MARCO-BOLO
STRENGTHENING BIODIVERSITY OBSERVATION IN SUPPORT OF DECISION MAKING

Deliverable 3.4

Report on effects of existing and future terrestrial and freshwater conservation areas on coastal and marine biodiversity

Version 1.2

30.01.2026

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Funded by the European Union

Funded by the European Union under the Horizon Europe Programme, Grant Agreement No. 101082021 (MARCO-BOLO). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

UK participants in MARCO-BOLO are supported by the UKRI's Horizon Europe Guarantee under the Grant No. 10068180 (MS); No. 10063994

UK Research and Innovation

Document Information

Grant Agreement	101082021
Project Acronym	MARCO-BOLO
Project Title	MARine COastal BiOdiversity Long-term Observations

Deliverable Number	D3.4
Work Package Number	WP3
Deliverable Title	Effects of Existing and Future Terrestrial and Freshwater Conservation Areas on Coastal and Marine Biodiversity and Ecosystem Services
Lead Beneficiary	UB, 14
Author(s)	Adamescu (UB), Arhire (UB)
Due Date	30.11.2025
Submission Date	26.11.2025
Dissemination Level	PU
Type of Deliverable	R

Version 1.1	26.11.2025, Adamescu, Arhire
Version 1.2.	30.01.2026, Nicholas Pade, Reviewer
Version N+2.N+2	DD.MM.YYYY, Author

Executive Summary

This deliverable assesses how terrestrial and freshwater conservation areas across four major European land–river–sea systems – the Danube–Black Sea, Po–Adriatic Sea, Elbe–North Sea, and Guadalquivir–Atlantic Ocean – influence downstream coastal and marine biodiversity and ecosystem services. Using the source-to-sea paradigm and a conceptual model linking upstream ecosystem service supply, mediating flows, and downstream ecological conditions, we analyse spatially distributed protected-area coverage, ecological quality (WFD EQR-based EQC), chlorophyll-a and nutrient concentrations. Complementary storylines co-developed with case-study teams summarise the narrative pathways through which upstream protection affects coastal outcomes. See Storyline – *Terrestrial protected areas effects on marine ecosystems*: https://arcg.is/1OmDji3.

Across all basins, the extent of protected areas has increased substantially since 1990, often in parallel with EU environmental policies. Statistical analyses reveal highly significant associations between upstream protected-area coverage, lower nitrogen and phosphorus concentrations, and improved ecological status – supporting the hypothesis that conservation enhances nutrient retention, hydrological buffering and habitat quality, with measurable positive signals along the freshwater–marine continuum.

However, a key challenge remains the lack of integrated data systems across freshwater and marine monitoring frameworks. Discontinuities in temporal resolution, indicator definitions, and ecosystem typologies limit the ability to fully capture cumulative effects along the land-to-sea continuum. Each basin presents unique hydrological, ecological, and governance contexts that require system-specific approaches—but within a harmonised, interoperable monitoring infrastructure. Addressing this integration gap is essential for building robust cross-domain evidence bases, aligning Water Framework Directive (WFD) and Marine Strategy Framework Directive (MSFD) assessments, and advancing the EU Biodiversity Strategy for 2030.

Strengthened basin-to-coast planning, integration of terrestrial/freshwater and marine policies, improved monitoring, and systematic inclusion of protected-area scenarios in modelling frameworks are essential for enhancing coastal biodiversity and ecosystem services.

This deliverable supports MARCO-BOLO’s broader objective of building an integrated evidence base to inform cross-domain management and the design of coherent conservation strategies across Europe’s land-to-sea continuum.

Contents

1. Introduction & rationale

Coastal and marine ecosystems — including estuaries, lagoons, seagrass meadows, coral reefs, and adjacent near-shore waters — are among the most biologically rich and societally important environments on Earth. They support extensive biodiversity, provide provisioning services such as fisheries and shell-fisheries, offer regulation services such as carbon sequestration and shoreline protection, and deliver cultural services including recreation, aesthetic value and heritage. Yet, these systems are increasingly threatened by anthropogenic pressures: nutrient enrichment, sediment overload, habitat loss, overfishing, and climate-induced changes (sea-level rise, extreme weather).

Effective conservation of coastal and marine systems often focuses on shoreline or ocean-based interventions—such as marine protected areas, reef restoration or mangrove afforestation—yet this seaward perspective can overlook the critical upstream dimension: the condition and management of terrestrial and freshwater systems that feed rivers, estuaries and coastal seas. Our approach is grounded in the source-to-sea paradigm, which emphasizes the continuum from land through rivers and lakes to estuaries, coasts and the open ocean. The paradigm identifies six key flows — water, sediment, pollutants, biota, materials, and ecosystem services (ES) - which link upstream systems with downstream marine outcomes (Mathews et al., 2019). Alteration of any of these flows in one segment of the continuum can propagate impacts throughout the system (SIWI, 2020). In our context, upstream protection influences these flows and thereby affects downstream outcomes. For example, by reducing sediment export, an upstream conservation area may enhance water clarity in the estuary and adjacent coastal zone, improving conditions for seagrass meadows, benthic fauna and nursery habitats for fish and so influencing human wellbeing. What happens upland matters downstream.

This deliverable seeks to examine how conservation efforts in terrestrial and freshwater domains (both existing and possible to be proposed) can influence downstream coastal biodiversity, ecosystem services, and ultimately human well-being. In doing so, it aims to inform integrated conservation planning that bridges land, freshwater, and marine domains.

In order to highlight the importance of existing terrestrial and freshwater upstream conservation areas for coastal and marine biodiversity and associated ES and hence, human well-being a series of narratives (storylines) were developed from the case studies. See Storyline - Terrestrial protected areas effects on marine ecosystems https://arcg.is/1OmDji3

Ecosystem Services Framework & Biodiversity Role

We adopt the CICES (Common International Classification of Ecosystem Services) framework to structure our analysis. CICES organizes ecosystem contributions into major categories: provisioning, regulation and maintenance, and cultural services, focusing on final services experienced by people rather than intermediate processes (Haines-Young & Potschin, 2017). Biodiversity, while not always explicitly classified as a service under CICES, is implicit in system resilience, multifunctionality and the capacity for ecosystems to deliver services reliably. In practical terms, upstream protected or conserved areas deliver a range of services: for example, sediment retention and erosion control, nutrient and pollutant filtration, flow regulation, carbon sequestration, habitat provisioning, and upstream recreation or cultural experiences. These upstream services, while often largely invisible to downstream users, form the supply side of our analytical chain.

2. Conceptual framework and hypotheses

Conceptual framework

Our conceptual model thus arranges the system into three interacting layers (table 1). The first layer comprises upstream conservation and ES supply. Here, protected terrestrial and freshwater areas constitute the structural foundation from which services such as erosion control, nutrient filtration, flow moderation, carbon sequestration and habitat provisioning emanate. The second layer comprises mediating flows and processes that transmit upstream ES supply into downstream ecological outcomes: for example, nutrient export, sediment flux, freshwater discharge, biotic connectivity and organic matter export. The third layer concerns downstream biodiversity, ecosystem condition and service outcomes in the coastal and marine realm, including habitat integrity, species diversity, fish recruitment, coastal protection, blue carbon sequestration and recreational services.

Key hypotheses

We posit that higher extent and enhanced integrity of upstream terrestrial or freshwater conservation areas in the hydrographical basin leads to more effective nutrient filtration and hydrological buffering, improving biodiversity by lowering nutrient export along the river–estuary–coast continuum and creating better habitat conditions along the land-to-sea continuum. We propose that the cumulative reduction of harmful upstream fluxes enhances ecosystem service provision, both directly through improved water purification and indirectly via conditions that can support downstream benefits.

Table 1. Conceptual linkages from upstream protected areas to downstream coastal conditions: ecosystem services (ES), flows, and ecological responses

No.	**Upstream Regulation ES**	**Upstream Indicator**	**Mediator (Flow/Process)**	**Downstream Indicator**	**Notes**	**References**
1	Sediment retention / Erosion control	% of catchment area protected or % forest/riparian buffer upstream	Sediment export to estuary/coast (tons/year)	Coastal water clarity / turbidity (NTU or visibility)	Protected upland areas reduce erosion & sediment flux → clearer coastal waters → healthier benthic habitats.	Noe, 2020; Ouillon, 2018; Oelsner, 2019
2	Nutrient / Pollutant filtration & retention	Area of upstream wetlands protected or width of riparian buffer	Nutrient export (kg N / P per year)	Coastal eutrophication index (e.g., algal bloom frequency)	Upstream filtering reduces nutrient loads downstream, thereby mitigating eutrophication in coastal zones.	Bertassello et al., 2025; Grizzetti et al., 2021; Beusen et al., 2022
3	Hydrological buffering / Flow regulation	% natural land cover protected upstream or upstream wetland retention area	Variability in discharge (peak: baseflow ratio)	Coastal/marine habitat condition (e.g., seagrass or mangrove integrity)	Conserved upstream catchments moderate flow extremes, reducing pulses of sediments/pollutants into coastal zones, stabilising marine habitats.	Pérez-Martín, 2023; Richardson et al., 2025
4	Carbon storage / Sequestration (terrestrial)	Biomass of protected forests upstream (tC/ha) or hectares of protected forest	Carbon fluxes via erosion or land-use change	Blue carbon stock in coastal/marine habitats or area of carbon-sequestering habitats	Upstream carbon storage supports system stability and downstream resilience though direct flux connections may be weaker than for sediment/nutrients.	Richardson et al., 2025
5	Habitat provision / Biodiversity refuge upstream	Upstream habitat integrity index (species richness, habitat connectivity)	Biotic connectivity (number of barriers, migration pathways)	Marine species diversity / recruitment in coastal zone	Upstream conservation maintains habitat and connectivity; mediator reflects barriers → downstream marine biodiversity improvement via species recruitment and connectivity.	Szabolcs, et al. 2022

3. Methods

3.1. Study units and site selection

This study focuses on four European land–river–sea case studies selected for their diversity of hydrological, ecological and governance contexts, and their alignment with the broader MARCO-BOLO project. These are the ***Danube – Black Sea, Po – Adriatic Sea, Elbe – North Sea and Guadalquivir – Atlantic Ocean*** (figure 1 and table 2). The spatial delineation follows hydro-geomorphic boundaries (catchments, sub-catchments) and hydrological connectivity to the coast. For each system we define three zones: freshwater (corresponding to the fluvial valley), transitional (estuary or delta) and coastal (near-shore marine area influenced by the river system).

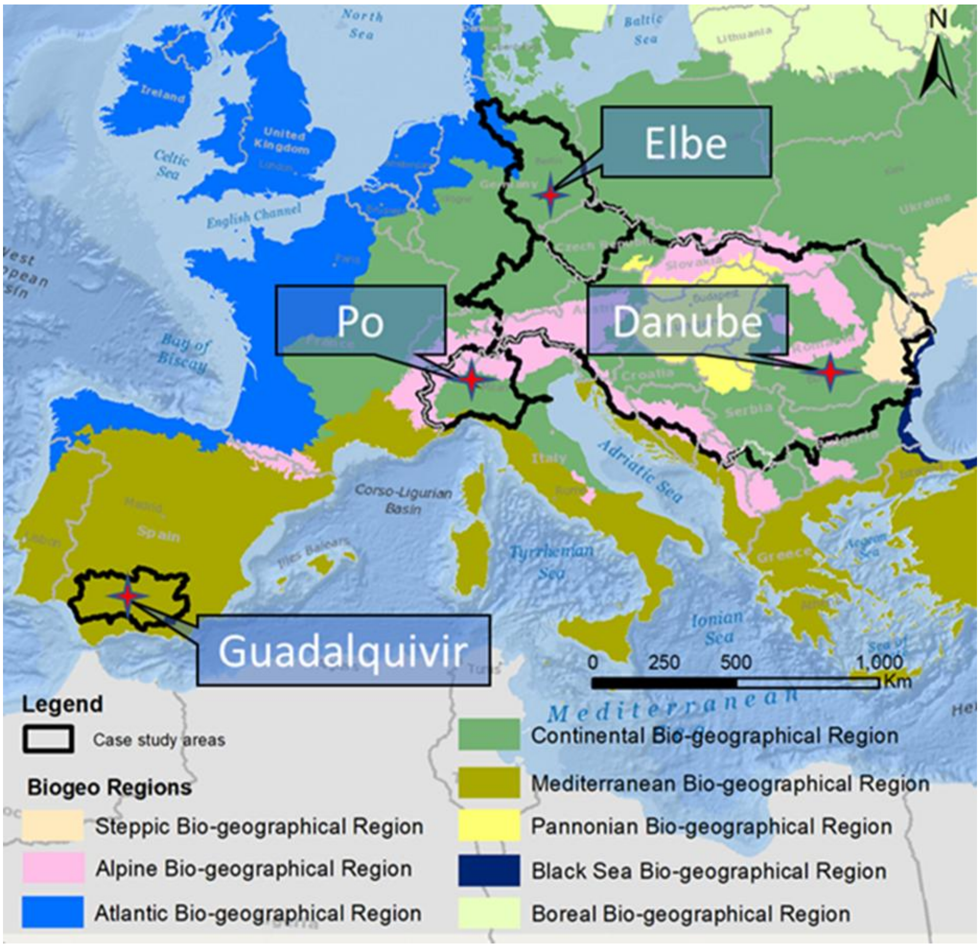


Figure 1. *Selected land-river-sea systems: Danube – Black Sea, Po – Adriatic Sea, Elbe – North Sea and Guadalquivir – Atlantic Ocean. Sources for map generation CCM2 dataset and Biogeographical regions dataset, Base Map - ESRI World Ocean.*

