage, and other relevant environmental indicators. By offering harmonized and interoperable datasets, the portal will enable users to efficiently apply the Prioritisation Framework without the need for extensive data collation, which is often one of the main barriers to carrying out EU-scale analyses. The eLakes platform is, therefore, a critical tool for end-users, including member states in their development of National Restoration Plans (NRPs).

Metadatabase



Welcome to the FutureLakes **eLakes Portal metadatabase**. This is an online catalogue of metadata for all datasets used in the FutureLakes European Upscaling work. For more information about the project in general, go to futurelakes.eu.

The diagram below shows how this metadatabase fits into the eLakes Data Portal and the **Knowledge Hub** - together, these form the **European Lakes Digital Innovation Hub (ELDIH)**. All the datasets are indexed underneath - click on any to get more information. If you have any questions, you can contact the FutureLakes Data Team: philior@ceh.ac.uk

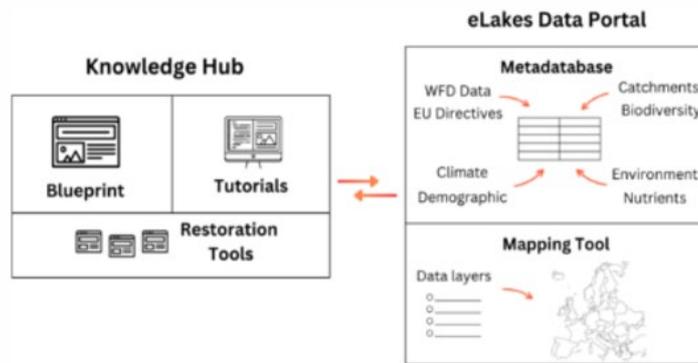


Figure 2. Overview of the eLakes metadatabase showing a wireframe diagram of its use in the context of the FutureLakes Project upscaling and prioritisation approach.

2 Conceptual Prioritisation Framework

2.1 Objectives and Framework Structure and Application Process

The main aim of the FutureLakes Prioritisation framework is to support upscaling and prioritisation processes for restoration focused on optimising the EU Mission ‘Restore our Ocean and Waters’ Goals of *protecting and restoring biodiversity; reducing pollution and delivering a carbon neutral and circular blue economy*. The framework also supports the WFD policy goal of all surface waters achieving good ecological status. The framework has two layers (Figure 3): (1) WFD & Biodiversity, and (2) Additional benefits to society. The prioritisation process utilises spatial datasets, where all lakes are included at the start of the process and a ranked list of priority lakes is generated based on weighting determined through stakeholder discussions. We demonstrate the application of the Prioritisation Framework below (Box 1) with initial analyses focussing on the WFD and Biodiversity followed by other societal benefits.

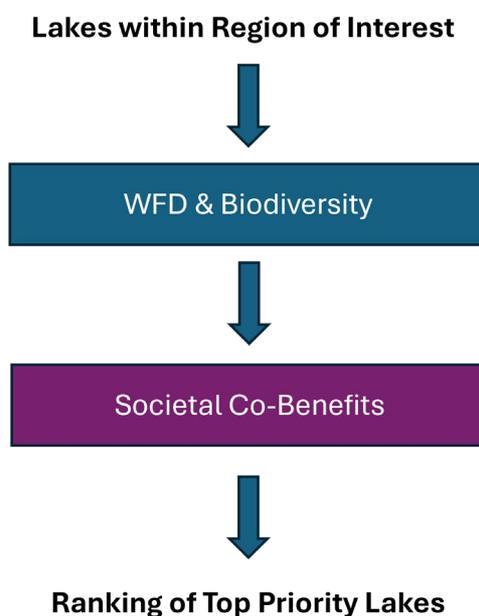


Figure 3. Conceptual overview of the FutureLakes Prioritisation Framework.

Box 1. Proposed Application Process for the FutureLakes Prioritisation Framework

1. Define Objectives and Gather Relevant Data

- Task Description: Identify restoration goals (e.g., WFD ecological improvement, biodiversity recovery, GHG reductions, socioeconomic benefits) and compile relevant datasets from the eLakes Data Portal.
- Expected Outcome: A clear meta-data description on national and harmonised EU-scale data layers for analysis.

2. Apply Layer 1 — WFD & Biodiversity Prioritisation

- Task Description: Use WFD ecological status, macrophyte BQE, trends, HD/BD assessments, and Natura 2000 coverage to classify lakes according to ecological and biodiversity status.
- Expected Outcome: A first-level list of lakes ranked by ecological restoration potential and biodiversity relevance.

3. Apply Layer 2 — Societal Benefits

- Task Description: Incorporate additional criteria—e.g., socioeconomic deprivation, population density, tourism value, pollutant exceedances, and methane-emission reduction potential.
- Expected Outcome: Identification of lakes that not only have ecological value but also deliver wider societal, climate, or pollution-reduction benefits.

4. Combine All Layers Using MCDA (Multi-Criteria Decision Analysis)

- Task Description: Weight selected criteria, normalise values, and calculate composite scores using an aggregation method (e.g., Weighted Linear Combination).
- Expected Outcome: A transparent, stakeholder-informed ranked list of priority lakes, or a spatial priority map, integrating all selected objectives.

5. Conduct Stressor Analysis for High-Priority Lakes

- Task Description: Examine underlying pressures at national scale (e.g., nutrient sources, hydromorphological alterations, climate vulnerability, pollutants).
- Expected Outcome: A diagnosis of the dominant stressors operating at national scale, their potential interactions to inform assessment of available restoration measures.

6. Perform Lake-Level System Analysis

- Task Description: Construct water and nutrient budgets, assess biological communities, sediment dynamics, groundwater inputs, and critical load thresholds, and identify potentially confounding stressors.
- Expected Outcome: A detailed understanding of system functioning and the drivers of degradation, and confirm that stressor abatement scenarios will result in benefits across relevant Framework layers, forming the evidence base for restoration planning and measures selection.

7. Select Appropriate Restoration Measures

- Task Description: Based on system analysis, choose cost-effective measures (catchment actions, in-lake interventions, biodiversity recovery actions, pollution control).
- Expected Outcome: A fully costed lake-specific restoration plan that addresses dominant pressures and maximises ecological and societal gains.

8. Integrate Outputs into Restoration Planning

- [Task Description: Translate prioritisation results and system analyses into national restoration strategies, suitable for National Restoration Plans under the EU Nature Restoration Regulation.](#)
- [Expected Outcome: Policy-ready restoration proposals that can be scaled, budgeted, and implemented at national or regional level.](#)

2.2 WFD & Biodiversity

Freshwater biodiversity is in crisis globally and in Europe, with steep declines in species abundance, habitat quality, and ecological connectivity. Recent global assessments show freshwater species populations have fallen by more than 80% since 1970, making lakes and wetlands among the most threatened ecosystems (WWF, 2022). This loss undermines ecosystem services such as water purification, carbon storage, and climate regulation, and it jeopardizes the EU’s ability to meet its biodiversity and climate goals.

Policy frameworks recognise this urgency. The EU Biodiversity Strategy 2030 sets ambitious targets to halt biodiversity loss and restore degraded ecosystems, including restoring at least 25,000 km of rivers to a free-flowing state and improving the condition of lakes and wetlands. The Nature Restoration Regulation introduces legally binding restoration obligations for freshwater ecosystems, aiming to reverse decades of degradation and fragmentation. The Habitats Directive (HD) and Birds Directive (BD) require Member States to support the long-term viability of species and habitats. Protected areas designated under these directives, Natura 2000 sites and Special Protection Areas, provide a cornerstone for biodiversity conservation in the EU. Reporting under Article 17 (HD) and Article 12 (BD) compiles data across entire biogeographic regions—not just protected areas—creating a comprehensive but not complete picture of species and habitat condition.

Meanwhile, the WFD focuses primarily on ecological status, an aggregate assessment combining biological, chemical, and physical indicators, but does not explicitly capture biodiversity outcomes.

To bridge this gap, our approach integrates WFD data with HD/BD conservation assessments and Natura 2000 coverage to identify lakes where restoration can be expected to deliver the greatest biodiversity gains.

To create a prioritised list of lakes, we combine three data streams (Figure 4):

- Water Framework Directive data for ecological status and pressures.
- Habitats and Birds Directive data for species and habitat conservation status.
- Natura 2000 coverage to identify areas with legal protection and restoration obligations.

This combined approach utilises multiple pieces of data so that biodiversity prioritisation is robust, evidence-based, and aligned with EU conservation and restoration objectives. This supports the overarching policy goal of halting biodiversity loss and achieving ecosystem recovery by 2050.

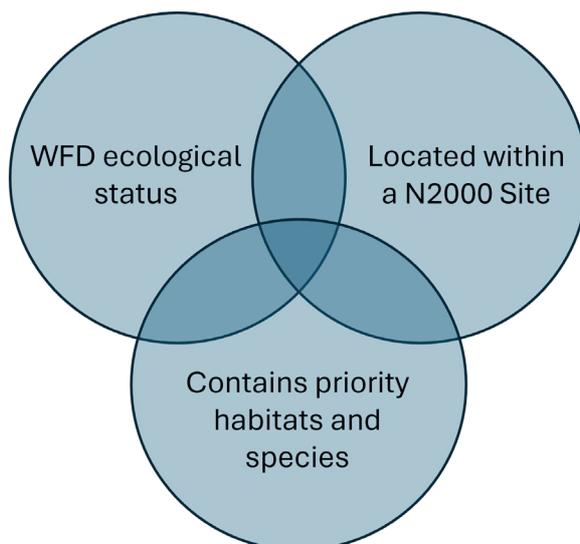


Figure 4. Conceptual example of combining approaches and data types on biodiversity.

2.2.1 Utilizing WFD data (Lake-level)

The WFD, adopted in 2000, is the foundation of EU water policy. Its primary objective is to achieve Good Ecological and Chemical Status for all surface waters, including lakes, rivers, and coastal waters. WFD assessments integrate biological, chemical, and hydromorphological indicators, or “Quality Elements”, to evaluate ecological status. Biological Quality Elements used in the assessment for lakes include phytoplankton, macrophytes, benthic invertebrates, and fish communities, while supporting elements cover nutrient concentrations, oxygen levels, and physical habitat conditions. WFD datasets (Tables 2 & 3) provide a comprehensive view of pressures and status at the waterbody scale. They include:

- **Ecological status classifications** (High, Good, Moderate, Poor, Bad) based on Biological Quality Elements.
- **Chemical status** for priority substances.
- **Pressures and impacts** such as nutrient enrichment, hydrological alterations, and pollution sources.
- **Monitoring data** collected through national programmes and reported to the European Environment Agency (EEA).

