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MS25 Concept to integrate use cases based on the Marine Strategy Framework Directive and the Water Framework Directive

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Summary

This milestone MS25 report presents the conceptual and technical design for integrating use cases of the Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD) as portable customized Biodiversity Analysis Tools (BATs) based on a common underlying infrastructure services platform. The platform provides the shared digital infrastructure supporting data access, analysis, and collaboration across disciplines, while BATs represent specific, purpose-built analytical workspaces,

tailored to defined scientific or policy use cases related to the WFD and MSFD. Based on the EU Regulation 2000/60/EC (WFD) and the EU Regulation 2008/56/EC (MSFD), it focuses on key aspects (environmental status assessment, temporal trends) that can be addressed using spatiotemporal data and modelling. The framework uses long-term monitoring data across freshwater and marine realms combined with environmental predictors to generate outputs such as trend analyses of freshwater and marine communities and their associated environmental drivers, as well as trends in environmental status. The BAT outputs from these specific use cases support monitoring, reporting, and management at both the Member State and EU level, to link legal obligations and stakeholder needs with data, workflows, and underlying computing and storage capacities in a reproducible, policy-relevant manner.

List of abbreviations

BAT	Biodiversity Analysis Tool
EEA	European Environmental Agency
EMODnet	European Marine Observation and Data Network
EQR	Ecological Quality Ratio
EU	European Union
GBIF	Global Biodiversity Information Facility
GES	Good Environmental Status
GRIIS	Global Register of Introduced and Invasive Species
IUCN	International Union for Conservation of Nature
MSFD	Marine Strategy Framework Directive
NGOs	Non-Governmental Organizations
OBIS	Ocean Biodiversity Information System
SDM	Species distribution model
WFD	Water Framework Directive

1. Conceptual framework

1.1. Purpose

The overarching goal of this milestone is to define a conceptual and technical framework for integrating use cases that support the Water Framework Directive (WFD) and the Marine Strategy Framework Directive into dedicated Biodiversity Assessment Tools (BATs). These BATs will facilitate coherent, reproducible and harmonized assessments of ecological quality, environmental status and long-term trends across European freshwater and marine ecosystems.

Each BAT provides analytical platforms to quantify long-term changes in community metrics of target biological organisms and identify environmental drivers of trends in degradation and recovery. The WFD BATs will focus on evaluating trends in Ecological Quality Ratios (EQRs) of freshwater ecosystems and associated changes in community metrics, such as richness, functional composition, and turnover of key taxonomic groups (e.g., macrophytes, benthic macroinvertebrates and fish). The MSFD BATs will focus on the evaluation of Good Environmental Status (GES) indicators and core ecosystem components (e.g., phytoplankton, macroalgae and phanerogames, benthic invertebrates, fishes, birds, marine mammals and reptiles) across various descriptors (e.g., biodiversity, eutrophication and physical pressure).

These efforts will deliver interoperable and standardized datasets that enable Member States to meet EU reporting requirements by providing harmonized inputs for coordinated assessments of ecological quality, environmental status, pressures, monitoring programs and measures. These data also underpin spatial planning, ecosystem-based management and evidence-informed policy development.

1.2. Scope

- Realms: Freshwater and marine ecosystems
- Spatial scales: Regional (incl. Natura 2000 sites, river basins), national, EU-wide assessments
- Biological levels: Species & community

Link to EU regulation on WFD:
https://environment.ec.europa.eu/topics/water/water-framework-directive_en
https://eur-lex.europa.eu/eli/dir/2000/60/oj

Link to EU regulation on MSFD:
https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32008L0056

1.3. Introduction

Water Framework Directive

Freshwater ecosystems are among the most threatened on the planet, yet they provide essential ecosystem services that are critical to human well-being, biodiversity, and ecosystem functioning (Vári et al. 2021). Climate change, land-use modification, resource extraction, and increasing pollution are placing unprecedented pressure on freshwater systems, threatening their ability to continue supplying clean water, food production, hydropower, transportation, and cultural benefits. The Water Framework Directive (WFD) aims to ensure that freshwater resources remain sufficient to meet human needs while safeguarding freshwater biodiversity and ecological integrity. The impacts of global change on freshwater ecosystems are multidimensional, spanning environmental, economic, and human health domains.