Table 2. Summary table of the main characteristics of the selected land-river-sea systems: Danube – Black Sea, Po – Adriatic Sea, Elbe – North Sea and Guadalquivir – Atlantic Ocean

#	Danube	Po	Elbe	Guadalquivir
Drainage area (km^2)	~800,000	~74,000	~148,000	~56,000
River length (km)	~2800	~650	~1000	~650
Countries - share of basin area (%)	Albania 0.02 Austria 10.03 Bosnia and Herzegovina 4.77 Bulgaria 5.88 Croatia 4.37 Czech Republic 2.7 Germany 7 Hungary 11.58 Italy 0.07 Republic of Moldova 1.56 Montenegro 0.9 North Macedonia 0.01 Poland 0.05 Romania 28.91 Serbia 10.21 Slovakia 5.86 Slovenia 2.04 Switzerland 0.23 Ukraine 3.81	Switzerland 5.4 Italy 94.6	Czech 33.7 Germany 65.4 Poland 0.2 Austria 0.6	Spain 100
Population (Mln)	83	17	25	4
Mean discharge at outlet (m^3/s)	> 6400	>1000	>700	>150
Outlet sea	Black Sea	Adriatic Sea	North Sea	Atlantic Ocean

3.2. Data sources and indicators

The empirical component draws on diverse data sources encompassing spatial information on protected area extent, hydrology, river water quality (nutrient loads), biodiversity indices, coastal habitat condition and fishery yield statistics.

Biodiversity data: biological quality elements extracted from the **WISE-2 Biology EEA, 2024 dataset** - availability of data for water ecological quality classes (EQC) based on ecological quality ratios (EQR) values as reported under the Water Framework Directive (WFD) for the case studies is summarised in table 3.

Table 3. Available data for water ecological quality classes in the case studies areas from WISE-2 Biology EEA, 2024 dataset

	No. of values	**Year Range**	***Reported values Peak Years (PY)***	***Share of total values in PY***
Danube – Black Sea	8543	2007-2023	*2019–2023*	*58 %*
Po – Adriatic Sea	3460	2009-2023	*2019–2023*	*58 %*
Elbe – North Sea	142	2007–2023	2011–2015	66 %
Guadalquivir – Atlantic Ocean	1372	2016–2020	2018, 2017	Over 60 %

For the available records of water ecological quality classes (EQC: 1 - High ecological status, or maximum ecolological potential, 2 - Good status or potential, 3 - Moderate status or potential, 4 - Poor status or potential, 5 - Bad status or potential) the following subbasin-related characteristics were added into the basin-wide spatially distributed analysis: nitrogen and phosphorus concentration categories and percentages of protected area coverage for each subbasin corresponding to the sampling point from the WISE-2 Biology - EEA dataset.

Nitrogen and phosphorus concentrations in European freshwater (1990-2018) extracted from **EC-JRC dataset, v. nov.202:** basin-wide spatially distributed values of nitrogen and phosphorus concentration classes estimated at the outlets of freshwater functional elementary catchments. Available data for Danube, Po, Elbe and Guadalquivir basins.

Protected areas surface extracted from World Database on Protected Areas (**WDPA, v. 2024**) and calculated in hectares (ha) and coverage percentages (%) for Danube, Po, Elbe, Guadalquivir basins and sub-catchments for the period 1990-2024.

Nitrogen and Phosphorus concentration water, in rivers (freshwaters), deltas and/or estuaries (transitional waters) and near-shore marine areas influenced by the river systems (coastal waters):

- Danube-Black Sea: period 2001-2021 data extracted from Danubius for Danube river before its delta, in Danube Delta and in Danube Delta Black Sea coastal zone (Total Nitrogen - **TN**, Nitrite, Total Phosphorus - **TP**, Phosphate) and period 1992-2023 for Black Sea (Nitrate) data extracted from https://data.marine.copernicus.eu ;
- Elbe-North Sea: data from FGG FIS for Elbe river before entering its estuary (period 1978-2023, missing years 1986, 1987: TN and TP) and in estuary (period 1979-2023: TN and TP); and data from North Sea provided by Landesamt für Umwelt des Landes Schleswig-Holstein (period 2012-2020: TN and TP);

- Po-Adriatic Sea: data from Regional Agency for Prevention, Environment and Energy of Emilia-Romagna for Po river before its delta (period 2010-2022: TN and TP) and data from the from Regional Agency for Prevention, Environment and Energy of Emilia-Romagna - Struttura Oceanografica Daphne for Po Delta and Adriatic Sea (period 2017-2022: TN and TP);
- Guadalquivir-Atlantic Ocean: a limited amount of data was found for the Guadalquivir river before its estuary and in estuary from WISE SoE - Water Quality in Inland, Coastal and Marine waters (WISE-6) - 7 values for TN and 12 values for TP - no regression analysis was performed.

Chlorophyll a (chl a) concentrations in rivers (freshwaters), deltas and/or estuaries (transitional waters) and near-shore marine areas influenced by the river systems (coastal waters):

- Danube-Black Sea: period 2001-2021 data extracted from Danubius for Danube river before its delta, in Danube Delta and in Danube Delta Black Sea coastal zone and period 1992-2023 data extracted from https://data.marine.copernicus.eu for Black Sea;
- Elbe-North Sea: period 1993-2023 data from FGG FIS for Elbe river before entering its estuary and in estuary; and period 2012-2020 data from North Sea provided by Landesamt für Umwelt des Landes Schleswig-Holstein;
- Po-Adriatic Sea: no data for the Po river before its delta and data from Regional Agency for Prevention, Environment and Energy of Emilia-Romagna and Regional Agency for Prevention, Environment and Energy of Emilia-Romagna - Struttura Oceanografica Daphne for the period 2017-2022 in Po Delta and Adriatic Sea;
- Guadalquivir-Atlantic Ocean: a limited amount of data was found for the Guadalquivir river before its estuary and in estuary from WISE SoE - Water Quality in Inland, Coastal and Marine waters (WISE-6) - 18 values for chl-a - no regression analysis was performed.

Net Primary Production in the Black Sea: data extracted from https://data.marine.copernicus.eu period 1992-2023.

Commercial fish capture and sardine captures in the Black Sea: period 1996-2016, source FAO report 2023.

3.3. Analyses

We ran exploratory data analyses to map descriptive relationships among upstream conservation extent, upstream service proxies, mediating flows and downstream outcomes: maps and graphs were used to visualise patterns and to identify potential relationships.

The hypothesis - greater upstream protection in the hydrographical basin leads to improved biodiversity by lowering nutrient export and creating better habitat conditions along land-to-sea continuum - was first tested by examining the spatially distributed relationships between protected area coverage (PA%), nutrient concentrations (nitrogen and phosphorus) and water ecological quality classes (EQC) based on biology EQR values as reported under WFD, using Chi-square tests of association and Cramér's V to measure the association strength. To evaluate how EQC changes with protected area coverage (PA%) non-parametric tests Kruskal–Wallis Test, Mann–Whitney U and Jonckheere–Terpstra (trend, Z) were used to compare distributions and detect if there are ordered trends. Then we analysed the nutrient and chlorophyll dynamics in the freshwater-marine continuum in relation to increased upstream protection, performing regression analysis.

We used Bayesian Belief Networks (BBNs) as a modelling tool to test the tool for the Danube basin. BBNs enable the integration of expert knowledge, quantitative evidence and qualitative information into a probabilistic graphical model that expresses uncertainties, captures non-linear relationships and responds flexibly to data gaps (Carriger & Litt, 2019). Scenario modelling utilising BBNs allowed us to explore the sensitivity of downstream outcomes to changes in upstream conservation extent, mediating flows or contextual moderators—thus enabling what-if analyses and decision-support simulations. Qualitative integration of stakeholder narratives and case-study storylines complements the quantitative work, allowing us to contextualise findings, refine model interpretation and identify governance or implementation constraints.

Causal-loop diagrams were used for detailing how upstream protection influences service supply, which in turn influences mediating flows and ultimately biodiversity and service provision in the coastal zone. Reinforcing and balancing feedback loops are embedded: a reinforcing loop might show how improved coastal biodiversity supports higher fisheries yield, which stimulates stakeholder willingness to invest in upstream conservation; a balancing loop could show how upstream degradation triggers high sediment export and nutrient concentrations reduced coastal habitat quality and diminishing service returns, which reduce investment upstream and lead to further degradation.

3.4. Limitations and assumptions

We acknowledge several important limitations. First, data availability for coastal and marine biodiversity and ES outcomes is uneven across sites, often necessitating use of proxy indicators rather than direct measurements. Second, attribution of downstream outcomes to upstream conservation remains inherently complex, given the multitude of local drivers (coastal development, fishing pressure, climate change) that may confound or override upstream effects. Third, temporal mismatch is a challenge: many upstream interventions may only show measurable downstream effects after years or decades, which may fall outside available data windows. Fourth, scale mismatches may dilute effect detection when upstream conservation areas represent relatively small proportions of large catchments. Fifth, ecological systems may exhibit non-linearity or threshold responses that are difficult to detect with linear modelling approaches. Finally, our assumption that upstream conservation will always result in beneficial downstream outcomes may not hold in every case—

some systems may require sediment export to maintain delta accretion or other services (Wohl, 2015).

4. Case studies

The Danube, Po, Elbe and Guadalquivir rivers experience intense pressures from human-induced drivers such as pollution, urbanization, industrial activities, and intensive agriculture, which significantly impact water quality, biodiversity, and ecosystem health. Extensive water extraction for agricultural, industrial, and urban needs depletes water resources. Similarly, agricultural runoff, inadequately treated wastewater, industrial discharges, and stormwater runoff introduce harmful pollutants, including nutrients, that degrade water quality and threaten aquatic life. These issues extend beyond the rivers, potentially impacting surrounding marine areas by carrying pollutants downstream and altering coastal ecosystems.

4.1. Danube – Black Sea

4.1.1. Introduction

The Danube river catchment of >800,000 km² drains into the Black Sea and connects 19 countries of contrasting economic, social, cultural, and environmental heritages including a large number of protected areas (e.g. the Danube Delta UNESCO Biosphere Reserve and the Black Sea protected areas). Due to its extensive size and diverse range of habitats, the Danube river assumes a primary role as a significant natural asset in Europe, serving as a basic element for the conservation of biodiversity. The river sustains a diverse community, accommodating over 2,000 plant and 5,000 animal species within its aquatic surroundings and adjacent ecosystems. Upon transitioning into the Danube Delta, the river attains the status of one of the world's preeminent wetlands, characterized by 30 distinct ecosystem types. Spanning an extensive area of more than 5,050 km^2, comprising marshes, canals, reed islets, and lakes, the Danube Delta emerges as the third-ranking global site for biodiversity.

Main degradation processes in the Danube basin:

- **Water Pollution:** Agricultural runoff, industrial discharges, and urban wastewater are the main drivers of water pollution in the Danube river basin, jointly degrading water quality and aquatic habitats (Mănoiu & Crăciun, 2021). Monitoring data indicate that nutrient pollution from agriculture, together with untreated or insufficiently treated wastewater from urban and industrial sources, remains a major pressure on achieving good ecological status, with elevated nutrient loads contributing to oxygen depletion and habitat degradation (ICPDR, 2021). Approximately 80% of nitrogen and two-thirds of phosphorus loads originate from agricultural activities, while urban wastewater remains a dominant source of organic pollution—together reinforcing eutrophication pressures and adversely affecting aquatic ecosystems in the Danube (Pistocchi et al. 2020).