These datasets are essential for identifying lakes that fail to meet Good Ecological Status and where restoration can deliver significant improvements. Data for individual elements are not routinely reported by Member States to the EEA but are publicly available in many countries through national databases. By combining WFD data with biodiversity and Natura 2000 information, the prioritisation framework aligns with both ecological integrity and EU legal obligations.

Table 2. Datasets needed for framework application

Concept	Dataset	File Type	Unit	Policy	Source
WFD	Ecological status	csv	Normalized, categorical	WFD	WISE database

WFD & Biodiversity	Macrophyte BQE	csv	Normalized, categorical	WFD	WISE database and national datasets
Biodiversity	Natura-2000 sites	shp	polygons	HD/BD	BISE database
Biodiversity	Priority species list	csv	Presence	HD/BD	BISE database
Biodiversity	Habitat Condition	csv	Normalized, categorical	HD/BD	

Table 3. Description of application of dataset in the framework

Concept	Dataset	Description & Interpretation	Priority Association	Challenges
WFD	Ecological status	Combines multiple criteria for status determination	Prioritise all lakes <good	Temporal resolution
WFD & Biodiversity	Macrophyte BQE	Proxy for habitat condition. Good/moderate boundary linked to shift in ecological functioning	Prioritise all lakes <good	Temporal resolution and availability of data not reported to the EEA
Biodiversity	Natura-2000 sites	Polygons showing locations of Natura-2000 protected areas	Prioritise inside the polygons	
Biodiversity	Priority species list	List of species of high priority	Prioritise lakes where these species are present and where ecological status < Good and/or habitat condition is <favourable.	Species and habitat data not reported at the individual lake scale to the EU. National datasets not often accessible.
Biodiversity	Habitat Condition	Condition of lake habitats defined under the Habitats Directive	Prioritise lakes where habitats are less than favourable condition	Difficult to obtain raw data on condition of lake habitat types for individual lakes at the EU scale. National datasets are not often accessible. Could use macrophyte BQE of individual lakes as a proxy for habitat condition as it is a plant community-level measure of biodiversity and comparable data are often used for Article 17 assessments.

To identify lakes where restoration can deliver the greatest biodiversity benefits, we suggest three options using data collected under the WFD.

Option 1 prioritises all lakes currently failing to achieve Good Ecological Status. Greater weighting could be given to Moderate status lakes over Poor and Bad status lakes, as Moderate status lakes may be more cost-effective to target for restoration measures and are also likely to be sites where biodiversity is more “recoverable” as they’ve been less impacted than Poor or Bad status lakes.

Option 2 identifies lakes with deteriorating status over time, particularly those declining from High to Good and Good to Moderate. Where normalized ecological quality ratio (nEQR) data are available, trends for individual BQEs can be analysed to detect consistent declines, providing an early warning for biodiversity loss. However, this option requires time-series data which are not always easily available.

Option 3 prioritises lakes where the macrophyte BQE is below Good status. This approach is simple, yet potentially highly effective since macrophytes are considered the most representative indicator of biodiversity because they form the structural habitat for other aquatic organisms. Importantly, macrophyte status under the WFD is typically assessed using plant community data that corresponds closely to the data used to assess habitat condition under Article 17 of the Habitats Directive for lake habitat types (considers the balance between characteristic plants of that habitat vs atypical plants recorded in a lake), macrophyte status, therefore, acts as a good proxy for habitat condition, and data are available at the individual lake scale. It has also been previously shown that the Good/Moderate boundary for macrophytes reflects a significant functional shift in lake ecosystems (Poikane et al., 2018), and macrophyte assessments offer a more stable, long-term measure of eutrophication impacts compared to more dynamic indicators such as phytoplankton (Lyche Solheim, 2013). We show an example of Option 3 for lakes in Denmark below (Figure 5) where data collected for 580 WFD lakes is used to select a prioritised list of 286 lakes where macrophyte status is currently < good, and where restoration could provide a boost to ecosystem functioning and biodiversity.

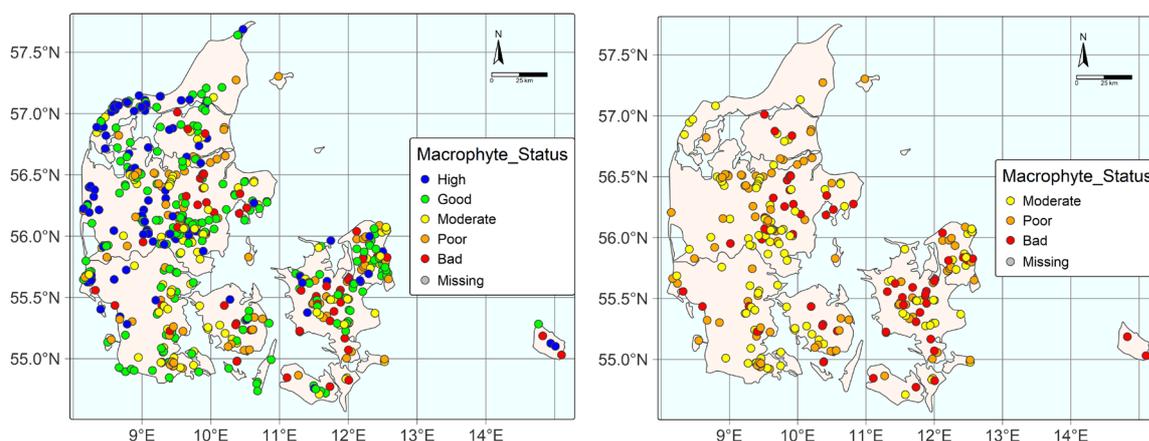


Figure 5. Macrophyte status for all lakes monitored for WFD (580, left) and lakes with macrophyte status < good (268, right) which would be selected as priority for restoration.

Option 1 is our initial default rule in prioritising European lakes for restoration to support WFD policy goals. Option 2 could be used separately to identify high or good status lakes in need of greater protection to avoid deterioration in status class. Option 3 may be useful for using WFD data as a proxy for Habitat condition, for evaluating the priorities for biodiversity restoration (see Section 4.2.2).

2.2.2 Utilizing HD/BD datasets

The Habitats Directive (HD) and Birds Directive (BD) form the backbone of EU nature conservation policy. They aim to support the long-term survival of Europe’s most valuable and threatened species and habitats. HD focuses on habitats and species listed in Annexes I and II, while the BD protects all wild bird species naturally occurring in the EU, with special attention to those listed in Annex I.

Datasets from these directives include:

- **Conservation status assessments** for priority species and habitats, reported under Article 17 (HD) and Article 12 (BD) every six years.
- **Distribution maps** and population trends for priority species.
- **Habitat condition data** at biogeographic region level.
- **Natura 2000 site boundaries and features**, which indicate areas designated for priority species and habitat protection.

These datasets provide a regional and site-level perspective on biodiversity, complementing the WFD’s ecological status data. Integrating HD and BD information helps identify lakes that support Annex-listed species or habitats and where restoration can contribute to EU biodiversity targets. We suggest 4 options for using these datasets:

Option 1 identifies lakes failing HD habitat condition assessments, focusing on which specific habitat types are in Unfavourable Condition and mapping their geographic distribution. Special attention is given to lakes within protected areas designated for priority lake habitat types under Natura 2000.

Option 2 addresses habitat dependencies of priority species, as required under the EU Nature Restoration Regulation, ensuring restoration of habitat types critical for priority species, even if these habitats are not currently protected. This option can be visualized as a dedicated map layer showing the spatial distribution of sites prioritised and if they are currently within a protected area (Natura 2000 or Spatial Protected Area as appropriate).

2.2.3 Combining WFD & Biodiversity priorities

Given multiple dimensions to both WFD Ecological Status and Habitat/Birds Directive datasets, we suggest two approaches for combining these datasets to strengthen biodiversity prioritisation. The first approach combines these two datasets spatially through the following 2 Options.

Option 1 combines WFD and HD data to highlight sites failing both ecological status and habitat condition. Lakes with less than good WFD status that are in Natura 2000 sites with Unfavourable Condition or priority species status are assigned the highest priority for restoration. An example of this is illustrated in Figure 6, where of the 580 lakes reported for Denmark, 110 lakes have a macrophyte BQE status < Good and are located within Natura-2000 sites (assigned based on a priority freshwater habitat type).

Option 2 targets lakes failing WFD status that also host HD-priority species. We show an example of this in Figure 7, where of the 580 lakes reported, only 3 lakes host priority macrophyte species. All of these lakes are within Natura-2000 sites and have a macrophyte status > Good, so while these 3 lakes would not be considered high priority, future work is needed to determine which lakes previously held populations of priority species, and which lakes could potentially host them in the future if restored.

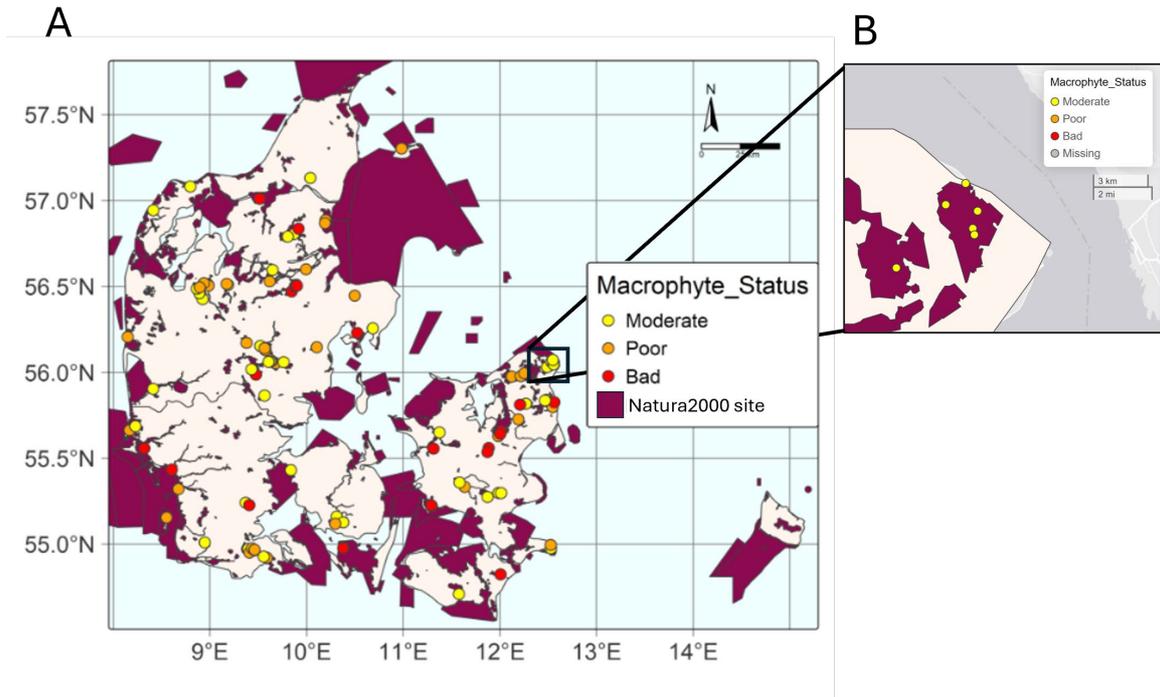


Figure 6. A) All lakes with macrophyte status < good that also fall within Natura2000 sites (in purple; 113 out of 580 sites, 110 for freshwater site types). B) Zoomed-in detail of 6 moderate status lakes in a Natura2000 site to clarify overlap in Figure 6A.