Environmental impacts

- Altered freshwater biodiversity and species distributions (Haase et al., 2023; Su et al., 2021)
- Disrupted ecological functions and food web stability (Ficke et al., 2006)
- Reduced capacity to support ecosystem services (e.g., fisheries, nutrient cycling) (Dodds et al.,

2013 , Ficke et al., 2006)

Economic impacts

- Increased costs and risks associated with reliance on clean water for food production, hydropower, and industry (du Plessis, 2022)
- Increased costs of water treatment and infrastructure adaptation (du Plessis, 2022)
- Impacts on inland/freshwater fisheries (Ficke et al., 2006; Harrod et al., 2019) Human health impacts
- Threats to drinking water quality from pollutants, pathogens, and harmful algal blooms (du Plessis, 2022)
- Increased water insecurity exacerbated by climate extremes (Stringer et al., 2021) ● Elevated risks to communities reliant on freshwater for subsistence and cultural practices (Lynch et al., 2024)

Marine Strategy Framework Directive

Marine ecosystems provide essential services, including food provisioning, climate regulation, coastal protection, nutrient cycling, and cultural value, yet they are increasingly threatened by climate change, pollution, habitat degradation, overfishing, and ocean acidification. These pressures undermine the ability of marine systems to maintain biodiversity and support human well-being. The Marine Strategy Framework Directive (MSFD) aims to achieve Good Environmental Status (GES) of EU marine waters by protecting ecosystems, enabling sustainable resource use, and safeguarding the services they provide. As with freshwater systems, the impacts of global change on marine ecosystems span environmental, economic, and human health dimensions

Environmental impacts

- Marine biodiversity loss (Worm & Lotze, 2021)
- Habitat degradation (e.g., seagrass loss, coral bleaching (Bekkby et al., 2017))
- Disrupted food web structure and stability (du Pontavice et al., 2021)
- Harmful algal blooms and hypoxic dead zones (Diaz and Rosenberg, 2008)

Economic impacts

- Reduced fishery productivity (Free et al., 2019)
- Impacts on maritime industries (tourism, shipping, coastal infrastructure)
- Costs of coastal protection from sea-level rise and storms

Human health impacts

- Contaminants in seafood (heavy metals, microplastics) (Thomsen et al., 2021) ● Pathogens and harmful algal bloom toxins affecting coastal communities (Dybal et al., 2008) ● Climate-driven risks (heatwaves (Smith et al., 2021), coastal flooding, waterborne diseases

Together, the WFD and the MSFD provide complementary governance frameworks aimed at securing the ecological integrity, service provisioning, and societal benefits of Europe's freshwater and marine systems under accelerating global change.

1.4. Regulatory background

Water Framework Directive

The WFD was established in 2000 and is the primary legislation for water protection in Europe. It applies to inland, transitional and coastal surface waters as well as groundwaters to ensure an integrated approach to water management that respects the integrity of whole ecosystems, including by regulating individual pollutants and setting corresponding regulatory standards. The objectives of the WFD require Member states to use their River Basin Management Plans (RBMPs) and Programmes of Measures (PoMs) to protect and, where necessary, restore water bodies in order to reach good status, and to prevent deterioration. Good status means both good chemical and good ecological status. The monitoring and research needs to support the WFD will be defined by stakeholders. Preliminary stakeholder priorities are as follows:

Stakeholders *(will be revised based on stakeholders' inputs; WP1)*

- Accessible visualizations of spatial and temporal changes in community metrics.
- Analytic support for river basin planning and decision-making.
- Tools for public engagement and awareness.