➢ **Altered hydrology and habitat degradation:** Urbanization and infrastructure projects can lead to habitat loss and fragmentation, affecting flora and fauna. Dams, channelization, and water abstraction alter the natural flow of rivers, impacting aquatic habitats and biodiversity. The key hydromorphological pressures in the Danube basin include the disruption of longitudinal ecological continuity; the alteration of river morphology and habitats; the disconnection of adjacent wetlands, floodplains and impoundments; and water abstractions or diversions and hydropeaking (abrupt flow fluctuations due to electricity production on demand) (ICPDR, 2015). Hydraulic works in the form of dams and reservoirs are found in all mountainous areas of the Danube basin, while most navigation canals, dyke and irrigation networks concentrate on the lowlands along the central and lower Danube. The building of large dike systems for flood protection started in the 16th century in Hungary. Old networks of drainage/irrigation systems exist in all basins, for instance in the Banat (northern YU) and in southern Romania. The first major Danube regulation works started in 1830 in Upper Austria; the first Danube hydro dam was built in 1927 at Vilshofen (lower Bavaria).

Protected areas in the Danube Basin

The Danube Basin is home to a diverse network of protected areas (Natura 2000 Sites, Ramsar Wetlands, National Parks and Biosphere Reserves) established to safeguard its rich biodiversity and enhance ES. The main aims of protected areas in the Danube basin are to protect native species, including flagship species like sturgeons and migratory birds, to reconnect wetlands and floodplains and to reduce nutrient runoff and improve water purification. Since 1990, when 7.52% of the basin surface was under protection, the network of protected areas has grown steadily, with initiatives like Natura 2000 and Ramsar designations adding critical habitats. From small, localized reserves to large transboundary sites, protected areas now cover 27.67% of the basin (figure 2).

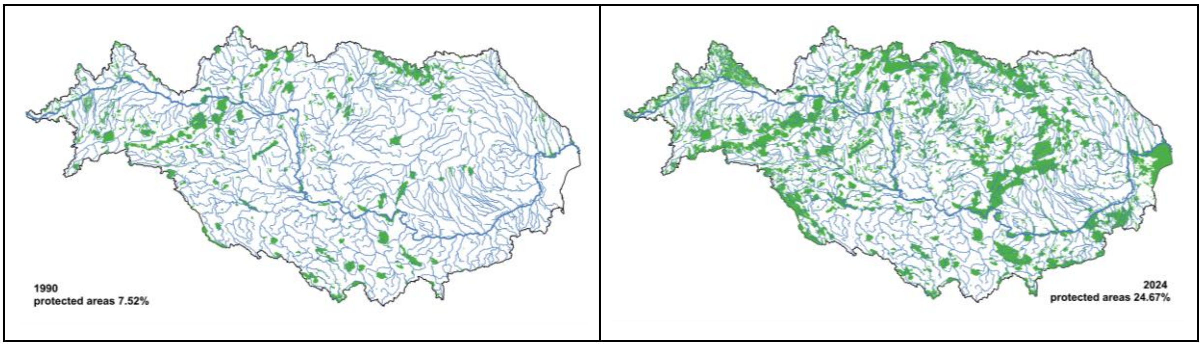


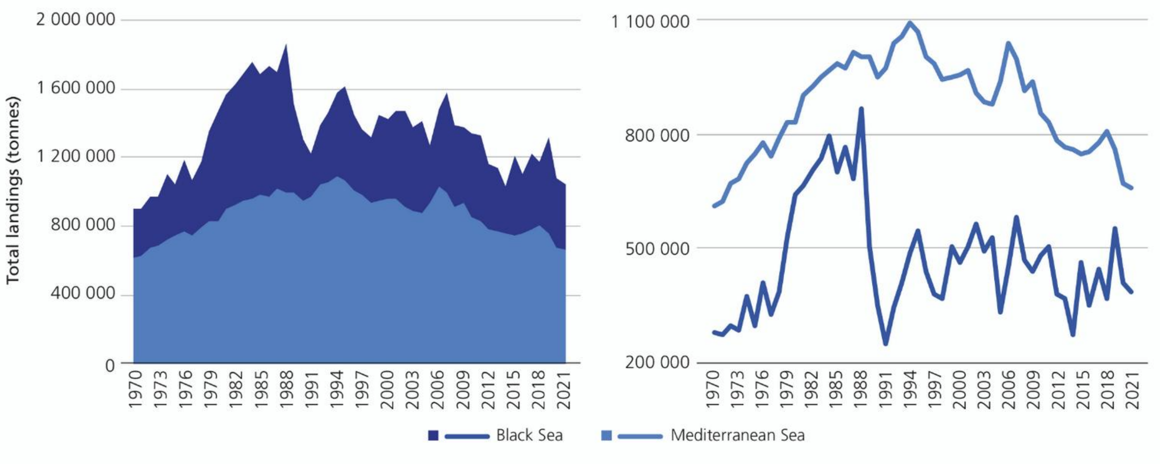
Figure 2. *Protected areas in the Danube basin (green) in 1990 and 2024 (dataset source WDPA, 2024)*

Black Sea ecosystem services (ES)

The Black Sea ecosystem provides a range of essential services that are critical to both the environment and human well-being. From provisioning services to regulating and supporting services up to cultural, the Black Sea ecosystems are supporting the well-being of human civilization for millennia. Among these, its role in fisheries stands out prominently, supplying commercially valuable species such as anchovies, sprat, turbot, and sturgeon. These fisheries not only ensure food security for the region but also sustain the livelihoods of countless coastal communities. Additionally, the sea supports aquaculture, contributing to the production of fish and shellfish, which further diversifies its economic importance.

Fisheries provide livelihoods for millions, with small-scale fisheries playing a crucial role in coastal economies. Migratory species, such as sturgeons, depend on the Danube for spawning, highlighting the interconnectedness of terrestrial and marine ecosystems. With almost 700,000 jobs (along the value chain) and an estimated revenue of almost 20.5 billion euro the fisheries sector is an important income source for many countries (SOMFI2023).

Environmental challenges, particularly eutrophication and overfishing: All of the ES face significant threats from pollution, overfishing, habitat loss, and climate change. Protecting the Black Sea's ecological integrity is essential to sustaining these services and ensuring that they continue to benefit both people and the environment for generations to come. The interconnected nature of its ES underscores the importance of holistic and cooperative management efforts across the region. For example, the impact of different threats caused a reduction in total landings in the Mediterranean and Black Sea (figure 3).



Note: Left panel shows cumulative trends from the Mediterranean and the Black Sea; right panel shows trends by basin (Mediterranean and Black Sea).

Figure 3. *Total landings (tonnes) in both Black and Mediterranean Sea (FAO, 2023)*

Beyond its provisioning role, the Black Sea plays a crucial part in ***regulating the environment*.** Coastal wetlands, including the Danube Delta, act as natural filters, reducing pollution and improving water quality by cycling nutrients and mitigating eutrophication. These areas also help regulate floods by absorbing storm surges and excess water, protecting coastal communities from disasters. The Black Sea contributes significantly to climate regulation as well, with its marine sediments and seagrasses sequestering carbon and influencing regional climate patterns by moderating temperature and humidity.

The Black Sea is also offering a diversity of ***supporting services*** acting as a reservoir of biodiversity, serving as a habitat for a wide range of species, including marine mammals, migratory birds, and endemic fish. Its waters and coastal ecosystems support the foundational processes of marine life, such as primary production by phytoplankton, which sustains the entire food web. These underlying ecological functions enable the Black Sea to maintain its productivity and resilience.

***Culturally*,** the Black Sea holds immense value for recreation, tourism, and education. Its coastal areas attract millions of visitors annually, with activities such as beach tourism, boating, and ecotourism in biodiversity hotspots like the Danube Delta. The region's scenic beauty and ecological richness provide aesthetic and spiritual inspiration while also serving as an outdoor laboratory for scientific research and environmental education. The cultural and historical significance of the Black Sea further enhances its importance, connecting modern communities to ancient maritime civilizations and traditions.

4.1.2. Results

Exploratory analysis

The concentrations of the major nutrients in the Danube basin decreased as more policies dedicated to protecting the entire basin were adopted (figure 4) during the entire analysed period (1992-2021). This decrease also corresponds with the increase of catchment area protected (as part of the conservation policies adopted). It is important to note that the Danube basin is just one of the several river basins that are discharging their nutrient load in the Black Sea (Strokal & Kroeze, 2013), although it is the first in annual discharge (ANEMONE, 2021). This means that the ecological situation in other catchments will also have a direct effect on the Black Sea environment. Nevertheless, the implications of the reduction of nutrients in the Danube River are also confirmed by analysing the trends of the nutrients and chlorophyll-a as well as the Net Primary Production in the shore of the Black Sea (figure 5).

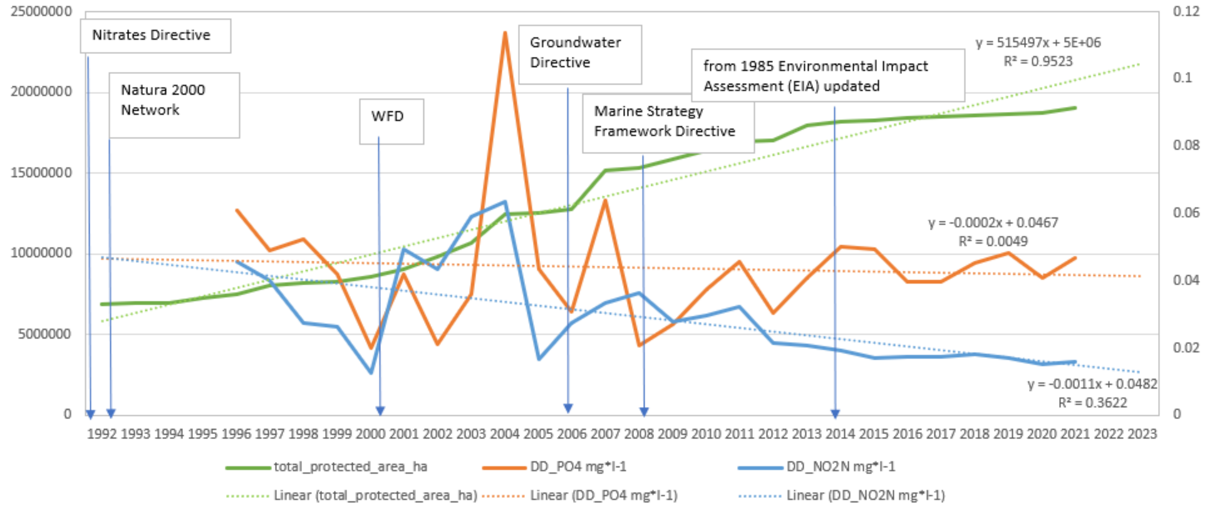


***Figure 4**. Trends in the surface area of protected zones within the Danube basin (ha), aligned with the enactment of major legislation on protected areas, as well as key water conservation and protection directives (e.g., Water Framework Directive, Nitrates Directive, Groundwater Directive, updated Environmental Impact Assessment Directive, and Marine Strategy Framework Directive), analysed alongside the dynamics of NO_2, chlorophyll-a (chl-a), and PO_4 concentrations in the Danube Delta Black Sea coastal zone (Chilia outlet).*

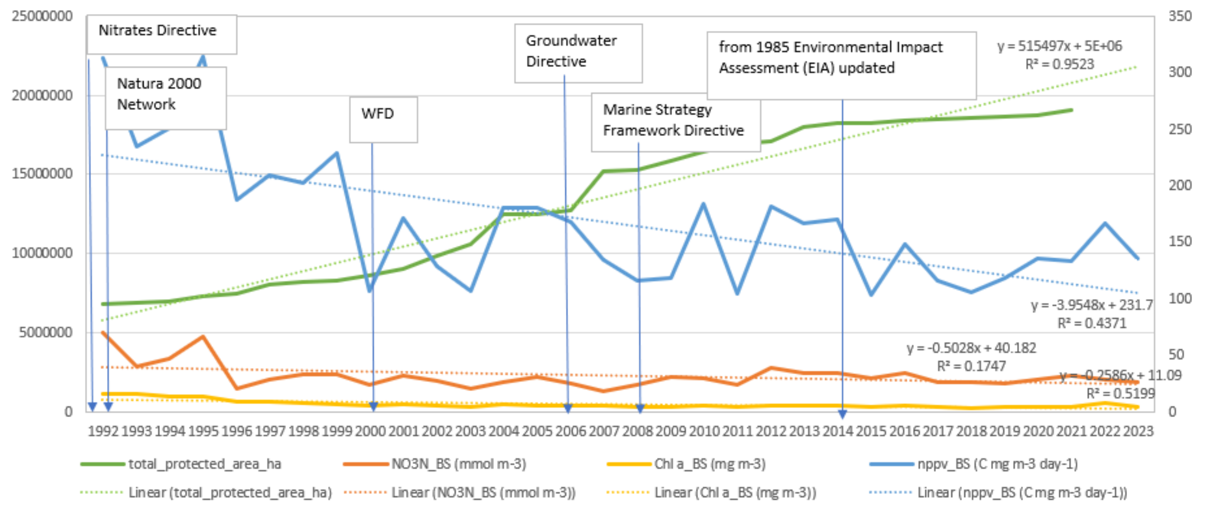


***Figure 5**. Trends in the surface area of protected zones within the Danube basin (ha), aligned with the enactment of major legislation on protected areas, as well as key water conservation and protection directives (e.g., Water Framework Directive, Nitrates Directive, Groundwater Directive, updated Environmental Impact Assessment Directive, and Marine Strategy Framework Directive), analysed alongside the dynamics of NO_3, chlorophyll-a (chl-a), and Net Primary Production in the Black Sea.*

However, the improvement in Black Sea conditions has not yet been reflected in fish captures (figure 6). Several factors could explain this, but the most likely reason is that the complex Black Sea ecosystem requires more time to recover. Changes in the ecosystem and food web take a considerable amount of time to propagate (Akoglu, 2023). Additionally, the system may still be "loaded" with nutrients stored in various compartments, such as sediments, which are released gradually, slowing the recovery of nutrient levels (Grégoire & Friedrich 2004).