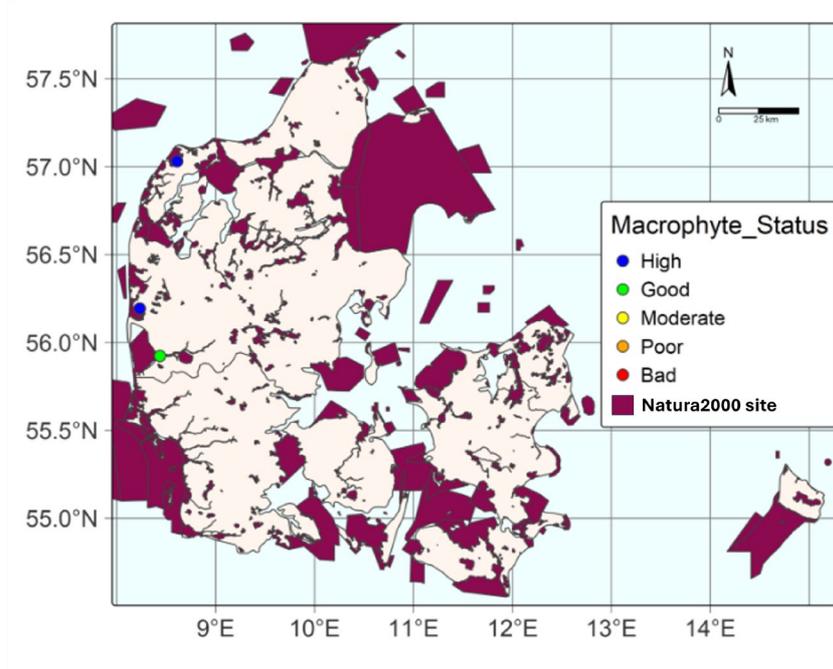


Figure 7. Map highlighting WFD macrophyte BQE status of lakes where priority macrophyte species are present (only 3 and all are > good status). Priority species present: *Najas flexilis*, *Luronium natans*, *Luronium natans f. submerses*.

The second approach for combing WFD and biodiversity datasets is to use a bivariate matrix plot, as used in Duarte et al (2023). For example, compliance with Habitats Directive goals could integrate the

condition of priority lake habitats as well as the condition of priority species and the status of both could be combined in a bivariate choropleth plot (Figure 8).

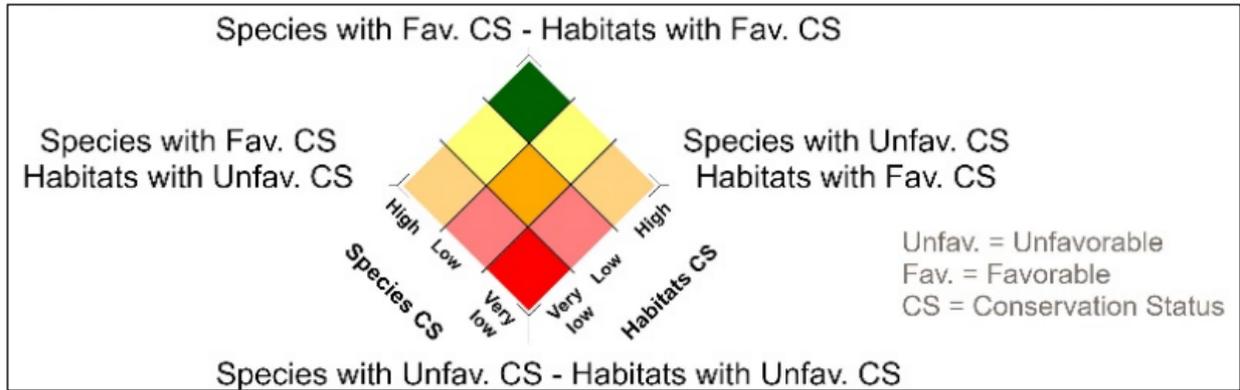


Figure 8. Combination of restoration need in relation to the Habitats Directive, based on whether priority lake species and habitats are in Favourable or Unfavourable Condition, using a bivariate choropleth map (Taken from Duarte et al., 2023).

A similar bivariate matrix approach can be used to combine restoration needs in terms of sites in less than Good WFD Ecological Status and Unfavourable Biodiversity Condition in relation to the Habitats Directive (Figure 9).

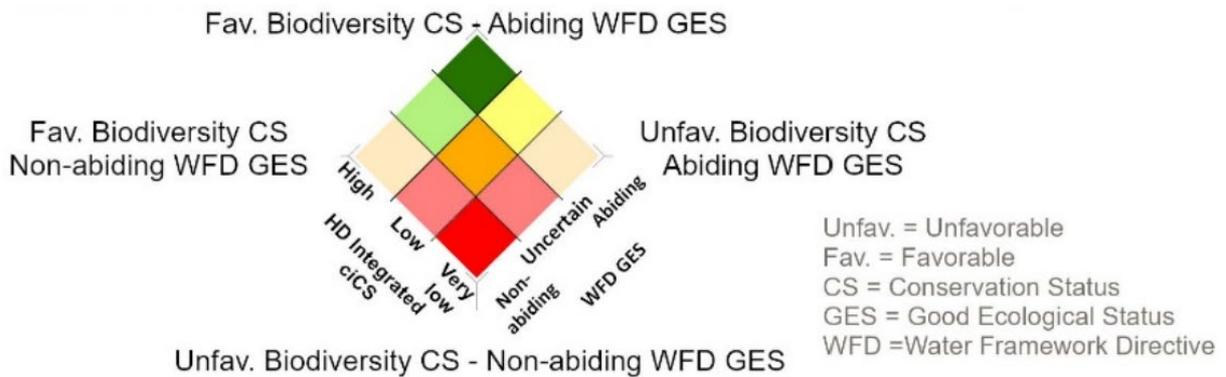


Figure 9. Integration of WFD and Habitats Directive restoration needs using a bivariate choropleth map (Taken from Duarte et al., 2023).

If a lake has no significant biodiversity interest under the Habitats or Birds Directives, the priority class could be based solely on WFD data.

2.3 Other Societal Benefits

For this part of the framework, we include additional optional secondary objectives that users can opt for if they have additional priorities in addition to WFD & Biodiversity policy goals. These include maximising Socio-Economic Benefits, GHG Emissions Reduction & Pollution Reduction (Figure 10).

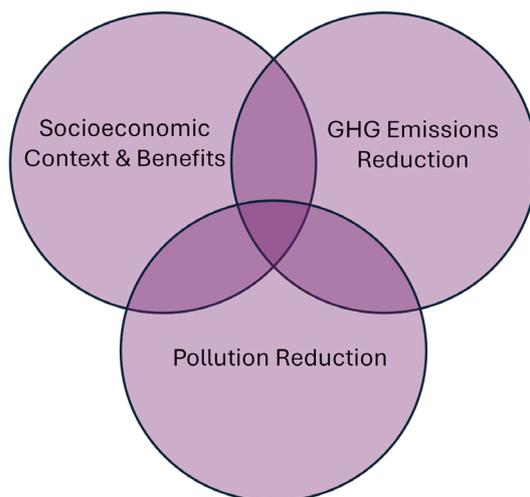


Figure 10. Conceptual overview of additional benefits to society.

2.3.1 Socioeconomic Context & Benefits

The restoration of freshwater ecosystems often focuses on biodiversity, ecological and climate objectives. However, prioritising economically deprived regions and promoting circular economies can make restoration more effective, fair, and sustainable (Barbier, 2010).

Economically deprived regions rely heavily on natural resources (e.g. water, fisheries, soils) for economic activities (UNEP, 2016). The degradation of lakes directly impacts the economic productivity (e.g., fisheries, crop yields, tourist visitors etc.) and local stakeholders’ income. As a result, local communities affected by freshwater ecosystem degradation record decreasing incomes and higher vulnerability towards natural resource scarcity and extreme climate events (UN Water & WWAP, 2018). Prioritising restoration in such areas, therefore, reduces inequality and supports climate justice. In parallel, lake restoration using Nature-based Solutions (NbS) can stimulate local economic sectors, such as eco-tourism and businesses associated with recreation in nature (Palmer & Filoso, 2009).

For the above reasons, the FutureLakes Prioritisation Framework will allow stakeholders to opt for prioritising lakes based on the socioeconomic context of the region as a measure to reduce poverty and stimulate well-being. This can be implemented using datasets (Tables 4 & 5) such as:

- Population density (layer 1): densely populated areas experience the greatest environmental pressures but equally have the highest number of people who can benefit from access to high quality nature.
- Socio-economic deprivation (layer 2): to address environmental inequities that often affect low-income communities. Restoring lakes in regions of high deprivation can stimulate the health and well-being of local citizens who may not have sufficient income to travel to more distant areas for accessing high quality nature.
- Tourism and recreational activities (layer 3): restored and healthy lakes are usually associated with high tourist and recreational activities (Meyerhoff et al., 2019; Wubalem et al., 2023). Prioritising lakes with existing moderate to high tourism levels for restoration measures may be important to sustain livelihoods of local communities that rely on tourism-generated income. Conversely, it could be argued to consider prioritising restoration measures at lakes with current low levels of tourism in order to stimulate a tourism industry. This, however, would involve checking that there was the potential for tourism to develop and that the main barrier was the status or condition of the lake. Our framework will be set up to focus more on prioritising restoration measures at lakes where there is an existing

tourism industry where there is a more definite impact on supporting the sustainability of the tourism sector and where measures may be needed to restore water quality or biodiversity at a lake due to the impacts from tourist pressures.