Directives

- Monitoring long-term ecological quality dynamics and status changes.
- Tracking changes in community indicators of aquatic degradation over time.
- Identifying sites/rivers at risk of degradation or in potential recovery.
- Providing consistent, harmonized data for EU reporting and assessment.
- Supporting evidence-based planning, restoration, and protection.

Marine Strategy Framework Directive

The EU adopted the MSFD in 2008 to maintain clean, healthy, productive and resilient marine ecosystems while securing a more sustainable use of marine resources. The Directive builds on existing EU legislation (e.g., the WFD, the Birds Directive, the Habitats Directive) and covers specific elements of the marine environment not addressed in other policies. The Directive requires Member States to develop national marine strategies in order to achieve, or maintain where it exists, Good Environmental Status (GES). The marine strategies comprise regular assessments of the marine environment, setting objectives and targets, establishing monitoring programmes and putting in place measures to improve the state of marine waters. The measures should also include spatial protection measures, such as a coherent and representative network of marine protected areas. All these actions must be done in close coordination with neighbouring countries at regional sea level.

To help EU countries achieve a GES, the MSFD sets out 11 illustrative qualitative descriptors (see here for details), which describe key aspects of marine ecosystem structure, function, and pressures. The monitoring and research needs to support the MSFD will be defined by stakeholders. Preliminary stakeholder priorities are as follows:

Stakeholders *(will be revised based on stakeholders' inputs; WP1)*

- Accessible visualization to explore spatial and temporal variations in GES indicators and key ecosystem components.
- Analytic support for marine policy implementation, conservation planning, and adaptive management strategies.
- Interactive and accessible interfaces for communication, outreach, and stakeholder awareness regarding marine environmental conditions and trends.

Directive

- Monitoring and evaluation of marine environmental status in line with MSFD descriptors (e.g. biodiversity, eutrophication).
- Detection and assessment of changes of target biological organisms indicative of degradation processes.
- Identification of marine regions, subregions, or ecological components at risk of failing to achieve or maintain GES.
- Provision of harmonized, quality-assured, and interoperable datasets to support EU and Regional Sea Convention reporting requirements.
- Contribution to integrated, science-based approaches for marine ecosystem management, restoration, and long-term protection in accordance with the MSFD's ecosystem-based framework.

The MSFD mandated that GES should have been achieved by 2020. The findings of the evaluation report published in March 2025 showed the Directive has been successful in setting up a comprehensive

framework for protecting EU marine waters and has also generated data and knowledge that have led to a better understanding of our seas and oceans. However, GES has not been achieved by Member States across all descriptors in all marine regions. This means that while there was some progress, for example, in reducing marine litter reduction, marine biodiversity generally continues to decline, while pollution overall is still at levels that cause harm to marine life. This highlights the continued need for monitoring, data integration and data analysis to support the objectives of the MSFD.

1.5. Related initiatives

WISE Freshwater (https://water.europa.eu/freshwater) provides information and data on the state of Europe's rivers, lakes, groundwaters, the pressures affecting them, and the measures and actions taken to protect and conserve the aquatic environment. Specifically, the section dedicated to the WFD presents the results on the status and pressures on groundwater and surface waters in Europe, based on data reported electronically to EEA for River Basin Management Plans. The results provide an overview at EU, Member State and River Basin District level. The platform features an interactive WISE Freshwater Map Viewer https://discomap.eea.europa.eu/wise-freshwaterviewer/, allowing users to visually explore spatial data on water bodies, river basin districts, and monitoring sites across Europe.

1.6. Potential integrated use cases across realms

Temporal trends

- Assess the temporal trends of community metrics (e.g., taxa richness & diversity) for target biological organisms and taxonomic groups relevant to the WFD and MSFD and ecological quality indices (eg., EQRs for WFD, GES for MSFD) at the levels of different spatial units (Natura 2000 sites, river basins, national, EU-wide, marine regions). Trends can be calculated based on abundance time series data (where available) or "raw" occurrence data (accounting for spatiotemporal trends in sampling effort), depending on data availability.
- Assessment of climate change impact on aquatic biodiversity and ecological health
- Model future climate change impact on community metrics and ecological quality based on available monitoring datasets.