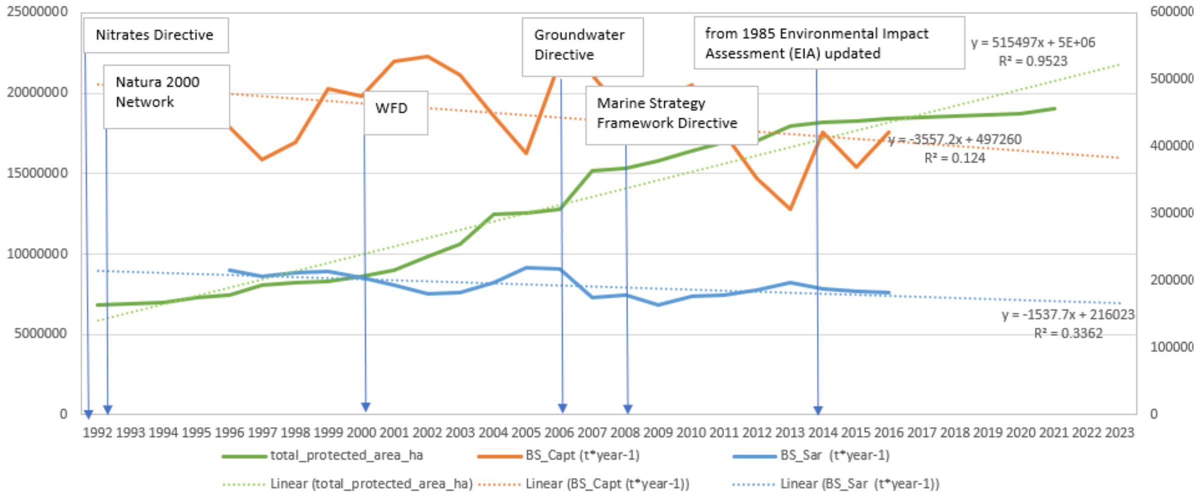


Figure 6. *Trends in the surface area of protected zones within the Danube basin (ha), aligned with the enactment of major legislation on protected areas, as well as key water conservation and protection directives (e.g., Water Framework Directive, Nitrates Directive, Groundwater Directive, updated Environmental Impact Assessment Directive, and Marine Strategy Framework Directive), analysed alongside the dynamics of total commercial fish capture (BS_Capt, t*year-1) and sardine captures (BS_Sar, t*year-1) in the Black Sea.*

Nitrogen and phosphorus pollution is widespread across the Danube Basin (figures 7 and 8), though phosphorus is generally at lower concentrations than nitrogen, with clear spatial and temporal patterns. Spatially, many upstream and mid-basin sub-catchments exhibit moderate to high nitrogen and low to moderate phosphorus concentrations (1–5 mg N/l and 0.02–0.1 mg P/l), while very high levels (≥5 mg N/l and ≥0.5 mg P/l) appear in certain hotspot areas - more intensively farmed or densely populated sub-basins in the central and lower basin. Low nitrogen and phosphorus areas (<1 mg N/l and <0.02 mg P/l) are mostly located in the mountainous and forested or less intensively used upstream regions. Temporally, the stacked-area charts indicate that since 1990 the basin has been dominated by intermediate nitrogen (1–2 mg N/l and 2–5 mg N/l) and phosphorus (0.06–0.1 mg P/l and 0.1–0.5 mg P/l) concentration classes, which together account for the largest share of basin area throughout the period.

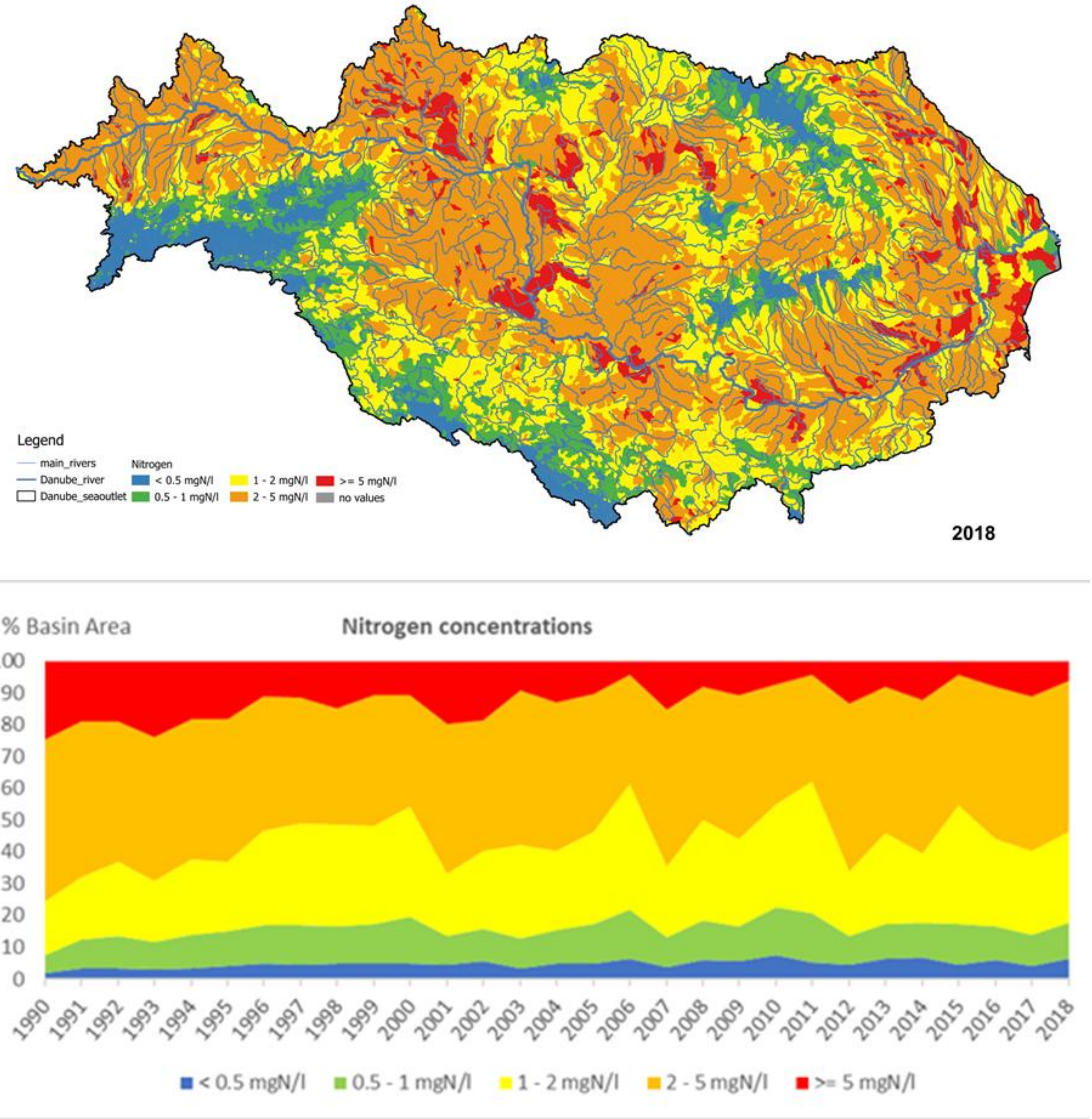


Figure 7. *Classes of mean annual Nitrogen concentrations in Danube basin estimated at the outlets of freshwater functional elementary catchments (source Grizzetti et al., 2022; dataset v. nov.2021)*

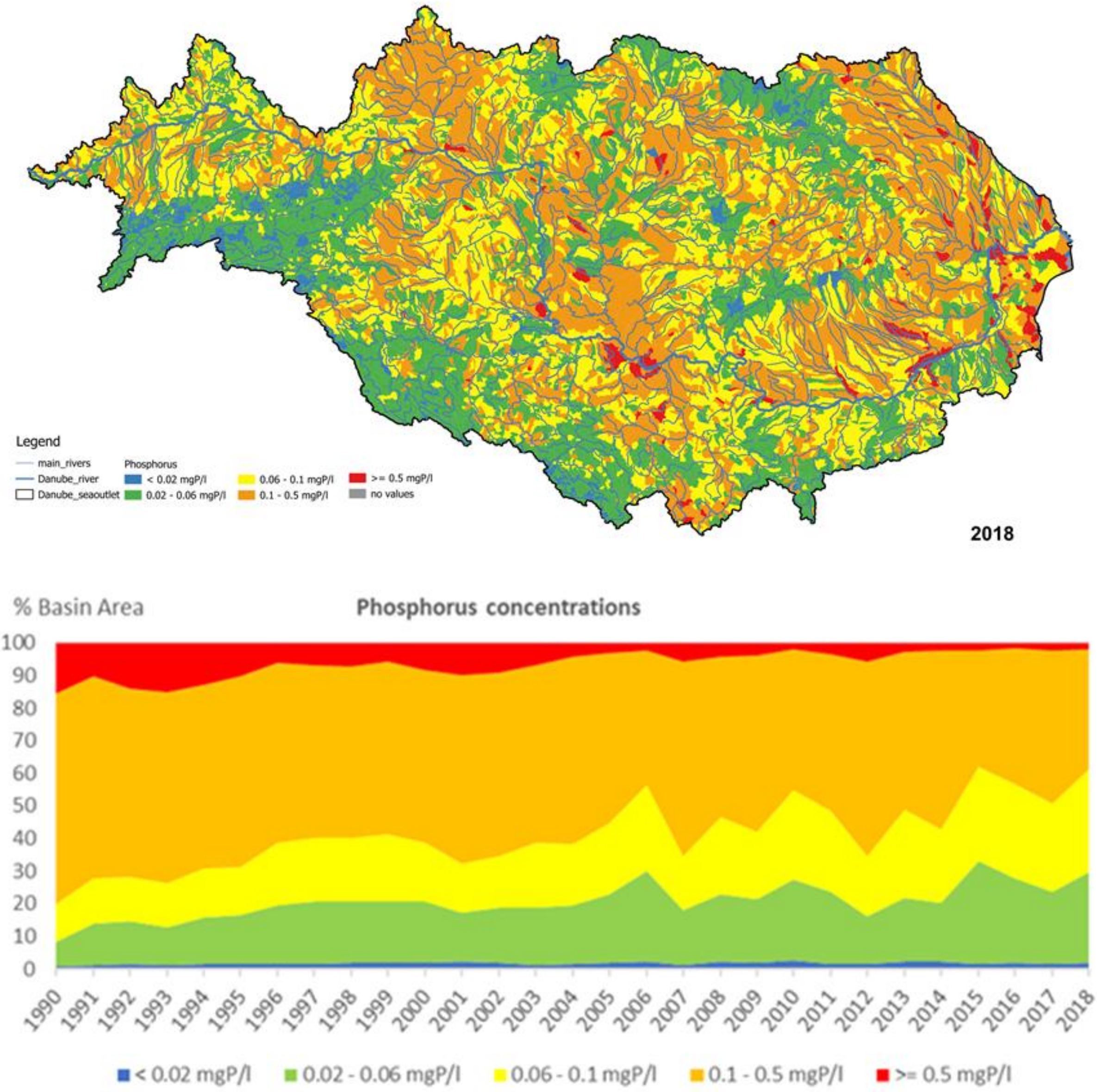


Figure 8. *Classes of mean annual Phosphorus concentrations in Danube basin estimated at the outlets of freshwater functional elementary catchments (source Grizzetti et al., 2022; dataset v. nov.2021)*

Although there are year-to-year fluctuations, there is no strong long-term basin-wide decline, suggesting that diffuse nitrogen and phosphorus inputs remain persistently high, reflecting continued agricultural pressures and only partial improvements in nutrient management across the basin. Overall, the nutrient loads remain sufficiently high to sustain ecological pressures across the Danube basin.