Table 4. Datasets needed for the FutureLakes Prioritisation Framework to incorporate Socio-Economic Benefits.

Concept	Dataset	File Type	Unit	Source
Economic context/need	Population density by NUTS2 region	File format Spreadsheet (.xlsx)  Spreadsheet (.xlsx) Tab separated values (.tsv) SDMX-CSV 1.0 (.csv) SDMX-CSV 2.0 (.csv) SDMX-ML 2.1 StructureSpecific (.xml) SDMX-ML 2.1 Generic (.xml) SDMX-ML 3.0 (.xml) JSON-stat (.json)	Persons /km ²	<u>Eurostat</u>
Economic context/need	Socio-economic Deprivation Index (by NUTS2 region)	csv To be computed considering socioeconomic factors ¹ , i.e. the <u>unemployment rate</u> by NUTS 2 region, <u>Gross domestic product (GDP)</u> at current market prices by NUTS 2 region, and <u>People at risk of poverty or social exclusion</u> by NUTS 2 region	%	Authors, based on Eurostat data
Socio-economic benefit	Tourism	csv <u>Establishments, bedrooms and bed-places in tourist accommodation</u> , by NUTS 2 region	bed-places	<u>Eurostat</u>

Table 5. Description of application of dataset in the framework (visualised in Figure 11).

Concept	Dataset	Description & Interpretation	Priority association
Economic context/need	Population	<80 inh./km ² = Low density (remote, rural region or semi-rural region) 80 – 150 balanced regions (mixed rural-urban, regional hubs, or moderately populated areas) 150 – 400 inh./km ² = urban or peri-urban regions. NUTS 2 regions centred on cities and agglomerations > 400 inh./km ² = Very densely populated regions	>150 inh./km ²
Economic context/need	Socio-economic	>70 % most deprived region 36- 69% moderately deprived region	>70 % most deprived region

¹ Users may add other factors such as [Severe material deprivation rate](#) by NUTS 2 region if data are available

	Deprivation Index (SEDI)	26-35% slightly deprived region <25% Least deprived region	
Socio-economic benefit	Tourism	< 100,000: Very low capacity and limited tourism activity 100,000 – 500,000 Low-to-moderate tourism regions >500,000 regions are major tourist destinations	>100.000 capacity (bed-places): regions qualified as tourism destinations prioritised to support sustainability of the tourism industry

Socio-economic Deprivation Index (SEDI): Users can choose **measurable factors** that reflect the social and economic deprivation. Common indicators include unemployment rate (in %), GDP (in Million euro, PPS²), and people at risk of poverty (% of total population). These factors (X_i) usually have different units which requires a first step of normalisation as outlined below.

$$X_{ij,normalized} = \frac{X_{ij} - X_{ij,min}}{X_{ij,max} - X_{ij,min}} \tag{1}$$

i = factor ; i: 1 ... n
j = region (NUTS2) ; j: 1 ... m

For indicators where higher values mean less deprivation (like GDP), users must invert the scale as follows:

$$X_{ij,inverted} = 1 - X_{ij,normalized} \tag{2}$$

i = factor ; i: 1 ... n
j = region (NUTS2) ; j: 1 ... m

$$SEDI_j = 100 * \sum_{i=1}^n w_i X_{i,normalized} \tag{3}$$

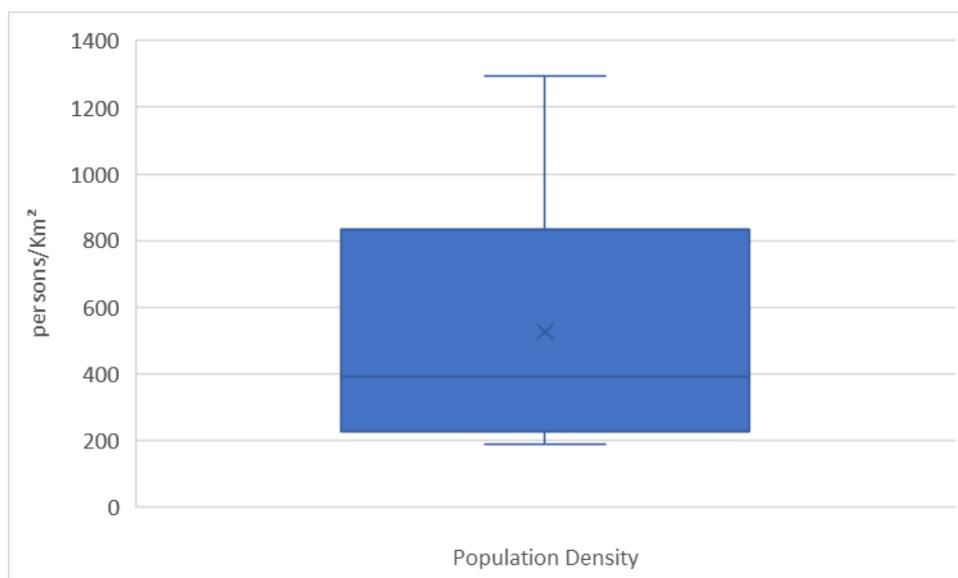
i = factor ; i: 1 ... n
j = region (NUTS2) ; j: 1 ... m
w = weights

SEDI_j ranges from 0% (least deprived) to 100% (most deprived). Table 6 shows an application of this index to the NUTS2 regions of the Netherlands.

² Purchasing power standard

Table 6. Calculated Socio-economic Deprivation Index in the Netherlands by NUTS 2 region (2023-2024 data)

NUTS level 2	$SEDI_j$ using 2023-2024 data	Classification
Groningen	97,77	most deprived
Friesland (NL)	77,76	most deprived
Drenthe	66,28	moderately deprived
Overijssel	60,13	moderately deprived
Gelderland	55,13	moderately deprived
Flevoland	76,62	most deprived
Utrecht	61,76	moderately deprived
Zuid-Holland	53,56	moderately deprived
Noord-Holland	43,59	moderately deprived
Zeeland	33,33	slightly deprived
Noord-Brabant	39,12	slightly deprived
Limburg (NL)	58,34	moderately deprived



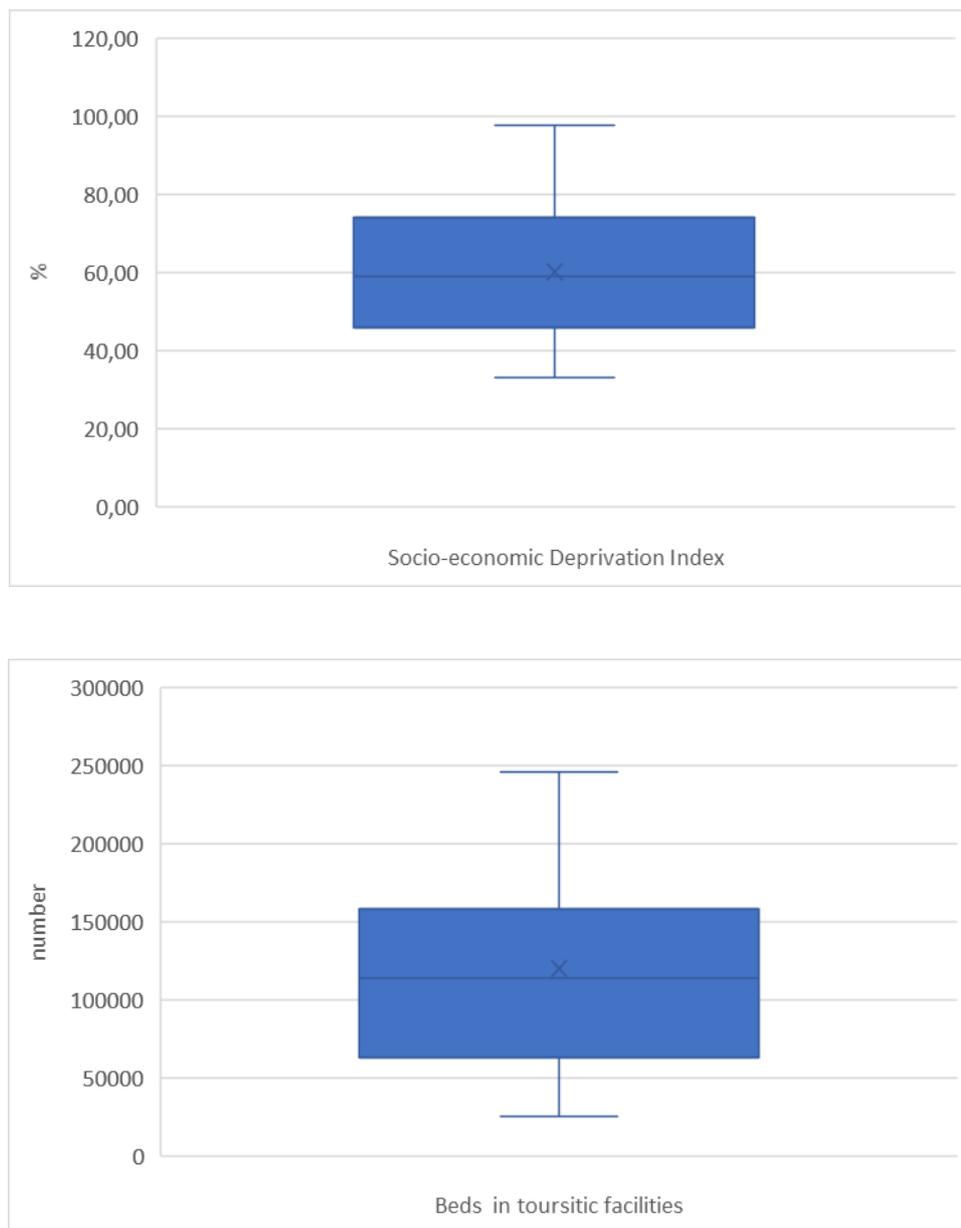


Figure 11. Box plots showing the distribution of the population density, deprivation index and number of bed places in tourist facilities in the Netherlands at NUTS2 level using 2023-2024 Eurostat data.