1.7. Implementation

The potential BATs will be implemented using the R programming language, which provides extensive libraries for biodiversity informatics, spatial analysis, and species distribution modeling. User-facing components will be delivered through interactive dashboards, offering an intuitive graphical user interface (GUI).

The design of the BAT will strictly follow the FAIR principles (Findable, Accessible, Interoperable, Reusable) to ensure long-term scientific and policy relevance:

- Rich and standardized metadata: All datasets and workflows will include detailed provenance documentation, specifying data source, date, version, and spatial/temporal resolution.

- Data governance and quality assessments: Built-in checks will ensure data consistency and reliability by adhering to data standards of authoritative systems (e.g., OBIS, and GBIF), where such standards are available and applicable.
- Reproducible workflows: Version-controlled scripts and containerized environments (e.g., via Docker) will enable fully repeatable and auditable analyses, supporting trustworthiness for regulatory reporting. A workflow engine will centralize workflow runs and act as a compute backend to the BAT.

Additionally, the BATs, based on different use cases to support the WFD and MSFD, will be scalable, from individual Natura 2000 sites to EU-wide analyses, and interoperable with existing EU infrastructures such as GBIF, and Copernicus. This ensures that outputs can be directly used for both regulatory compliance and stakeholder decision support.

1.8. Data resources

Species occurrence data

- GBIF and OBIS: Occurrence records for species relevant to MSFD and WFD.

Biodiversity and abundance time-series data

Freshwater

- TREAM dataset (https://www.nature.com/articles/s41597-024-03445-3)
- RivFishTIME dataset (https://onlinelibrary.wiley.com/doi/full/10.1111/geb.13210)
- BioTIME dataset (https://onlinelibrary.wiley.com/doi/10.1111/geb.70003)

Marine

- **EMODnet Biology** (https://emodnet.ec.europa.eu/en/biology)
- BioTIME dataset (https://onlinelibrary.wiley.com/doi/10.1111/geb.70003)

Environmental predictor data

Freshwater

- CHELSA Bioclimatic variables
- CORINE land cover/use data
- Environment90m
- Hydrography90m
- Other realms/taxon-specific environmental factors

Marine

- Bio-ORACLE v2.2 (https://www.bio-oracle.org/downloads-to-email-v2.php?version=2_2) and MARSPEC (https://marspec.weebly.com/)
- EMODnet Seabed Habitats (EMODnet Seabed Habitats), Chemistry (https://emodnet.ec.europa.eu/en/chemistry) and Physics (https://emodnet.ec.europa.eu/en/physics)
- Copernicus Marine Service (CMEMS - https://marine.copernicus.eu/)

2. Design of a Biodiversity Analysis Tools (BAT)

2.1. BAT design methodology

Fig. 1 illustrates the conceptual framework used for defining the BATs, focused on use cases to support the WFD and MSFD (Oeser, 2025). The design process begins by defining monitoring requirements based on input from relevant stakeholders. In detail, stakeholder input will be gathered through co-design workshops, for example, in the form of user stories, and will inform workflow design, user interfaces, and data presentation to ensure the BATs are practical, user-friendly, and aligned with end-user needs. They will be incorporated iteratively throughout the design and prototyping phases to refine outputs and confirm usability. Based on the identified monitoring needs, we will design multiple BATs addressing the monitoring and assessment of marine ecosystem status under the MSFD and for monitoring freshwater ecological quality under the WFD. This requires the input of multiple work packages of BMD and thus should be a collaborative process. To design specific analyses in the BAT, we need to define four conceptual key components:

- Task: Short description of the specific monitoring task/question the BAT addresses. These tasks are derived from monitoring needs defined based on stakeholder requirements (e.g., based on user stories) and directives. [WP1] [WP5]
- Data: Description of relevant required and available datasets. [WP2] [WP5]
- Methods: Description of data analysis and modeling methods. [WP5]
- Outputs: Description of outputs (required/provided) and their formatting. [WP1] [WP5]