To test the hypothesis that greater upstream protection in the Danube basin leads to improved biodiversity by lowering nutrient export and creating better habitat conditions along land-to-Black Sea continuum the spatially distributed relationships between protected area coverage (PA%), nutrient concentrations (nitrogen and phosphorus) and water ecological quality classes (EQC) based on biology EQR values as reported under WFD were examined.

Associations tests between protected area coverage, nutrients and water ecological quality classes

The Chi-square test statistics demonstrate highly significant relationships between protected area (PA) coverage, water EQC (based on EQRs) and nutrient concentrations (N, P). Better water ecological quality is expected to co-occur with higher PA coverage and lower N and P concentrations to occur more frequently where PA coverage is higher. Despite being significantly correlated ($p < .0001$) Cramér's V values (~0.09–0.12) indicate a weak association between variables (table 4).

Table 4. Association tests between protected area coverage, water ecological quality classes (EQC) and nutrient concentrations in Danube basin

Variable Pair	Chi-square	df	p-value	Cramér's V
Protected Area vs water EQC	189.948	12	**< .0001**	0.086
Protected Area vs Nitrogen	216.935	12	**< .0001**	0.121
Protected Area vs Phosphorus	143.107	12	**< .0001**	0.098

$p < 0.0001$ - very strong statistical significance

To further assess the relationship between protected area coverage (PA) and water EQC, additional non-parametric tests were applied to compare distributions and detect if there are ordered trends . Non-parametric tests showed that subbasins with high coverage of protected areas have better water EQC and that the ecological status improves steadily as protected area coverage increases (table 5). This pattern supports a dose–response relationship where increased conservation coverage aligns with improved ecological conditions.

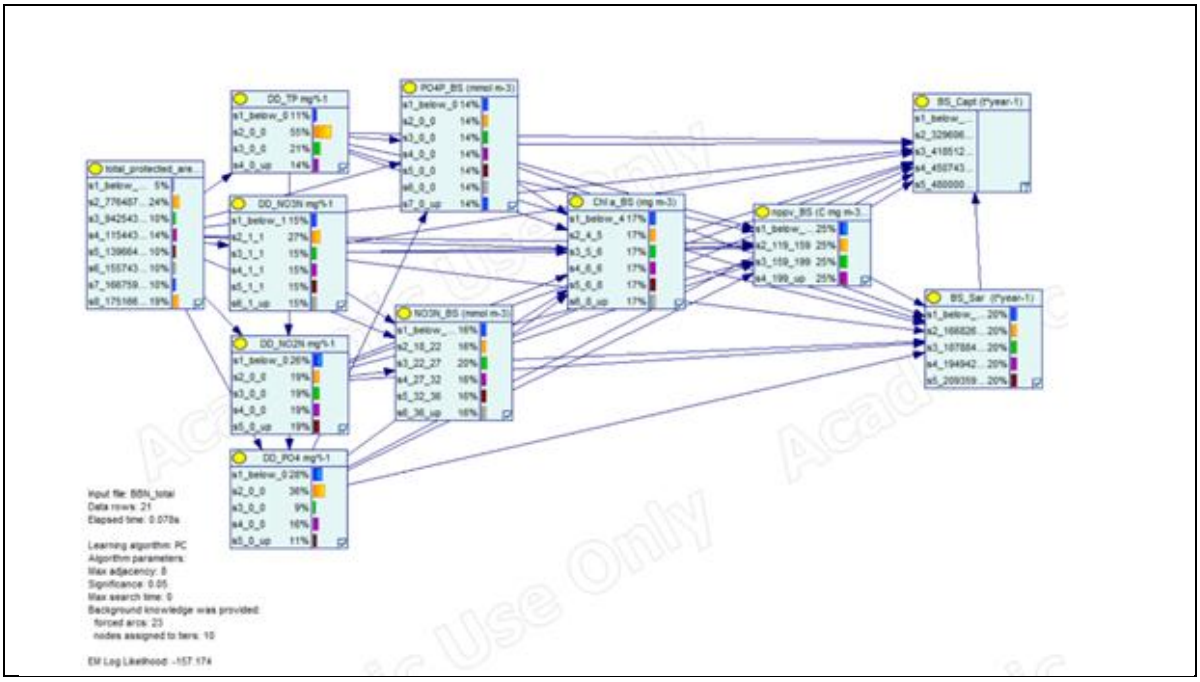
Table 5. Tests to evaluate how water ecological quality classes (EQC) changes with protected area coverage (PA%) in Danube basin

Test	Statistic	p-value	Interpretation
Kruskal–Wallis Test (4 PA categories*)	136.064	**< .0001**	Highly significant difference in water EQC between PA categories
Mann–Whitney U (Low vs Very high PA)	2443750	**< .0001**	Highly significant Low PA (0–25%) vs Very High PA (75–100%) difference in water EQC
Jonckheere–Terpstra (trend, Z)	-16.099	**< .0001**	Highly significant monotonic trend (higher PA → better water EQC)

**PA categories: Low (0–25%); Moderate (25–50%); High (50–75%); Very high (75–100%)*

BBN

A BBN model was generated linking Protected Areas in the Danube with fish captures in the Black Sea (figure 9). It considers key factors, including major nutrient concentrations at the Danube outlet (Chilia Arm), changes in the protected area surface in the Danube Basin (from 1992 to 2023), nutrient dynamics in the Black Sea, chlorophyll-a concentrations, and net primary production. The model's outputs focus on two critical ecosystem services essential for the wellbeing of local communities: total fish captures and sardine captures.



```
Input file: BBN_total
Data rows: 21
Elapsed time: 0.078s

Learning algorithm: PC
Algorithm parameters:
Max adjacency: 8
Significance: 0.05
Max search time: 0
Background knowledge was provided:
  forced arcs: 23
  nodes assigned to tiers: 10

EM Log Likelihood: -157.174
```

Figure 9. BBN to investigate the links between the dynamic of the size of protected areas in the Danube basin and the influence on the ES (primary production and fish captures) in the Black Sea over more than 20 years.

The figures present the probability distributions of each variable in the Bayesian Belief Network (BBN), as derived from field measurements and long-term monitoring data. These distributions reflect the observed variability and uncertainty associated with each environmental driver and response variable, ensuring that the model is empirically grounded rather than purely theoretical. In this BBN framework, each node represents a key variable—such as nutrient concentrations at the Danube outlet (Chilia Arm), the extent of protected areas in the Danube Basin (1992–2023), nutrient dynamics and chlorophyll-a concentrations in the Black Sea, and net primary production—while the directional links describe probabilistic dependencies based on both field data and expert knowledge. Technically, the BBN model integrates these heterogeneous datasets into a coherent probabilistic structure, allowing the propagation of uncertainty through conditional probability tables (CPTs). These CPTs were calibrated using the empirical distributions observed in the field, meaning that each variable's probability state corresponds to the range and likelihood of conditions actually recorded during monitoring campaigns. This approach makes it possible to quantify how changes in upstream management —such as the expansion of protected areas or the reduction of nutrient loads—affect downstream ecological processes and, ultimately, marine ecosystem services.

The resulting outputs emphasize two key ecosystem services of socio-economic importance: total fish captures and sardine captures in the Black Sea. Through probabilistic inference, the model can estimate how variations in nutrient inputs and primary production influence fishery yields, offering a transparent and data-driven means to assess management scenarios. Consequently, the figures not only visualize the empirical foundations of the model but also highlight the causal structure and uncertainty propagation inherent in the BBN, providing a robust decision-support tool for ecosystem-based management across the Danube–Black Sea continuum.

4.1.3. Conclusions

In the Danube basin the spatially distributed analysis showed highly significant relationships between protected area (PA) coverage, water EQC (based on EQRs) and nutrient concentrations (N, P). Better water ecological quality is expected to co-occur with higher PA coverage and lower N and P concentrations to occur more frequently where PA coverage is higher. Sub-catchments with high coverage of protected areas have better water EQC and the ecological status improves steadily as protected area coverage increases.

4.2. Po – Adriatic Sea

4.2.1 Introduction

The Po River is the longest river in Italy, stretching over 650 kilometres from its source in the Alps near the French border to its delta in the Adriatic Sea. Its basin is the largest Italian catchment covering an area of 74,000 km ^{2}. Flowing eastward across northern Italy, the Po is fed by numerous tributaries, originating from both the Alps and the Apennines, creating an extensive network that supports agriculture, industry, and urban centers across the region. The Po Basin's ecosystems are vital for biodiversity, supporting numerous threatened plant species and serving as Italy's most important heron breeding area. Besides, the region hosts over 20,000 waterbirds, including storks, ducks, and raptors. Its waters also sustain several endemic fish species and function as nurseries for rare and threatened species, such as the critically endangered Adriatic sturgeon and the endangered Italian nase (*Chondrostoma soetta*). Upon reaching its expansive delta, the Po River forms one of the most significant wetland ecosystems in the Mediterranean, encompassing a diverse mosaic of habitats, including marshes, lagoons, reed beds, and sandbars. Covering approximately 380 km², the Po Delta is recognized as a biodiversity hotspot, hosting a vast array of plant and animal species, including several endemic and threatened species.

Main degradation process in the Po Basin

➢ **Water Quality Degradation:** Poor water quality due to pollution from agricultural runoff, industrial discharge, and sewage. Water quality in the Po River Basin has been a persistent concern, with nutrient pollution stemming primarily from agricultural runoff, wastewater discharges, and industrial activities (Soana et al., 2024). Fifty-one percent of the Nitrogen load (carried in superficial waters) derives from agriculture and livestock (fertilizer use and manure spreading), while 40% from civil and industrial sectors. Concerning phosphorus loads the major contribution is provided by civil and industrial sectors (62% of TP load). Pirrone et al. 2005). High levels of nitrogen and phosphorus contribute to eutrophication, leading to algal blooms that deplete oxygen and disrupt aquatic ecosystems (Penna et al., 2004). These changes threaten biodiversity, water usability, and the overall ecological balance of the basin (Grizzetti et al., 2021).

Protected areas in Po Basin

The Po Basin hosts a network of protected areas aimed at preserving its rich biodiversity and maintaining essential ecosystem structure, functions and related services. Over the years, efforts have been made to enhance conservation measures, focusing on key objectives such as habitat protection, water quality improvement, and ecosystem restoration (Montanari, 2012). Moreover, The Po Delta Biosphere Reserve, designated by UNESCO in 2015 and expanded in 2018, is a crucial wetland ecosystem, promoting biodiversity conservation, sustainable development, and scientific research while balancing environmental protection with local economic activities. Since 1990 protected area coverage in the basin has increased from 4.20% to 16.45% (figure 10). The expansion of protected areas in the Po Basin has been driven by initiatives such as the Natura 2000 network and Ramsar site designations, ensuring the conservation of critical habitats, safeguarding native species, including migratory birds and endangered fish such as the Adriatic sturgeon (*Acipenser naccarii*) (Soorae, 2010). Protected wetlands help filter pollutants, reducing nitrogen and phosphorus loads entering the Po River and the Adriatic Sea (Grizzetti et al., 2021).

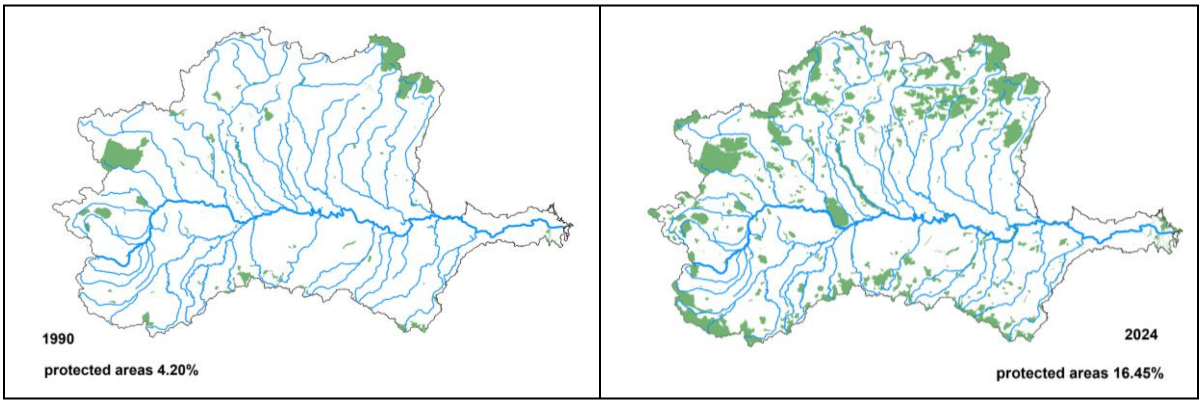


Figure 10. *Protected areas in the Po basin (green) in 1990 and 2024 **(**dataset source: WDPA)*

The Adriatic Sea region and the ecosystem services (ES)

The Adriatic Sea is a semi-enclosed basin located in the Central Mediterranean Sea and characterized by different types of coasts, with sandy beaches on the Westside, and rocky shores on the Eastside.