2.3.2 GHG Emission Reduction

For this component of the framework, users can estimate the benefits of restoration, in the context of how improvements in WFD ecological status impact emissions of greenhouse gases, in particular methane (CH₄). This provides a framework for prioritising lakes for restoration based on their capacity to reduce GHG emissions.

In terms of inventories of anthropogenic emissions compiled nationally under the guidelines from the IPCC, emissions from most fresh waters have not been included as they are from ‘natural’ ecosystems. There are exceptions with some types of fresh water and some GHGs included in national inventories. For example, emissions of CH₄ from reservoirs are included if the reservoir is man-made (i.e “flooded

land”) and the reservoir is >20 years old. For these reservoirs the IPCC has guidelines for emissions factors. A second example are emissions of nitrous oxide from natural systems, but where the emission is unequivocally the results of human activity, in this case the indirect effects of fertiliser application. However, it has become increasingly evident through a range of studies that fresh waters in general, and lakes in particular, emit increased amounts of CH₄ because of human induced changes in ecological status (Beaulieu et al., 2019; Davidson et al., 2018). The patterns and processes behind emissions are complex, resulting in very large spatial and temporal variation in fluxes of GHGs. Thus, identifying cause and effect and separating natural from anthropogenic emissions remains challenging. Notwithstanding this uncertainty, the general pattern linking lake ecological status, as reflected by chlorophyll-a concentration, and CH₄ emissions has some predictive power. On the basis of this, we have developed for the FutureLakes Prioritisation Framework, preliminary estimates of the potential of lake restoration for reducing CH₄ emissions. These estimates are based specifically in terms of reducing chlorophyll-a concentrations until Good ecological status is achieved for this BQE sub-element.

The relationships between chlorophyll-a and CH₄ fluxes described in Del Sontro et al. 2018 were reanalysed using a Bayesian statistical framework which provides more accurate mean estimates for emissions and better characterises the uncertainty of emissions estimates.

The final model allows estimation of CH₄ efflux from lakes based on their chlorophyll-a concentration and lake surface water area (Tables 7 & 8), allowing the assessment of the benefit of lake restoration, albeit with a high degree of uncertainty.

Table 7. Datasets needed for framework application

Concept	Dataset	File Type	Unit	Source
Emission reduction	Lake area	csv	km ²	Hydrolakes
Emission Reduction	chlorophyll-a	csv	concentration	National database odaforalle
Emission Reduction	Class Boundaries for Chlorophyll-a	csv	Categorical (high/good, good/moderate)	

Table 8. Description of application of dataset in the framework

Concept	Dataset	Description & Interpretation	Priority association
Emission reduction	Lake area	Lake area	Larger lakes with higher emissions per square meter are high priority
Emission reduction	chlorophyll-a	Chlorophyll-a concentrations	Used for analysis only
Emission reduction	Class Boundaries for Chlorophyll-a	Class boundary values (i.e. high/good, good/moderate) of Chlorophyll a for each lake type were determined	

Step-by-step methodology (conceptual):

Step 1 Recalculation of relationship between chlorophyll-a and CH₄ emission within the Bayesian framework to allow for better estimation of both mean emissions and their uncertainty.

Step 2 identify data sets with chlorophyll-a data and lake area or with lake area and lake type identified.

Step 3 application of model to lake with 'real' data to estimate current CH₄ emission and also the benefits of improving water quality and/or ecological status.

Step 4 applying model to large dataset of European lakes and estimating the benefits of achieving Good status versus lakes currently in Moderate, Poor or Bad Ecological Status, using the lake area and Lake Type Specific Boundary Values for chlorophyll-a (visualized in Figure 12).

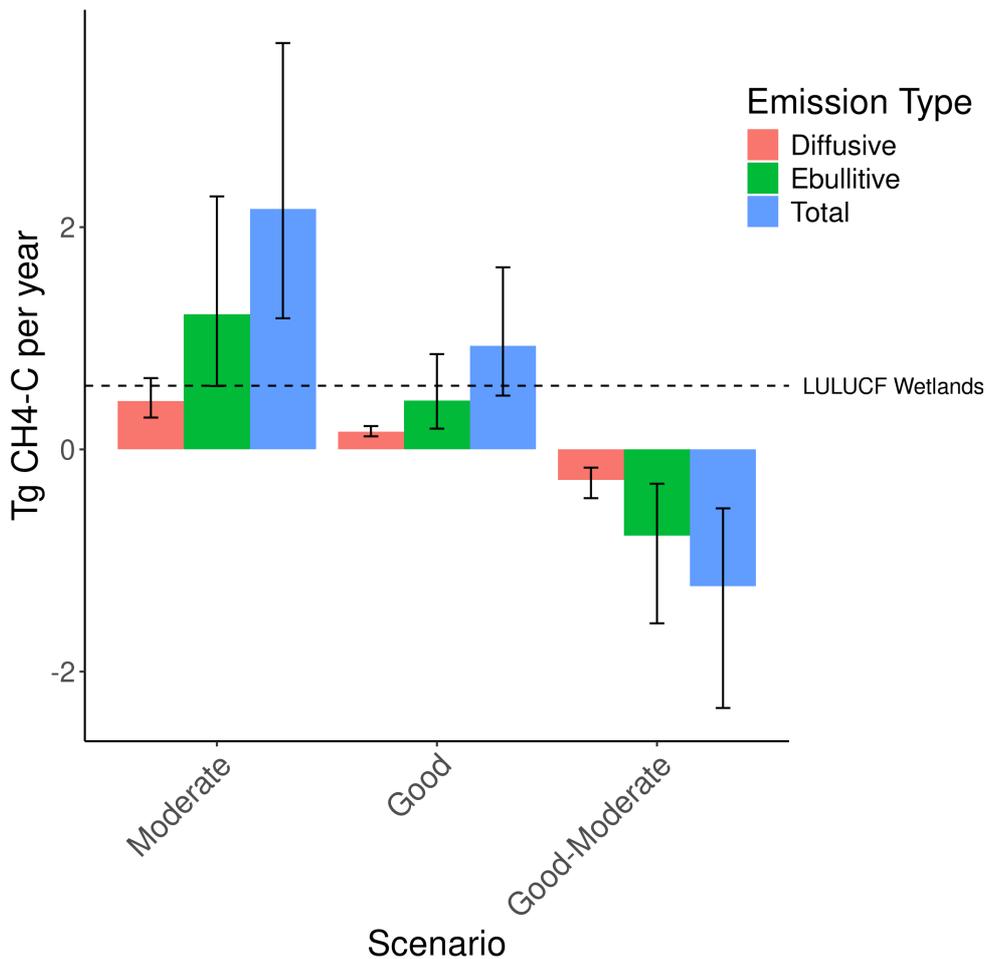


Figure 12. Bar plots showing the methane emissions under Good or Moderate chlorophyll-a scenarios for 8000 EU lakes and the difference in emissions between them (Good-Moderate). Emissions have been scaled by a factor of 3.92 to account for the entire European lake population. The average EEA wetland inventory from 1990-2022 is shown by the dotted line (and has been converted to Tg CH₄-C y⁻¹ from MT CO₂ eq).

2.3.3 Pollution Reduction

An additional scope of the Prioritisation Framework includes the option to prioritise lakes based on priority substances to tackle catchment sources of pollution. For example, this may include an

assessment of per- and polyfluoroalkyl substances (PFAS, informally referred to as "forever chemicals") pollution of waterbodies. While current restoration practices do little to remove current pollution of PFAS in waterbodies, catchment measures can cut off pollution at the source. For this optional layer of the prioritisation framework, the WFD dataset for priority substances (Tables 9 & 10) is used to see where lakes are failing based on monitoring data on priority substances.

Table 9. Datasets needed for framework application

Concept	Dataset	File Type	Unit	Source
Pollution	Priority substances	csv	Status classes	WFD

Table 10. Description of application of dataset in the framework

Concept	Dataset	Description & Interpretation	Priority association
Pollution	Priority substances	Status classes based on priority substances	Prioritise where < Good

3 Combining Framework Layers

For combining the layers in the framework, we suggest using Multi-Criteria Decision Analysis (MCDA), which provides a structured and transparent method for integrating multiple objectives (Casados et al., 2025, Silva et al., 2023; Comín et al., 2018). This makes it particularly suited for restoration planning where decision-makers are interested in addressing multiple objectives. In our lake prioritisation framework, MCDA serves as the mechanism for combining two or more layers—WFD, biodiversity contribution and societal co-benefits—into a single, actionable ranking.

A critical feature of MCDA is the assignment of weights to the different criteria, reflecting their relative importance in decision-making. In our framework, weighting will be open, flexible, and stakeholder-informed, so that priorities align with policy objectives and specific community needs. Weights can be determined through expert consultation, workshops, or iterative engagement processes, allowing users to tailor the prioritisation to specific contexts. This flexibility allows the framework to remain adaptable to diverse governance settings and restoration goals.

Once weights are established, criteria scores are normalized and combined using an aggregation method—such as Weighted Linear Combination—to produce composite scores for each lake. These scores are then translated into priority rankings or spatially explicit maps, providing decision-makers with a clear and transparent basis for action. By explicitly incorporating stakeholder preferences into weighting, MCDA fosters collaboration, and allows restoration planning to deliver both ecological and societal benefits.

Given our stakeholder-led approach to weighting, we will develop a priority list and maps of European lakes for restoration based on a number of default weightings to illustrate and compare the outcomes from weighting different policy goals. We envisage national priority lists and maps will be developed through workshops with national stakeholders.

4 Identifying the relevant pressures causing degradation

Our Framework encourages the end-user to explore multiple data sets through the eLakes Portal to provide supplementary stressor analyses to inform initial prioritisation scenarios. Such analyses should help to identify the dominant stressors at play, and therefore, provide context on the categories of measures that will be of relevance at this scale. Understanding the pressures driving lake degradation is essential for designing effective restoration strategies. Some of the data sets described above have been used previously to explore the effects of multiple stressors and their interactions on indicators of water quality and biodiversity in lakes and statistical methods are available to tailor such assessments (Birk et al., 2020; Spears et al., 2021). Politi et al. (2024) outline a number of datasets that can be used to classify lake sensitivity to nutrient pressures, incorporating both catchment and lake characteristics that affect the delivery and transformation of nutrients into algal biomass.