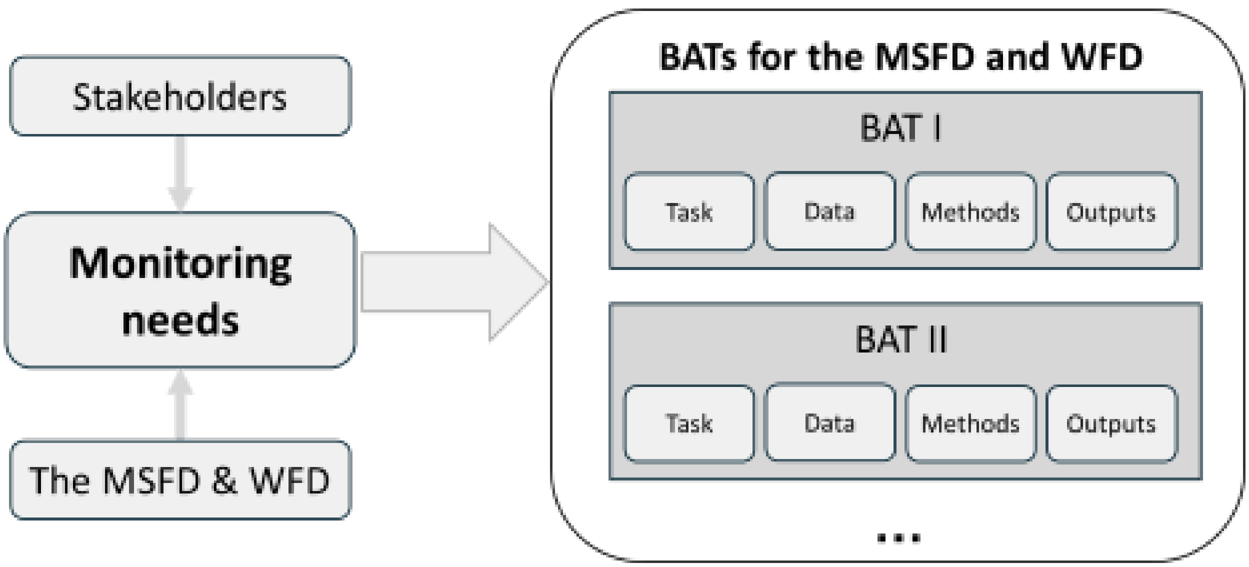

Figure 1: Conceptual representation of the BAT design workflow. The BAT is designed to integrate multiple analyses for use cases, based on monitoring needs.

The complete workflow as well as model parametrisation will be documented in a FAIR way, following the protocol suggested by Zurell et al. (2020). While this is specifically for species distribution models, we will adapt the respective parts also for temporal analyses.

2.2. BAT list

BATs correspond to specific MSFD and WFD use cases across freshwater and marine realms. The tables summarize the relevant task, data, methods, outputs, and key issues for each realm. Specific analyses for each BAT will be co-designed with stakeholder communities (WP1).

Table 1: BAT 1 for assessing long-term changes in freshwater community metrics relevant to WFD

Task	Assess long-term changes in community metrics relevant to WFD, determine the factors driving their variations and associated changes in ecological quality.
Data	Freshwater biodiversity data: Harmonised time-series data of European freshwater invertebrates https://www.nature.com/articles/s41597-024-03445-3 Additional harmonized time-series datasets on freshwater taxa can be obtained through the Synthesis Center on Freshwater Biodiversity Change in Europe at SGN (https://www.senckenberg.de/en/synthesis-center-on-freshwater-biodiversity-ch ange-in-europe/). Predictor data: ● CHELSA Bioclim ● Land cover/use ● Elevation ● Hydrographic data (https://hydrography.org/hydrography90m/hydrography90m_laye rs) ● River basin and subcatchment ● Flow accumulation ● Stream slope ● Stream order ● Stream power and compound topographic index ● **Environment90m dataset** - contains harmonized data of the above predictors by subcatchment in table format (txt) https://hydrography.org/environment90m/environment90m_laye rs) ● EQR data to evaluate trends in ecological quality ● Other factors: Human footprint index or settlement index The selection of specific datasets depends on their integration in the BMD data catalogue.