The Northern-Central Adriatic Sea is a shallow basin, with an average depth of about 80 m and it represents the widest continental shelf in the Mediterranean Sea. The Northern Adriatic Sea, where the Po River flows into, provides vital ES essential for both the environment and human well-being (figure 11) (Basconi et al., 2023).

Cultural and recreational services are particularly prominent, as beaches, coastal landscapes, and nearshore waters provide opportunities for tourism, swimming, and a wide range of nature-based experiences. Leisure navigation in coastal waters supports a growing boating and yachting industry. Complementing these benefits are key **regulating services**, with natural habitats such as seagrass meadows and dunes, help stabilize coastlines and mitigate erosion. Marine ecosystems contribute to climate regulation by storing greenhouse gases. In parallel, the region supports important **provisioning services**, including both **aquaculture and industrial fisheries**. Mussel farming (*Mytilus galloprovincialis*) and seabream & seabass (*Sparus aurata*, *Dicentrarchus labrax*) farming sustain seafood production. Industrial fisheries sector relies on trawl nets and purse seine fishing, targeting commercially valuable species

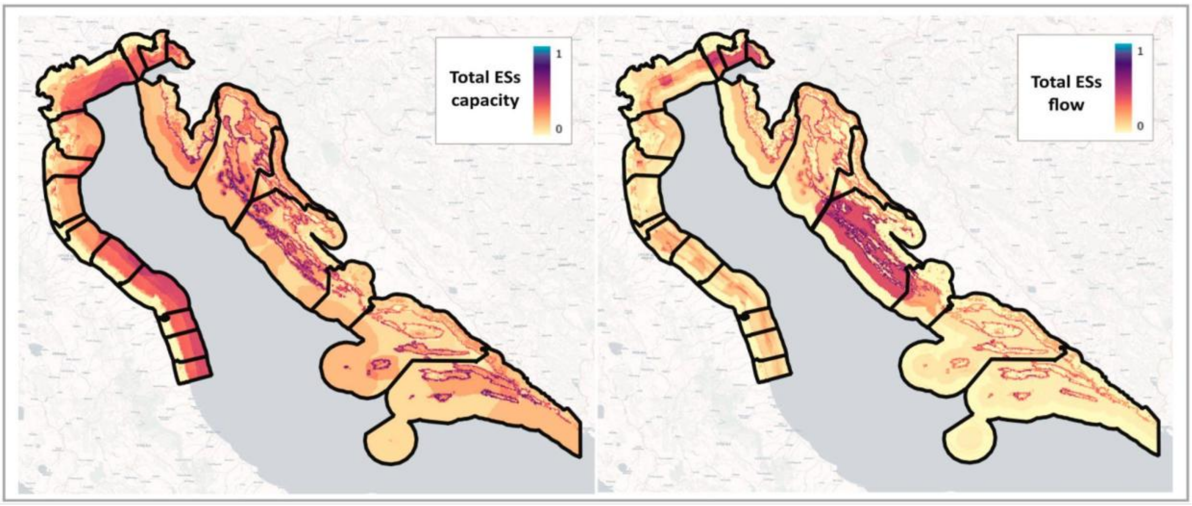


Figure 11. *Maps of total ecosystem services (ES) capacity and flow of the Northern-Central coastal-marine Adriatic system (from Basconi et al., 2023)*

4.2.2. Results

Exploratory analysis

Annual (2010-2022) data reported for the Po river before delta for TN concentrations show a modest but consistent decline, while TP remains very low and largely stable—reflecting long-term improvements in wastewater treatment and point-source control. The combination of expanding protected areas and gradually decreasing TN suggests strengthening upstream regulating services, although reductions remain limited relative to the basin's high agricultural intensity. Overall, the Po

Basin shows slow but positive nutrient improvements that align broadly with the progressive implementation of EU directives (figure 12).

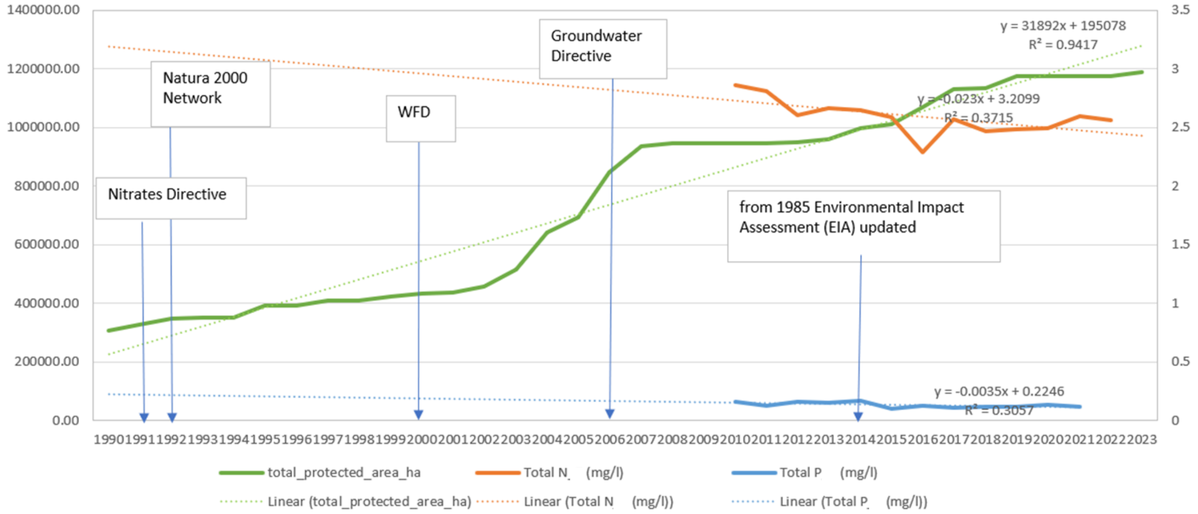


***Figure 12**. Dynamics of Total Nitrogen and Total Phosphorus in the Po river before its delta, aligned with the enactment of major legislation on protected areas, as well as key water conservation and protection directives (e.g., Water Framework Directive, Nitrates Directive, Groundwater Directive, updated Environmental Impact Assessment Directive), alongside the corresponding basin surface area of protected zones (ha).*

The spatial distribution of nutrient concentrations in the Po River Basin (figure 13 and 14) reveals persistent and extensive nitrogen and phosphorus enrichment, particularly in the central and southern agricultural lowlands. The maps show that large areas of the basin fall within the high to very high concentration classes (2–5 mgN/l and ≥5 mgN/l for nitrogen; 0.1–0.5 mgP/l and ≥0.5 mgP/l for phosphorus), reflecting the influence of intensive farming, livestock production, and nutrient-rich runoff. In contrast, upland headwaters and alpine regions exhibit lower nutrient levels, dominated by the lowest concentration classes due to reduced anthropogenic pressure. The long-term basin-area time series presented in the stacked-area charts confirm these patterns: throughout 1990–2018, elevated nutrient classes consistently occupy the largest share of the basin, with only modest fluctuations over time. Nitrogen concentrations remain dominated by the 1–2 mgN/l and ≥5 mgN/l classes, while phosphorus shows a persistent dominance of the 0.1–0.5 mgP/l class.

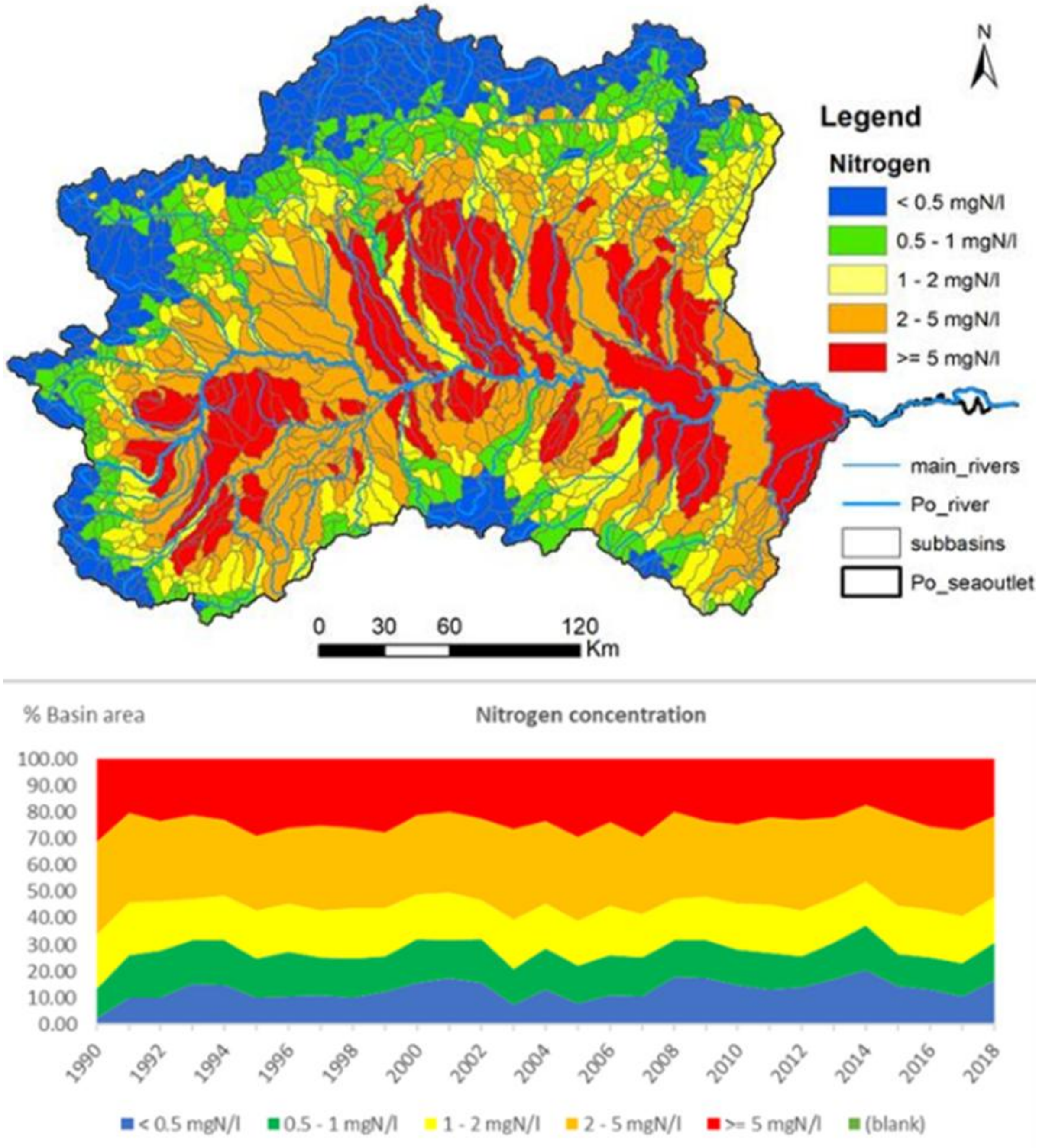


Figure 13. *Classes of mean annual Nitrogen concentrations in Po basin estimated at the outlets of freshwater functional elementary catchments (data source Grizzetti et al., 2022; dataset v. nov.2021)*