Additional assessments could also be considered to develop ‘stressor assessments’ for socio-economic and climate regulation indicators, although these are less well developed in the literature. For example, at the national scale, additional analysis of lake monitoring data can be carried out to determine whether nutrient enrichment is primarily due to internal loading, external loading, or a combination of both. In this case, WFD monitoring datasets offer detailed water quality information, including seasonal trends in total and bioavailable nitrogen and phosphorus concentrations. These data can help distinguish between point-source and diffuse-source contributions and assess whether internal loading, a process of cycling of phosphorus between the bed sediment and the water column, is significant. Additionally, WISE datasets on chemical status failures can identify the occurrence and concentrations of Pollutants of Concern, such as PFAS from catchment sources, versus atmospheric contaminants like mercury, which commonly drive non-compliance. Habitats Directive data may identify occurrence of non-native invasive species and their extent of invasion.

Climate-related pressures should also be considered and lake typology and climate change scenario projections may be used to examine sensitivity categories for lakes. For example, lakes with short retention times (<1 year) are highly sensitive to changes in rainfall patterns (Carvalho et al, 2011), while those with annual average temperatures below 17°C have been shown to experience increased algal bloom risk under warming scenarios (Richardson et al., 2018). These climate change mediated effects will be highly spatially distinct and most European countries will have access to downscaled climate projection data for precipitation, air temperature, and wind with which to map climate change sensitivity across lakes.

Downscaled climate-change projections for use in freshwater ecosystem assessment and restoration planning can be obtained from several high-quality European data sources. The Copernicus Climate Change Service (C3S) provides the most widely used source of high-resolution regional climate projections via its Climate Data Store, including bias-adjusted and downscaled datasets derived from CMIP5 and CMIP6 models. Of relevance is the C3S “Downscaled bioclimatic indicators for Europe” dataset, which offers 1-km resolution projections of temperature-, moisture- and energy-related bioclimatic variables under RCP 4.5 and 8.5 scenarios — suitable for ecological and hydrological modelling. Complementing these projections, lake-specific essential climate variables (e.g., lake surface temperature, water level, ice phenology) are available through the European Space Agency’s Lakes Climate Change Initiative (Lakes_cci), which provides observational climate datasets that can support calibration or validation of lake-response models. Together, these resources provide spatially explicit inputs for assessing climate-related pressures in the prioritisation framework. As an example of how

such data can be applied at national scale, was an assessment for Scottish lochs using downscaled, scenario-based, climate data alongside observational monitoring to project future warming in Scottish lochs and reservoirs, assess risks of algal blooms, and support recommendations for adaptive water-management strategies (May et al. 2022).

One major issue on the application of the Prioritisation Framework is data paucity. Complementary datasets, such as the Bloomin' Algae App which produces citizen science records and satellite remote sensing products which produce time series of chlorophyll-a concentrations and suspended sediments can help identify 'blind spots' in national regulatory monitoring programmes under the WFD and HD.

This stressor analysis is more easily done at the national-scale, where data are typically more available or national risk models have been developed. Analyses can identify the most common causes of lake degradation to inform identification of suites of restoration measures that may be useful to consider at the national scale. This should help to identify any capacity gaps with respect to procuring and implementing measures at scale to meet the stressor needs of any member state. A national analysis can also accelerate the design and implementation of the next step: a systems analysis and selection of solutions, following the process outlined below.

5 System Analysis and Solution Selection

A key part of constructing Nature Restoration Plans in response to the new NRR is deciding which restoration measures are needed. This is outside the scope of the prioritisation framework outlined above, but once the list of prioritised lakes has been agreed, this is the next step. Here we will elaborate on how to evaluate which measures are needed.

A lake restoration process commonly begins after a problem occurs, which is usually a clearly visible symptom of eutrophication, such as massive plant growth, turbid water, foul odours, fish kills, or dense cyanobacterial blooms. However, lake users (e.g., fishermen, scuba divers, etc.) can often detect changes in a lake before more obvious symptoms become visible to all, and therefore, they could play a more prominent role in problem identification than is currently the case.

It is important to involve stakeholders at the earliest, so that the communities involved can agree on a vision for the goals for the lake and what they need to restore in relation to water quantity, water quality, biodiversity, and ecosystem services. For example, anglers may want lots of fish and few submerged and floating plants, boaters and swimmers may also want few aquatic plants, but naturalists will want aquatic plants for the broad biodiversity they support. From a water quality perspective, dense beds of aquatic plants can help reduce the chance of massive cyanobacterial blooms that also impact swimming, boating and fishing, so a balance often needs to be considered. Stakeholder meetings are needed to agree a vision for a restored lake.

Early detection of water quality degradation and the implementation of preventive measures to halt the degradation of healthy ecosystems should have priority in sustainable lake management over reactive management. Once problems become so severe, they become more difficult and costly to repair. In addition to information provided by lake users, mapping stressors at the sub-catchment scale may provide a clearer view of regions where lakes may be at higher risk. Here, E.U. scale data on water use in the catchment or nutrient losses to water at the catchment level can help identify pressures and whether lakes are located in regions with relatively large nutrient losses and diffuse loads or in regions with relatively low nutrient losses. (https://knowledge4policy.ec.europa.eu/visualisation/nutrient-flows-losses-water_en).

In all cases, insight into, and understanding of, the operating mechanisms at the individual lake level are needed to ensure the highest chance for successful protection or restoration of lakes. This insight is

delivered through a system analysis of the lake and its catchment, accounting for specific characteristics that can alter the transfer and retention of nutrients (Figure 13).

A system analysis ideally includes quantifying water and nutrient budgets (preferably phosphorus and nitrogen), determining the biological composition of the lake ecosystem, and assessing the ecosystem services provided by the lake, which will elucidate the main drivers of the water quality degradation and guide the most promising set of measures to reduce, or stop, the cause of it. Evaluating the costs and benefits of potential measures is included. The system analysis aids in selecting the most appropriate measure(s) while simultaneously considering potential drawbacks, and it also provides a basis for doing nothing when it becomes too difficult and/or expensive to restore a specific lake.

The most important characteristic of a lake is that it holds a volume of water. This water can enter and leave a lake in multiple ways. Therefore, the water balance is the first step and with insight into discharges and nutrient concentrations, an estimate of water-related external nutrient load can be derived. Common water inputs are direct precipitation, run-off, inflow via streams, and groundwater inflow, whereas outputs are usually via evaporation, outflowing streams and groundwater (Figure 13). Surface flows (S_{in} , S_{out}) and precipitation (Prp) can be measured; evaporation (EV) is usually calculated; groundwater is more difficult to measure, and its contribution is traditionally estimated from the water balance equation: $\Delta V/\Delta t = S_{in} + G_{in} + Prp - S_{out} - G_{out} - EV$ (see for example, Waajen et al., 2016).

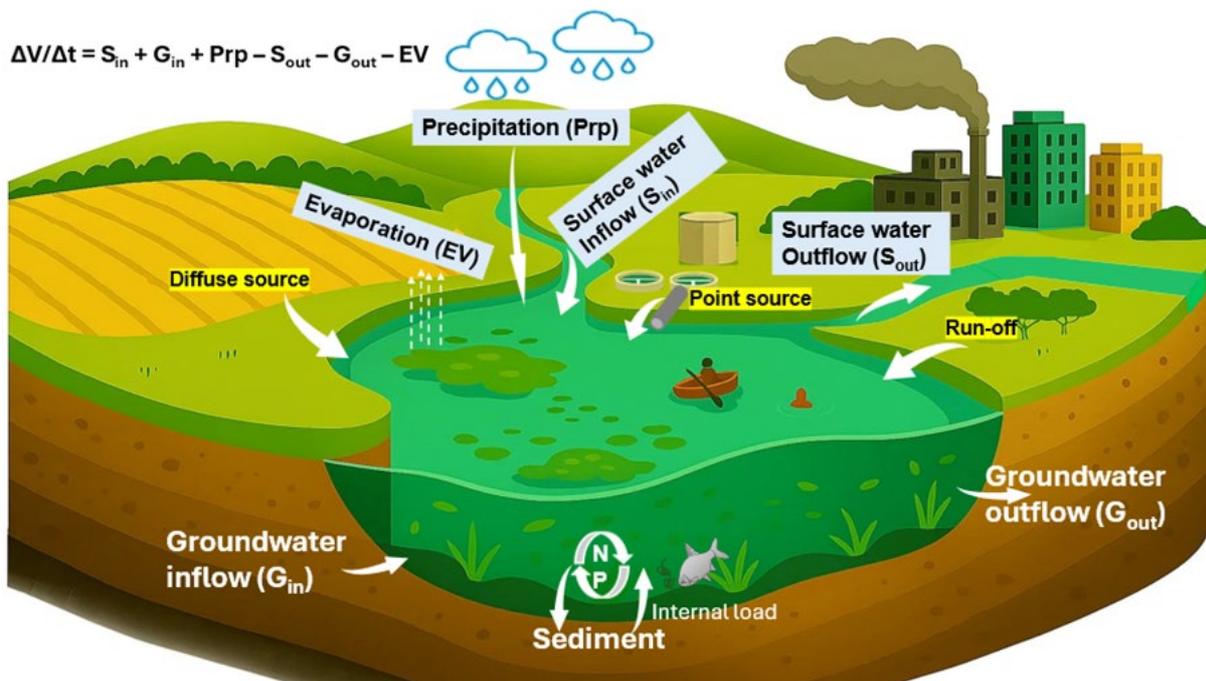


Figure 13. Schematic representation of water inputs and outputs in a lake (water balance), as well as some sources of nutrients (drawing composed using ChatGPT 5.0).

Almost all lakes are connected to groundwater, and the water balance of some lakes is dominated by groundwater flows, making good estimates of groundwater inflow rates increasingly important, particularly in regions where diffuse nutrient loads can be intense. Here, radon (^{222}Rn), as a natural tracer, provides a strong means to quantify the local groundwater flux to lakes (Kluge et al., 2007). The availability of portable ^{222}Rn detectors (RAD7, DurrIDGE Co., Inc.) allows quantification of groundwater inflow rates by solving a ^{222}Rn mass-balance model and, when nutrients are also measured

simultaneously, groundwater nutrient loads. Further, ^{222}Rn detectors can provide continuous monitoring of groundwater inflow at hourly to daily resolution (Gilfedder et al., 2015). Hence, the system analysis could benefit from including more accurate estimates of groundwater nutrient loads. This will also aid in deciding on the implementation of measures to reduce the impact of such diffuse loads whilst catchment reduction, eventually minimising groundwater nutrient input.