Methods	• Temporal trend detection using robust regression or mann-kendall test. • Identification of drivers of trends using linear mixed effect models or generalized additive mixed models.
Outputs	• Site-level trend map: A spatial map of Europe displaying temporal trends at each monitoring site (based on slopes or S statistics). • Regional trend summary: Plots illustrating trend estimates (with 95% confidence intervals) for community metrics aggregated by Member State or river basin. • Driver effect visualizations: Plots showing estimated effects (with 95% confidence intervals) of predictors on temporal trends.
Issues	Variability in sampling frequency across sites and countries may reduce temporal resolution. Differences in monitoring start and end years can complicate consistent trend analysis.

Table 2: BAT 2 for assessing long-term changes in target marine organisms relevant to MSFD

Task	Assess long-term changes in community metrics of target biological organisms relevant to MSFD and determine the factors driving their variations.
Data	Marine biodiversity data: • **GBIF** records of all marine organisms; • **OBIS** (Ocean Biodiversity Information System; https://obis.org) for global marine organisms observations; • **EMODnet Biology** (https://emodnet.ec.europa.eu/en/biology) for harmonized biological datasets across European marine regions; • **BioTIME** (https://onlinelibrary.wiley.com/doi/10.1111/geb.70003). Predictor data: • **Bio-ORACLE v2.2** (https://www.bio-oracle.org/downloads-to-email-v2.php?version=2_2) and **MARSPEC** (https://marspec.weebly.com/) datasets for marine environmental variables (e.g. sea surface temperature, salinity, chlorophyll-a, current velocity, dissolved oxygen, pH); • **EMODnet Seabed Habitats** (EMODnet Seabed Habitats) for benthic substrate type, depth zones, and habitat classification; • **EMODnet Chemistry** marine chemical data (https://emodnet.ec.europa.eu/en/chemistry);

	● **EMODnet Physics** in situ ocean physics time-series data and vertical profiles (https://emodnet.ec.europa.eu/en/physics); ● **Copernicus Marine Service** (CMEMS - https://marine.copernicus.eu/) for physical and biogeochemical parameters at high spatial and temporal resolution.
Methods	● Temporal trend detection using robust regression or mann-kendall test. ● Identification of drivers of trends using linear mixed effect models or generalized additive mixed models.
Outputs	● Site-level trend map: A spatial map of Marine regions displaying temporal trends (based on slopes or S statistics). ● Regional trend summary: Plots illustrating trend estimates (with 95% confidence intervals) for community metrics aggregated by Marine region. ● Driver effect visualizations: Plots showing estimated effects (with 95% confidence intervals) of predictors on temporal trends.
Issues	● Variability in sampling frequency across sites and countries may reduce temporal resolution. ● Differences in monitoring start and end years can complicate consistent trend analysis.

3. Technical implementation

Below, we describe the analytical approaches that will be packaged within the BATs to examine environmental drivers of temporal trends in both freshwater and marine communities. The BATs will be accessible to users through interactive user interfaces, which will be co-developed through an iterative process with stakeholders (WP1). Each step included in the BAT analysis pipeline will be defined in a research object crate (RO-Crate) to align with FAIR principles. The analyses are based on currently available taxonomic biodiversity data but are flexible to adapt to additional biodiversity data (e.g., operational taxonomic units (OTUs) from eDNA) collected through high-throughput monitoring efforts.

3.1. Temporal analyses with abundance data

For use cases where sufficient data on community composition and associated abundance are available, the analysis of temporal trends can be structured across three spatial scales using available monitoring datasets (Sinclair et al., 2024). At each scale, trends in biodiversity metrics such as taxa richness, diversity (e.g., Shannon-Weiner diversity, functional diversity) and abundance can be assessed.