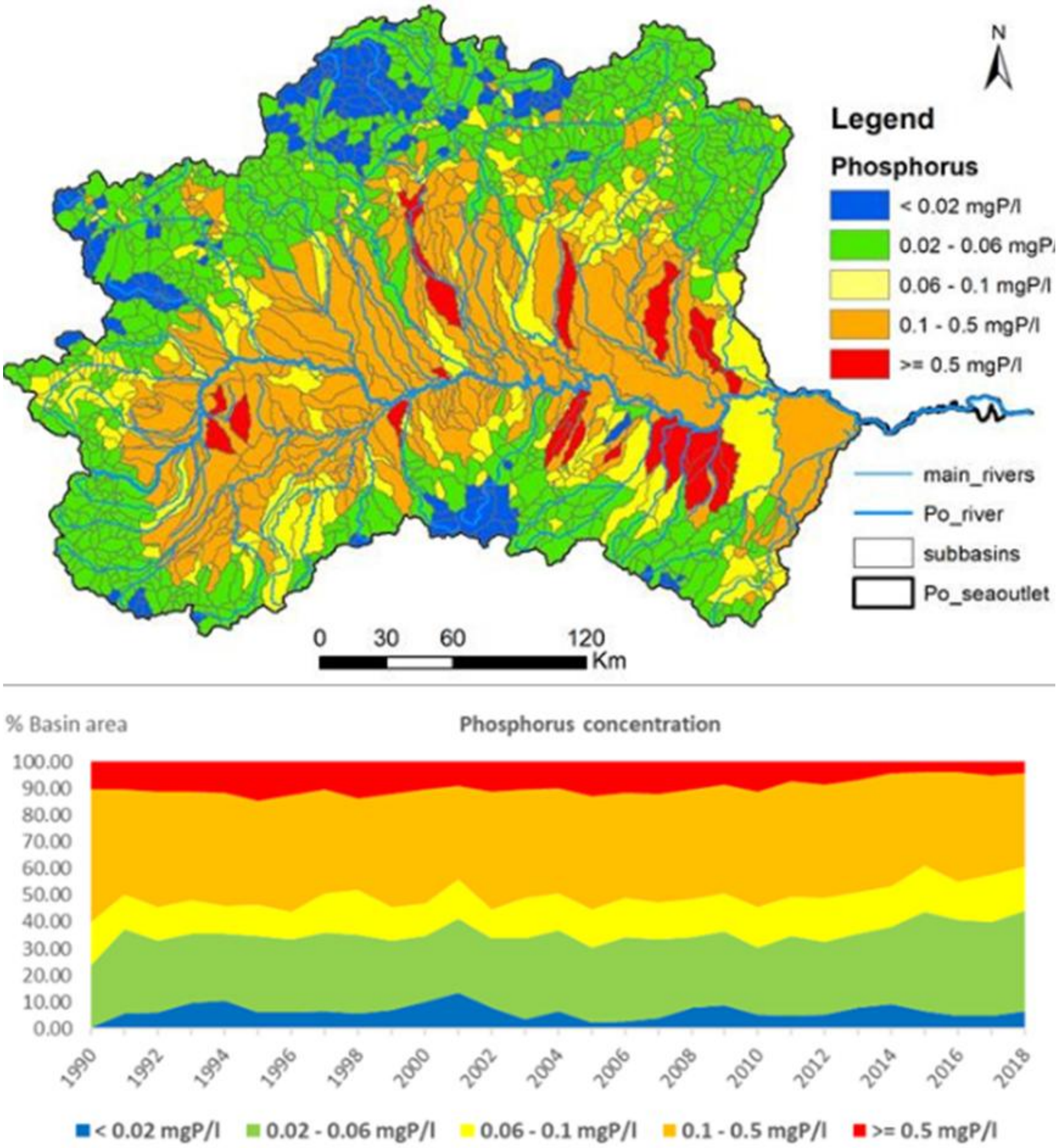


Figure 14. *Classes of mean annual Phosphorus concentrations in Po basin estimated at the outlets of freshwater functional elementary catchments (data source Grizzetti et al., 2022; dataset v. nov.2021)*

These combined spatial and temporal trends indicate the need for long-term, basin-wide nutrient management strategies to mitigate eutrophication risks and protect downstream coastal ecosystems.

To test the hypothesis that greater upstream protection in the Po basin leads to improved biodiversity by lowering nutrient export and creating better habitat conditions along land-to- Adriatic Sea continuum the spatially distributed relationships between protected area coverage (PA%), nutrient concentrations (nitrogen and phosphorus) and water ecological quality classes (EQC) based on biology EQR values as reported under WFD were examined.

Associations tests between protected area coverage, nutrients and water ecological quality classes

The Chi-square test statistics demonstrates highly significant relationships between protected area (PA) coverage, water EQC (based on biology EQRs) and nutrient concentrations (N, P) (table 6). Better water ecological quality is expected to co-occur with higher PA coverage and lower N and P concentrations to occur more frequently where PA coverage is higher. Cramér's V values (~0.15–0.27) indicate weak-to-moderate range effect sizes**,** but combined with p < .0001, the associations are statistically robust at the basin scale.

Table 6. Association tests between protected area coverage, water ecological quality classes (EQC) and nutrient concentrations in Po Basin

Variable Pair	Chi-square	df	p-value	Cramér's V
Protected Area vs water EQC	239.891	12	**<.0001**	0.152
Protected Area vs Nitrogen	302.026	12	**<.0001**	0.265
Protected Area vs Phosphorus	189.712	12	**<.0001**	0.210

p < .0001 **-** *very strong statistical significance***.**

To further assess the relationship between protected area coverage (PA) and water EQC, additional non-parametric tests were applied to compare distributions and detect if there are ordered trends (table 7).

Table 7. Tests to evaluate how water ecological quality classes (EQC) changes with protected area coverage (PA%) in Po Basin

Test	Statistic	p-value	Interpretation
Kruskal–Wallis Test (4 PA categories*)	215.281	**<.0001**	Highly significant difference in water EQC between PA categories
Mann–Whitney U (Low vs Very high PA)	367125.5	**<.0001**	Highly significant Low PA (0–25%) vs Very High PA (75–100%) difference in water EQC
Jonckheere–Terpstra (trend, Z)	0.306	**<.7597**	No significant trend

**PA categories: Low (0–25%); Moderate (25–50%); High (50–75%); Very high (75–100%)*

Kruskal–Wallis and Mann–Whitney tests both show highly significant differences in water EQC as a function of protected area coverage (p < .0001). The strongest contrast occurs between low and very high PA subbasins. However, the Jonckheere–Terpstra test does not detect a monotonic ordered trend (p = .7597), indicating that improvements do not follow a smooth Low → Moderate → High → Very High progression. Instead, the differences may be non-linear, influenced by local conditions, or concentrated in specific PA categories rather than following a strict progression.

4.2.3. Conclusions

In the Po basin the spatially distributed analysis showed highly significant relationships between protected area (PA) coverage, water EQC (based on biology EQRs) and nutrient levels (N, P). Better water ecological quality is expected to co-occur with higher PA coverage, but the improvements in EQC classes do not follow a linear progression with the increase of the protected area (PA) coverage. Lower N and P concentrations occur more frequently where PA coverage is higher.

4.3. Elbe – North Sea

4.3.1. Introduction

The catchment area of the Elbe River stretches from the Krkonoše Mountains in Czech Republic to the North Sea in Germany, also including parts of Poland and Austria. Along its 1094 km long way through low mountains ranges and a large lowland valley shaped by glacial processes, the Elbe is fed by many tributaries, the major ones are the rivers Vltava, Ohře, Saale, Havel, Mulde, and Schwarze Elster. 140 km after Hamburg a 20 km wide Elbe estuary reaches the Wadden Sea in the southern North Sea. The Elbe river basin offers a plethora of habitats and harbors more than 1,300 vascular plant species, more than 60 mammals, about 170 breeding bird species and almost 100 fish species (Scholten et al., 2005). One of the largest continuous floodplain forests in Europe is located in the basin of the Middle Elbe, home to beavers, black storks, lesser-spotted eagle as well as species threatened with extinction, like the water soldier (*Stratiotes gloides*), the fire-bellied toad (*Bombina bombina*) or the moor frog (*Rana gryalis*) (Scholten, 2005).

The last 140 km of the Elbe, starting at Geesthacht weir, is influenced by the tides. The tidal waves transport huge amounts of sediments back and forth and increase the residence time of the water in the system. About 20 km before Glückstadt the Elbe's freshwater starts to mix with saltwater, creating a transitional brackish water zone with increasing sea water influence until the stream reaches into the North Sea. Between up to 50 m high geest slopes, wide marshlands attract many rare birds to breed, the transition zone from fresh to seawater creates floodplain forests, mudflats, and reed areas, with unique fauna and flora, including endemic species like the Elbe water dropwort (*Oenanthe conioides*) and the hairgrass (*Deschampsia wibelian*). The Elbe reaches the North Sea in the Wadden Sea, the world's biggest mud flat, and UNESCO World Heritage site. It offers a multitude of habitats like tidal channels, sandy shoals, sea-grass meadows, mussel beds, salt marshes, beaches and dunes. The Wadden Sea is home to numerous plant and animal species, including harbour seal (*Phoca vitulina*), grey seal (*Halichoerus grypus*) and harbour porpoise (*Phocoena phocoena*), and is considered one of the most important regions for migratory birds.

Main degradation processes in the Elbe Basin

➢ **Diffuse and point source pollution**: Runoff from agriculture and urban areas introduces pollutants, excess nutrients, pesticides, medicine residuals and plastics into the river system. Discharges from wastewater treatment plants and industrial facilities release pollutants directly into the river. The current water quality status is not good, and the majority of all surface waters in the Elbe basin do not reach the good ecological status that is requested by the water framework directive (IKSE, 2016). Eutrophication, the excess of nutrients (figure 15), is a major pressure on the surface waters of the basin and the coastal ecosystems, and leads to large phytoplankton blooms, anoxia, an increase in opportunistic macroalgae and a decrease in seagrass (van Beusekom et al., 2001). Eutrophication is driven mainly by diffuse pollution from agricultural run-off and from wastewater treatment plants. For more information about eutrophication in the Wadden Sea see: *Eutrophication. The role of nutrients on the coast*

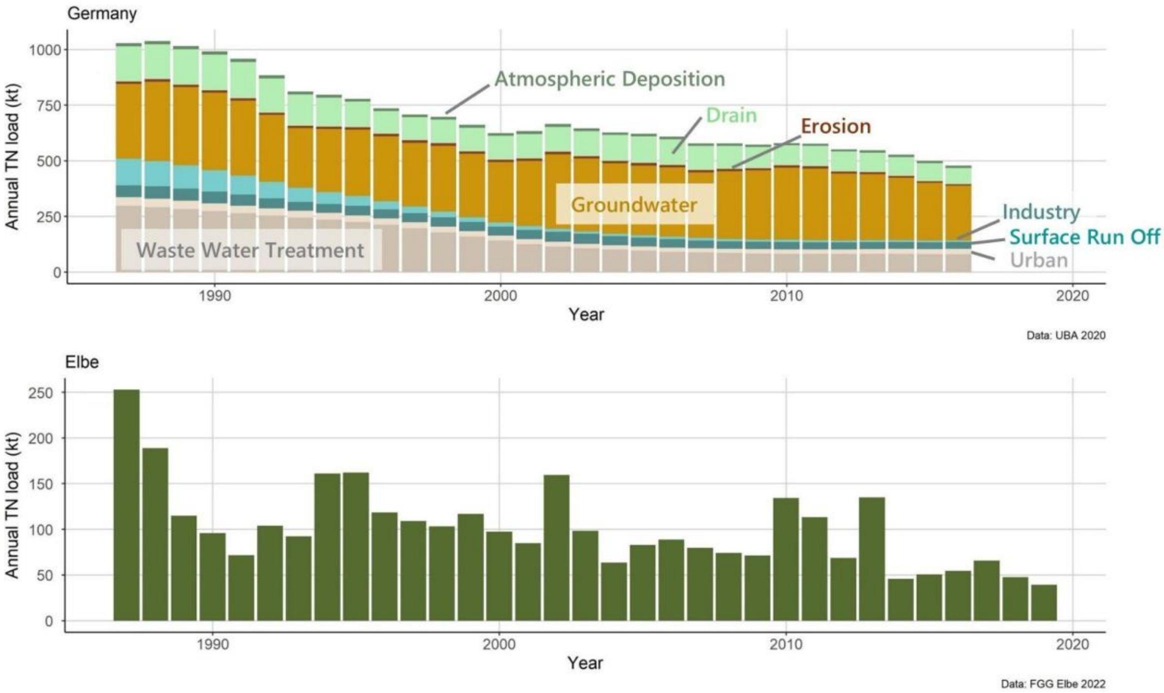


***Figure 15**. Annual total nitrogen emission from Germany and its sources, data provided from UBA (2020). The lower figure shows annual total nitrogen loads from entering the Elbe estuary at the weir Geesthacht, data from FGG Elbe (2002) (graph is modified from Schulz et al., 2023)*

- **Hydromorphological alterations**: River straightening, damming, dredging, embankments and groynes disrupt natural flow regimes and habitats. The Elbe river and its tributaries have been altered since centuries, but most alterations to the Elbe have been conducted in the 19th century to improve navigation and flood protection. Since then, the Elbe has been a developed waterway, controlled by structures like channels, dykes and groynes. As a consequence, sand and gravel are transported away which deepens the riverbed. On the other hand, in the estuary, the riverbed is constantly dredged to keep the water depth in the fairway deep enough for the Hamburg port to grant access for huge container ships. The Elbe floodplains have been disconnected and converted into arable land and settlement areas, so that more than 80% of these important ecosystems are lost. Nevertheless, the Elbe is still considered one of the least obstructed and relatively natural streams in Central Europe.