Other external, non-water-related nutrient inputs include leaf litter, waterfowl faeces, anglers using bait, humans feeding fish and birds, and dry atmospheric deposition, including pollen, insects, and dust. Most of these sources are usually negligible compared with pollution sources from wastewater, agriculture and industry.

The external water sources bring nutrients into the lake, of which a part will be exported via the outflow, and a part is retained and stored in the sediments of the lake. These nutrients may be periodically recycled from the sediments, a process known as internal loading. Internal loading can be estimated using a mass balance approach but is more accurately determined by taking sediment cores from which the nutrient release is measured. Sequential phosphorus fractionation from sediment samples is also used to get insight into the potential realisable P pool in the sediment.

Use of models to estimate critical nutrient loads can help determine how far loads need to be reduced to achieve improved water quality. Process-based models, such as PCLake or PCLake+, can be used. For water managers, an online metamodel is available (<https://www.witteveenbos.com/digital-solutions/pclake-metamodel>). Based on some basic lake characteristics (sediment type, water depth, fetch, flow rate, light extinction coefficient and the relative surface area of swamp), critical P loads ($\text{mg}/\text{m}^2/\text{day}$) are estimated (Table 11). The metamodel also indicates whether the current P load is above, below or within the critical limits, and what the expected water quality will be (e.g., turbid and rich in algae, clear and rich in vegetation).

The mapping of external and internal nutrient fluxes elucidates the main nutrient sources to the lake and provides guidance on which sources should be targeted to reduce eutrophication-related nuisance. It thus guides towards measures that could be best implemented to reduce nutrient loads.

There is a plethora of measures available, but the majority should be viewed as “effect-oriented” measures, i.e., cleaning up nutrients from lakes, whilst leaving the tap running (Wiering et al. 2020). If external nutrient loads are too high, point sources, such as WWTPs or industrial effluents, can be tackled more easily than diffuse loads. The diffuse loads mostly originate from agricultural activities and, even after policy changes to strongly reduce nutrient use, crop yields, and livestock numbers, there will be long time lags before the effects of reduced nutrient loading become apparent. Nonetheless, there are numerous external (catchment) measures supporting lake protection, as well as in-lake actions that not only reduce nutrient fluxes but also improve resilience to disturbances. An overview of measures is given in Härkönen et al. (2025).

Certain in-lake interventions follow directly from the system analysis (Table 13). For example, if the lake is over-stocked with high biomass of sediment-resuspending fish (bream, carp), fish stock reduction is straightforward to reduce stirring up sediment and plants, thereby increasing water transparency, reducing sediment and nutrient resuspension and giving plants a higher chance to establish. The system analysis will almost always indicate that multiple measures are needed. This can involve combining preventative catchment measures with restorative in-lake solutions, multiple catchment measures or several in-lake measures. An example of combining measures based on a system analysis is given by

FutureLakes’ Innovation site Lake Groote Melanen (<https://futurelakes.eu/innovation-measures/groote-melanen-the-netherlands>). The water quality of Groote Melanen improved greatly when in-lake measures such as fish removal, dredging, capping of peat-rich sediment with sand and an active barrier (lanthanum-modified bentonite), reconstruction of banks, and planting macrophytes were combined with external nutrient-load control. The latter involved the diversion of two inlet streams (Lürling et al. 2024). This example is elaborated below according to the various steps of the system analysis.

Example Groote Melanen

The problem: Cyanobacterial blooms and fish kills. The lake was used for recreation, mostly angling and walking along the shoreline, but suffered from annual cyanobacterial blooms comprised of potentially toxin-producing species, such as *Microcystis* spp., *Dolichospermum* spp., and *Aphanizomenon* spp. and experienced massive fish kills in 2009 and 2010.

The stakeholder meetings: The Province Noord-Brabant had allocated De Groote Melanen the function of nature. The municipality, citizens, and lake users were all on the same page regarding the need to improve water quality. There was strong consensus on the need to minimise the risk of cyanobacterial blooms and fish kills, to promote clear water with vegetation, and to create nature-friendly shorelines to enhance biodiversity. The suggested strong reduction of carp met some resistance from individual anglers, whereas the angling society supported the plan for biomanipulation and changing the fish community from benthic fish to a more diverse community of pike-roach type.

Table 11. Lake characteristics: To get more insight in the lake functioning and structure a monitoring program was started before the intervention to determine lake characteristics:

Characteristic	Value
Inflow, 2 streams (m ³ d ⁻¹)	57.8 (SD ± 114.8); 71.6 (SD ± 195.4)
Groundwater (m ³ d ⁻¹)	124
Outflow, 1 weir (m ³ d ⁻¹)	270.3 (SD ± 946.5).
Surface area (ha)	4.8
Summer flow (mm d ⁻¹)	4.7
Residence time (month)	8
Mean water depth (m)	1.2
Maximum water depth (m)	1.6
Sediment	0.65 m on top of sand and peat
Coverage of submerged plants (%)	0
Fish biomass (kg ha ⁻¹)	268 (78% carp, 5% Prussian carp, 4% bream)
TP (mg L ⁻¹)	0.50 (SD 0.1, n = 34)
Chlorophyll-a (µg L ⁻¹)	54 (SD 53, n = 34)
Cyanobacteria chlorophyll-a (µg L ⁻¹)	33 (SD 47, n = 34)

The water balance (m³ year⁻¹; $\Delta V/\Delta t = 0 = S_{in} + G_{in} + Prp - S_{out} - G_{out} - EV$) was: Precipitation (Prp) on open water (35,000) + inflow from two streams (S_{in}) (42,000) + groundwater seepage (G_{in}) (45,000) = Evaporation from open water (EV) (33,000) + outlet via weir (S_{out}) and residual (G_{out}) 89,000).

Estimation of **critical P loads** was carried out using the PCLake metamodel (Table 12):

Input used:

- Sediment type (situation after restoration): sand
- Mean water depth (situation after restoration): 1.5 m
- Fetch: 300 m (min. setting)
- Flow rate: 4.7 mm d⁻¹
- Extinction coefficient: 0.5 m⁻¹ (default setting)
- Swamp area (8,300 m² planned/47,884 m²): 14.8 % (the swamp area is corresponding a municipal reconstruction plan)

Critical P loads (mg P m⁻² d⁻¹): Turbid to clear water: 1.04

Clear to turbid water: 3.48

Table 12. Estimated and measured **external and internal P loads** (mg P m⁻² d⁻¹) before the restoration:

External P-sources (before restoration)	P loads (mg P m ⁻² d ⁻¹)
Stream 1 (Jankenbergløopje)	0.48
Stream 2 (volkstuintcomplex)	2.09
Groundwater	0.03
Surface run-off	0.60
Water fowl	0.03
Feeding water birds	0.05
Angling bait	0.02
Leaf litter	0.45
Dry and wet deposition	0.02
Total external P-sources	3.77
Internal P-source (before restoration)	
Sediment release	1.90
Total P load	5.67

The P-load to the lake elucidated that the estimated P load (5.67 mg P m⁻² d⁻¹) was almost double the upper critical P load (3.48 mg P m⁻² d⁻¹), and although critical P load estimates come with a ~30–40 % uncertainty, the magnitude of the estimated P load indicated that without P load reduction the lake would always return to a turbid, phytoplankton-dominated state. To increase the likelihood of bringing the lake to the desired clear-water state, a package of measures was designed to reduce internal and external P loads, improve biodiversity, and increase the lake's resilience.

Table 13. The intervention: restoration measures implemented between February 2015 and May 2016.

Measure	Period
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Fish removal: turning net, 325 m seine net, 225 m seine net, electrofishing. All caught fish were released in nearby Lake Binnenschelde	February 26-27, 2015
Suction dredging: sediment layer removed until the original sand or peat layer, in total 29,000 m ³ removed.	April 9 - July 25, 2015.
Diversion of two inflow streams, creating diversion stream bypassing the lake	October - November 2015
Reconstructing shoreline: pruning bushes, removing overhanging vegetation, removing hard revetments, construction of more natural vegetated banks, creating walking paths and accessible angling sites.	October - November 2015
Sand capping using nutrient-poor washed sand: 28 cm layer (13,000 m ³ sand) with an active barrier with 14 tonnes of the P binder Phoslock in the lowest sand layer	November 2015 – January 2016
Water column stripping of P and enhanced P binding using 3200 L poly-aluminium chloride (PAX18 + 25 kg calcium hydroxide as pH buffer) and 13.65 tonnes Phoslock	April 18 – 20, 2016
Planting helophytes and macrophytes with the help of local primary school kids	May 27, 2016

The results: no cyanobacteria blooms since intervention, strongly reduced nutrient concentrations, no fish kills, and gradually expanding macrophyte and helophyte coverage (see Lüring et al., 2024).

6 Beyond this Report – Testing, Demonstration and Application of the Framework

Looking ahead, the continued development of the FutureLakes Prioritisation Framework will focus on deepening collaboration with end-users to ensure that the approach remains practical, scalable, and responsive to real-world restoration needs. A central component of this next phase will be developing a fully tested framework applied at European and national scales, with a focus of illustrating the approach to support development of National Restoration Plans under the NRR. Testing will be carried out for Europe and a few example countries to evaluate data availability at different scales, validate prioritisation approaches and outputs, and assess how well the framework aligns with national policy goals and governance contexts. We will also work closely with the project’s Demonstration Lakes and Associated Regions in Cyprus, Ukraine, and Ireland, specifically to review and refine later stages in the framework for evaluating pressures and system analysis.

Through iterative testing, targeted case studies, and joint evaluation workshops with national authorities, basin managers, and stakeholders, the FutureLakes team will refine the weighting schemes, enhance data integration workflows, and strengthen usability within the eLakes Portal. The team will develop a suite of guidance documents, user instructions, and best-practice examples to support

application of the framework by the wider community, including EU Member States preparing National Restoration Plans under the NRR.

Together, these activities will ensure that the prioritisation methodology becomes a robust, user-driven, and operational tool capable of guiding effective, evidence-based lake restoration across Europe and directly supporting delivery of the EU Nature Restoration Regulation, Water Framework Directive, and broader biodiversity and climate policy objectives.

Finally, the insights and results emerging from this work will inform the FutureLakes Blueprint on Lake Restoration and will supply evidence-based case studies to inform policy makers through the Roadmap for Upscaling Lake Restoration Across Europe.