- Site scale: Examination of local scale variability in trends.
- Country scale: Evaluation of country-scale variability in these trends.
- Continental scale: Assessment of overall temporal trends at continental scale .

To quantify continental-scale changes in aquatic communities, temporal trends in richness and diversity can be modelled using Generalized Additive Mixed Models (GAMMs). This approach is suitable for capturing potential nonlinear temporal patterns. The model structure should be designed to ensure robust results by accounting for key sources of variance. This can include incorporating a random slope and intercept for countries to address differences in national sampling methodologies and effort, as well as random intercepts for sampling year and month to control for temporal non-independence. A first-order autoregressive (AR1) structure may also be incorporated to account for temporal autocorrelation at repeatedly sampled sites, while spatial autocorrelation will be formally evaluated.

This analytical framework can subsequently be applied to investigate country-scale trends. This phase would focus on countries with robust monitoring datasets, for instance, those containing a minimum of ten monitoring sites, to ensure model reliability (Sinclair et al., 2024). Temporal trends in richness and diversity within these selected countries can then be modelled using GAMMs.

At the site scale, temporal trends can be quantified using the slopes of community metrics, calculated via robust regression. This method reduces the influence of outliers in the first and last years of time series, yielding more reliable trend estimates. These slope estimates can subsequently serve as the response variable in analyses aimed at identifying drivers of community change (Haase et al., 2023).

An alternative meta-analytic approach, following the methodology of Pilotta et al. (2020), may be implemented to synthesize trends across all three spatial scales. This framework consists of two key steps. First, non-parametric Mann-Kendall tests would be applied to calculate S-statistics (representing trend direction and strength) and their variances for each individual site. Second, these site-level trends would be synthesized using random-effects meta-analysis models. These models would use the S-statistics as effect sizes, weighted by their inverse variances to grant more influence to precisely estimated site trends. This synthesis, performed using the rma function from the metafor package in R, would yield overall estimates of trend direction and significance for Europe and for individual countries. A meta-analytic trend can be considered statistically significant where its 95% confidence interval does not contain zero.

3.2. Temporal analyses with occurrence data

Without systematically collected data on species abundance, which may occur in some instances for these use cases, approaches that robustly estimate population trends are limited. A robust approach for opportunistically sampled presence-only data (e.g., corresponding to most data available via GBIF, including eDNA data) are occupancy models. While occupancy models require so-called detection histories containing presence-absence data collected through repeated visits to a set of study sites (e.g., collected through surveys), opportunistic occurrence data can be aggregated into detection histories for their use in occupancy models (Isaac et al., 2014). Occupancy models employ a hierarchical modeling approach to separately model species occupancy (presence/absence) and the observation process (detection/non-detection). In the context of opportunistic data, non-detections can be inferred from visits to a site (e.g., pixel in a raster grid) without the target species being detected, while the length of species lists compiled by observers (“list length”) can be used as a proxy for sampling effort. For details on the implementation of occupancy models for opportunistic data, see, for example: Kéry et al 2010], van Strien et al 2013, Dennis et al 2017. In R, occupancy models can be fit, for example, using the unmarked package (https://cran.r-project.org/web/packages/unmarked/index.html).

A second robust approach for analyzing temporal trends based on opportunistic occurrence data is the Frescalo method (Goury, 2025). Instead of the site-level, Frescalo operates at a broader, neighborhood scale (typically around 10-100 km size) to correct for uneven recording effort. Its core principle is local frequency scaling, which adjusts the observed frequency of a species based on how well-recorded a given area and time period were, using other species as a reference. For details on the implementation of the Frescalo method for unstructured data, see Goury et al 2025. In R, the Frescalo method can be implemented using the sparta package (https://github.com/BiologicalRecordsCentre/sparta).