Annex 1. Applying the FutureLakes Data Portal

The FutureLakes metadatabase (<https://futurelakes.eu/elakes/metadatabase>) lists 100+ datasets that can be used for analyses. The metadatabase helps:

- Understand data scope and availability
- Combine geospatial, biodiversity and socio-economic data
- Upscale analyses from local to global

The metadatabase can be browsed based on the categories below:

1. **Biodiversity:**

1. Habitat condition and protected areas
2. Protected species
3. WFD ecological status

2. **Benefits to society:**

1. Pollution reduction
2. Socio-economic context & benefits
3. Climate regulation

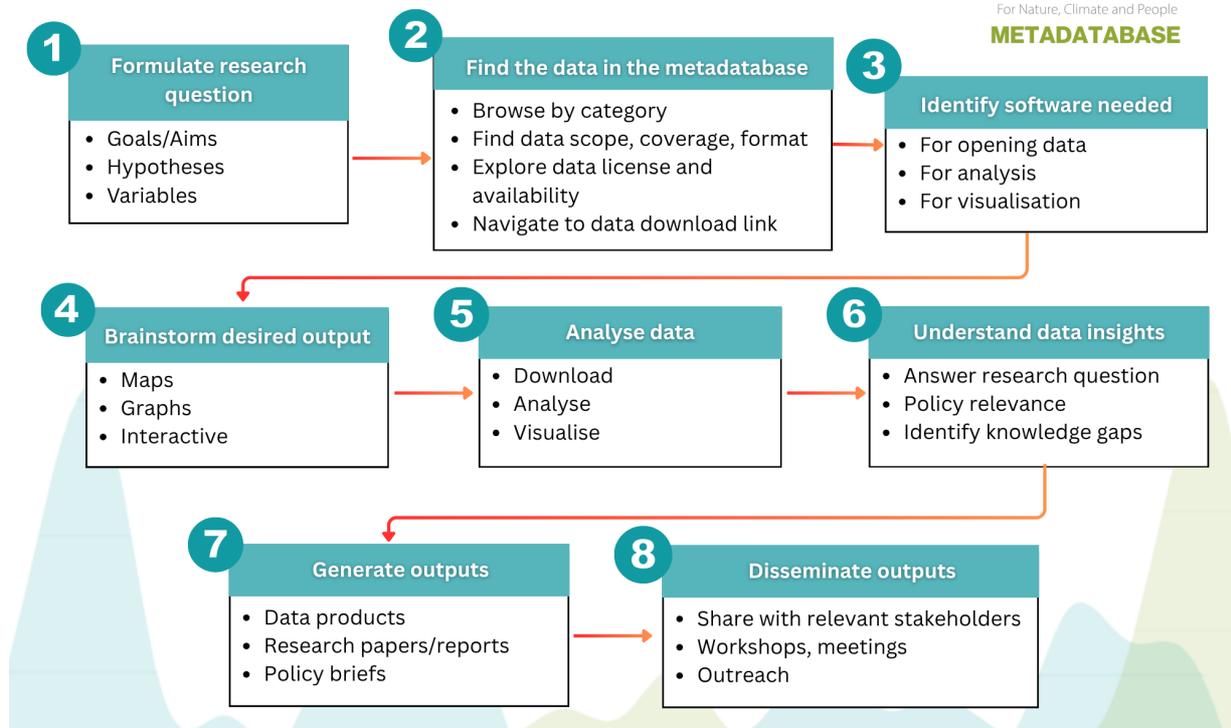
3. **Geospatial:**

1. Boundaries
2. Hydrology
3. Geography

Below, you can find 2 step-by-step examples of how you can use the metadatabase to answer a research question.

How to use the Metadatabase

a step-by-step workflow example guide



1. Biodiversity example

1.1 Formulate your research question:

Where are Red Listed freshwater species hotspots *outside* of Natura 2000 protected areas?

Goal: Identify geographic areas with high concentrations of threatened freshwater species (from the IUCN Red List) that are not covered by Natura 2000 protected areas, to help identify areas for future protection or strengthening conservation efforts in unprotected areas.

1.2 Find the data needed to investigate your question

Dataset	Link in Metadatabase	Description	Format
HydroBASINS	FL2	Vectorized polygon layers that depict sub-basin boundaries at a global scale	shapefile
IUCN Red List of Threatened species	FL35	Freshwater species are mapped to pre-defined lake catchment units called HydroBASINS . N.B individual groups (e.g. crabs, crayfish)	ESRI shp (polygons), csv (points) and csv (hydrobasins level 10)
Natura 2000 protected area	FL9	Lake-rich Natura 2000 sites protected under the European Union’s Habitats Directive.	geopackage

1.3 Identify software needed

- QGIS or ArcGIS: For scoping the data, e.g. spatial overlay.
- Python or R: For filtering, counting species, and identifying unprotected hotspots.
- Excel: For basic summaries if using tabular HydroBASINS data.

1.4 Brainstorm desired outputs

- A map showing catchments by number of threatened freshwater species, overlaid with protected areas.
- A bar chart comparing protected vs. unprotected catchments by species richness.

1.5 Analyse data

- Load data in software of choice
- Use HydroBASINS-linked tables to extract Red Listed freshwater species (VU, EN, CR).
- Count red-listed species per HydroBASINS catchment and weight counts by IUCN category CR>EN>VU.
- Overlay Natura 2000 boundaries with HydroBASINS and identify which catchments fall outside Natura 2000 areas.
- Visualise data in a map: colour catchments by red-list species richness count or weighted “red-list richness” (continuous scale), highlighting those outside Natura 2000.
- Summarise data in a table: List top 10 unprotected hotspots with species names and threat levels. Understand data insights
- Reveals where freshwater biodiversity is most at risk
- Highlights gaps in freshwater biodiversity protection.
- Supports evidence-based expansion of Natura 2000 or other conservation designations.
- Can guide funding and policy decisions for freshwater ecosystem conservation.

1.6 Generate outputs

- Create an interactive web-app, where layers can be selected/unselected and species can be explored by threat level.
- Summarise findings in a research paper/report or policy brief.

1.7 Disseminate outputs

- Results can be shared with relevant freshwater experts, policymakers, and stakeholders via presentations at meetings or workshops.
- Hackathons can be organised for a more in-depth capacity-development experience.
- Insights can inspire outreach events, focused on species most at threat.

2. GHG example

2.1 Formulate your research question:

What were the methane emissions from Dutch lakes from 2009-2024 based on chlorophyll-a (chl-a) data?

Goal: Use a Bayesian model to predict methane emissions from Dutch lakes with the goal of better understanding how lake restoration could affect methane emissions by reducing chl-a concentrations.

2.2 Find the data needed to investigate your question

Dataset	Link in Metadatabase	Description	Format
HydroLakes	FL1	Shoreline polygons of all global lakes with a surface area of at least 10 ha and four points	Shapefile and geodatabase
Dutch Water Framework Directive lake data	FL52	Chl-a values (ug/L) measured from Dutch lakes	csv or json (using API)
EU WFD chl-a water quality boundaries	To be made available in 2026	Chl-a boundaries in ug/L that determine water quality status (i.e. good, moderate, poor) for different EU countries.	PDF
LLUCUF Inventories	To be made available in 2026	Current LLUCUF inventories for different EU countries.	Web page
Bayesian model for predicting lake methane emissions from chlorophyll-a data	To be made available in 2026	A Bayesian model that predicts Total, Ebuillitive and Diffusive methane emissions from chlorophyll-a values and lake surface area.	.R code

2.3 Identify software needed

- Python, R or QGIS: For processing the HydroLakes and Dutch lake csv files so they can be read by the Bayesian model code.
- Translation service such as Google Translate or a Large Language Model (e.g. ChatGPT or similar) for translating the column names of the Dutch data.
- R: For running the Bayesian model.

2.4 Brainstorm desired outputs

- A map showing Dutch lakes marked by scatter points scaled in size by emission releases.
- Bar charts showing the predicted current methane emissions from Dutch lakes and how they might change based on reductions in chlorophyll-a concentrations.

2.5 Analyse data

- Load data in software of choice
- The chlorophyll-a data needs to be translated, loaded into Python, QGIS or R, and filtered to the columns of interest: lake ID, sampling date, latitude, longitude and chl-a value (ug/L).
- Perform a spatial merge of the HydroLakes Data with the Dutch chl-a data to confirm which sampling points are in lakes of at least 10 ha, and then to calculate the surface area of these lakes.
- The resulting dataframe should have the following columns: lake ID, sampling date, latitude, longitude, chl-a value (ug/L) and lake area (km²).
- This will require reprojecting the Dutch data to the same Co-ordinate Reference System (CRS) as the HydroLakes Data.
- For each lake ID take the mean chl-a values across the entire period of record (2009-2024) to produce one concentration per lake.
- Should you include lakes that were only sampled in a single year, or a single season? Write a couple of lines of text to justify your choice in which lakes to include in the mean chl-a calculation. Save the resulting dataframe as a .csv file.
- Load the average chl-a dataframe into R, ensure the column names of the dataframe and the structure matches those set out as requirements in the documentation for the Bayesian model.
- Run the Bayesian model using the supplied code, replacing the example dataframe with the average chl-a data.
- Save the model predictions as a .csv file to analyse them outside of R, or continue working in R.
- Map: create a map of the Netherlands with each lake signified by a scatter point, scale the size of the scatter point by the predicted Total methane emission from the model. How does the geographic distribution of methane emissions from Dutch lakes look? Consider normalising the prediction by the lake area, to get a methane prediction per m². How does that affect the interpretation of the map?
- Bar Charts: create bar charts to show what the current yearly ebullitive, diffusive and total methane emissions from Danish lakes. Use the 95% credible interval supplied by the Bayesian model to add error bars to the bar charts. You could include the yearly LLUCUF methane inventories for the Netherlands as a horizontal dotted line on the bar chart.

2.6 Understand data insights

- Reveals the benefits of lake restoration in terms of reducing methane emissions.
- Highlights gaps in the current LLULUF methane inventories for the Netherlands, and which lakes are hotspots of methane emissions.
- Supports evidence-based lake restoration measures.
- Can guide future lake restoration and monitoring by regulatory agencies.

2.7 Generate outputs

- Create an interactive web-app, where methane emissions from Danish lakes can be visualised under differing investment and chl-a reduction scenarios.
- Summarise findings in a research paper/report or policy brief.

2.8 Disseminate outputs

- Results can be shared with relevant freshwater experts, policymakers, and stakeholders via presentations at meetings or workshops.
- Hackathons can be organised to apply the modelling method to other countries or regions.

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