Finally, trend indices could be generated by setting occurrence record numbers in relation to indicators of sampling effort (for example, number of records for target-group taxon, or number of observers), could be calculated (Knape et al., 2022). In addition, a resampling-based abundance index could be calculated (Zbinden et al., 2014).

The three described approaches differ in their levels of data availability requirements (occupancy models > Frescalo > trend indices) and which of them can be used in BATs thus depends on data availability for different regions/taxa. For comparability and consistency, using the same approaches across target IAS and sites (Natura2000 sites and/or Member states) would be desirable. Which of these approaches will be feasible will depend on the spatiotemporal availability of occurrence records for species, as well as for reference species used to infer sampling effort.

3.3. Drivers of change

To investigate and identify environmental drivers of trends in community metrics, developed from either abundance data or occurrence data, Linear Mixed-Effects models (LME) or GAMMs can be applied. Site-level trends, represented either slope estimates or S-statistics, would serve as the response variable. Fixed effects (drivers) would include environmental variables such as climate, land use, and hydrotopography. Random effects, such as ecoregion, country, marine regions or river basin, can be incorporated to account for broader scale spatial structure not explained by predictors. Prior to model fitting, a multicollinearity assessment will be conducted using Variance Inflation Factors (VIF) with a predefined threshold (e.g., VIF > 5) and/or analysis of pairwise correlation coefficients to identify and address highly correlated variables.

3.4 User interface and outputs

The analysis approaches described above will be packaged into BATs and accessible to users through interactive user interfaces. User interfaces for the BATs should be accessible to non-technical users and provide simple options for selecting the relevant spatial units (e.g., river basins, Natura2000 sites, Member States, marine sub-regions) and biological groups of interest. These interfaces should rely on intuitive components such as searchable dropdown menus and predefined selections linked to EU- or national-level reporting units. Given the diverse user base, the analytical workflows should run in a largely automated manner, requiring minimal user input and no manual parameterization.

Outputs are expected to include both visual and downloadable products that communicate trends in community metrics, biodiversity indicators, ecological quality (EQRs), and environmental status (GES components). Visual outputs can be displayed through the visualization tools developed in Work Package 4 and may include:

- Interactive maps of sampling locations, spatial units, or indicator values
- Time-series plots showing trends in community metrics, diversity indices, and ecological quality indicators
- Trend summaries for selected descriptors or biological groups

Downloadable outputs can be provided via the Single Access Point (SAP) developed in Work Package 6 and may include:

- Tables summarizing biodiversity and community metrics over time
- Tabular outputs of ecological quality ratios (EQRs), GES indicators, and associated trends
- Extracted environmental and pressure datasets used in analyses
- Summary statistics, model results (if relevant), and uncertainty estimates

The BATs should also include clear, non-technical explanations of the implemented analyses, including descriptions of indicators, data sources, and methodological limitations. Uncertainties associated with trend assessments—such as data gaps, sampling inconsistencies, indicator variability, or driver attribution—should be communicated transparently so that users can correctly interpret outputs in the context of WFD and MSFD reporting requirements.

4. Conclusion and future steps

This MS25 presents the conceptual framework for integrating Water Framework Directive and Marine Strategy Framework Directive use cases into Biodiversity Analysis Tools (BATs). By aligning regulatory requirements under the EU Regulation 2000/60/EC (WFD) and the EU Regulation 2008/56/EC (MSFD) with standardized data, workflows, and outputs, the proposed BATs provide a reproducible and scalable solution for monitoring, reporting, and management.

Stakeholder feedback will play a central role in refining the BATs. Input from regulatory authorities, site managers, and NGOs will inform user interfaces, workflow design, and data presentation, ensuring the BATs are practical, user-friendly, and directly supportive of decision-making.

The next steps include workflow prototyping, stakeholder co-design workshops, and Single Access Point integration, in line with deliverable D5.2 and D5.3. By involving stakeholders throughout these phases, we can ensure the BAT not only meets regulatory requirements but also genuinely addresses the needs of the end-users.

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