Protected areas in Elbe Basin

Numerous protected areas, ranging from UNESCO Biosphere Reserves to smaller nature parks were created especially after 1990 in the Elbe River basin to conserve natural habitats and biodiversity. The largest terrestrial Biosphere Reserve 'Flusslandschaft Elbe' was established 1997 and covers almost 400 km of the Elbe River and a total of 342.000 ha. Several National Parks are situated within the Elbe basin, e.g. the Krkonoše National Park, the Bohemian Switzerland National Park and Saxon Switzerland National Parks which include picturesque Elbe sandstone mountains. The basin further includes almost 20 RAMSAR wetland sites, some since 1976, and numerous bird sanctuaries and Flora Fauna Habitats that were declared within the Natura 2000 framework. Since 1990 protected area coverage in the basin has increased from 13.46% to 33.99% (figure16).

Long-term renaturation projects are initiated to restore the typical river and floodplain environments and to give the Elbe and its tributaries room to expand. Floodplains filter and store water, sequester CO_2, and ensure natural flood protection. Dykes are relocated and plains reopened to relieve the main stream at high waters. This way, 420 ha new floodplain have been created with the Lenzen dyke relocation project in Brandenburg (Damm, 2013), which now provides habitats like alluvial forests, meadows, and wetlands, for numerous animal and plant species. In another project in Saxony-Anhalt 600 ha of new floodplain are now protected by the "Middle Elbe between Mulde and Saale" nature reserve.

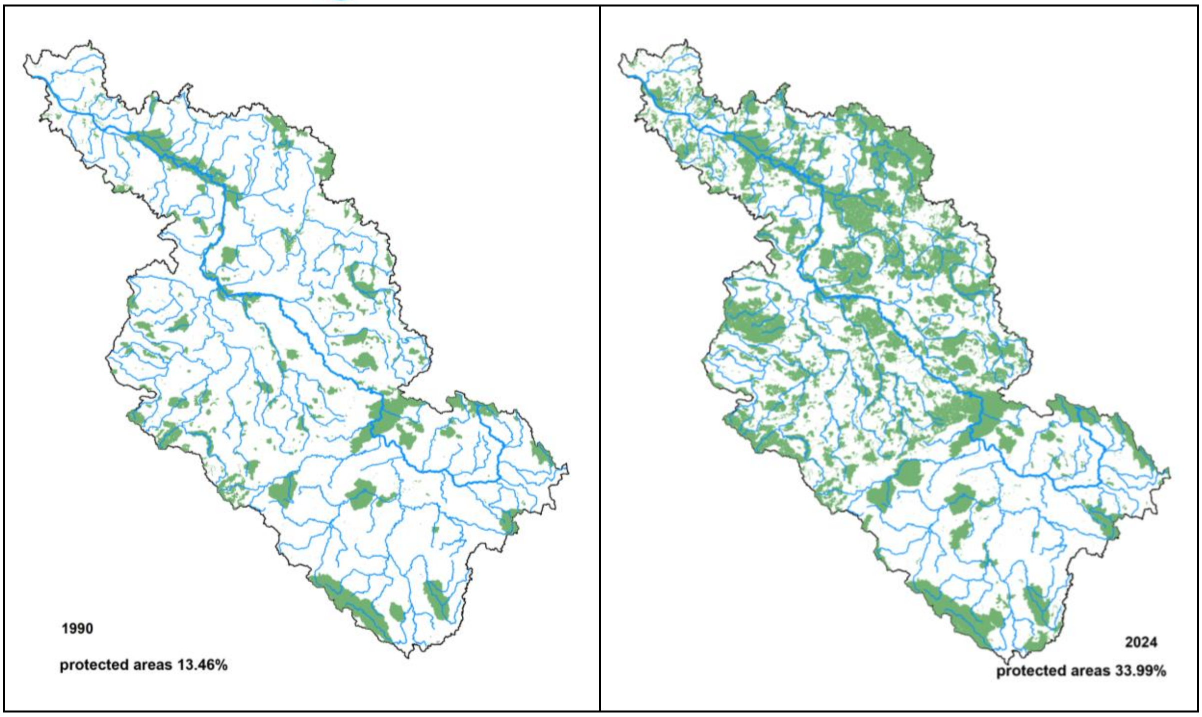


Figure 16. *Protected area in the Elbe basin (green) in 1990 and 2024* ***(****dataset source WDPA)*

The North Sea and the ecosystem services (ES)

The North Sea in the German Bight is a shallow sea characterized by wide tidal flats, particularly in the Wadden Sea region. It provides crucial ES essential for both the environment and human well-being. ***Provisioning services*** include its role as one of Europe's most important **fisheries**, supplying substantial quantities of seafood and sustaining coastal livelihoods. These benefits are supported by fundamental **life-cycle maintenance processes**, as phytoplankton and seaweeds form the base of the marine food web. The region is also a major centre of **energy production**, fossil fuels are extracted from the seabed and offshore wind farms are expanding rapidly, providing sustainable energy. In addition, the North Sea functions as a critical corridor for **marine traffic**, with several major shipping routes with the approach to the Port of Hamburg passing through it.

Equally important are the ***regulating services*** provided by the North Sea and its coastal ecosystems. **Coastal protection** is delivered by wetlands, seagrass meadows, dunes and island barriers which help to stabilize coastlines and mitigate erosion. The water absorbs carbon dioxide and heat, and marine sediments, oyster reefs and seagrass meadows **sequester carbon.** Furthermore, the system supports nutrient cycling and natural filtration, as biogeochemical processes in the water column and sediments help remove excess nutrients and pollutants, thereby maintaining water quality and overall ecosystem functioning.

Cultural & Recreational Services: the region is popular for beaches, biking, sailing, fishing, and birdwatching and attracts millions of visitors annually

Many of the ES face significant threats from pollution, overfishing, habitat loss, and climate change. Protecting the North Sea's ecological integrity is essential to sustaining these services and ensuring that they continue to benefit both people and the environment for generations to come. The interconnected nature of its ES underscores the importance of holistic and cooperative management efforts across the region.

Seagrass for example helps stabilize the seabed, improves water quality, absorbs and stores carbon from the air, and provides nursery grounds for fish, and shelter for small organisms like snails and crabs. This makes it also a food source for migratory and coastal birds. Seagrass beds in the Wadden Sea disappeared almost completely due to excess nutrients introduced from the rivers, which lead to the spread of green algae, suffocating the seagrass beneath a thick layer. After many years and improvements in water quality, seagrass beds have recovered in areas mostly farther away from the river mouths (figure 17). This shows how important it is to reduce nutrient loads in the basin to recover and protect these vital and crucial habitats in the North Sea.

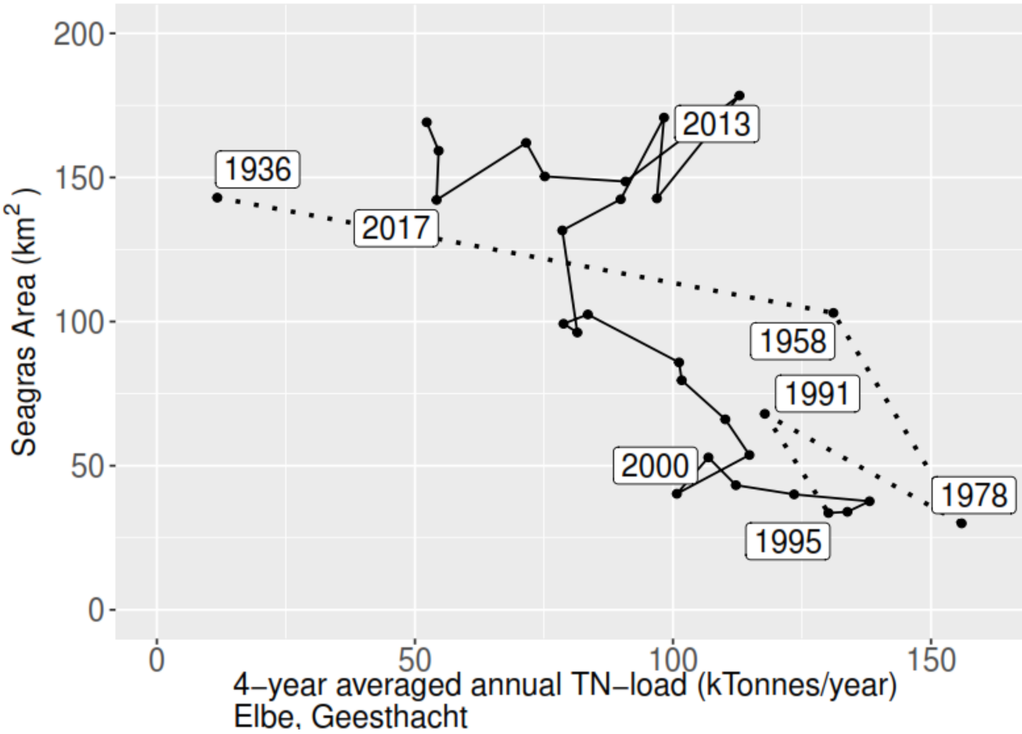


Figure 17. *Relation between 4-year averaged riverine total nitrogen load of the Elbe and seagrass coverage in the North Frisian region, modified from van Katwijk et al. (2024), the dotted lines were added for visualization where time points are further away from each other*

4.3.2. Results

Exploratory analysis

In the late 1980s, the Elbe was one of the most polluted rivers in Europe. Since then, there has been a significant improvement in water quality of the Elbe River and its tributaries, mainly due to the implementation of environmental policies, closure of industrial enterprises and upgrading of sewage treatment plants.

Long-term annual (1978-2023) data reported for the Elbe river before the estuary show that both nitrogen and phosphorus concentrations exhibit downward trends (figure 18). TN decreases markedly from the high values of the 1970s–1980s to much lower levels after 2000, and TP is stabilizing at low concentrations after the early 1990s. These reductions align temporally with successive EU policy interventions (Nitrates Directive, WFD, Groundwater Directive, Natura 2000 expansion) suggesting cumulative regulatory effects. Despite year-to-year variability, the overall pattern reflects substantial nutrient mitigation, driven by improved wastewater treatment, agricultural management reforms, and tightening environmental standards, while conservation efforts intensified in parallel through rapid protected-area designation across the corresponding catchment. In the North Sea nutrient reductions remain modest, and chl-a increases, suggesting continuing eutrophication potential (figure 19).

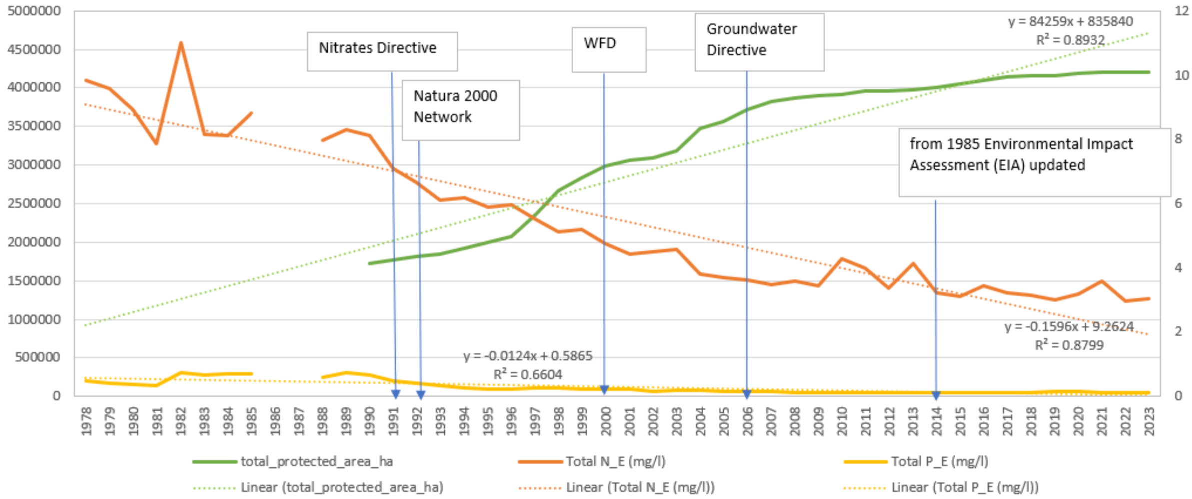


***Figure 18**. Dynamics of Total Nitrogen and Total Phosphorus in the Elbe river before its estuary, aligned with the enactment of major legislation on protected areas, as well as key water conservation and protection directives (e.g., Water Framework Directive, Nitrates Directive, Groundwater Directive, updated Environmental Impact Assessment Directive), alongside the corresponding basin surface area of protected zones (ha).*

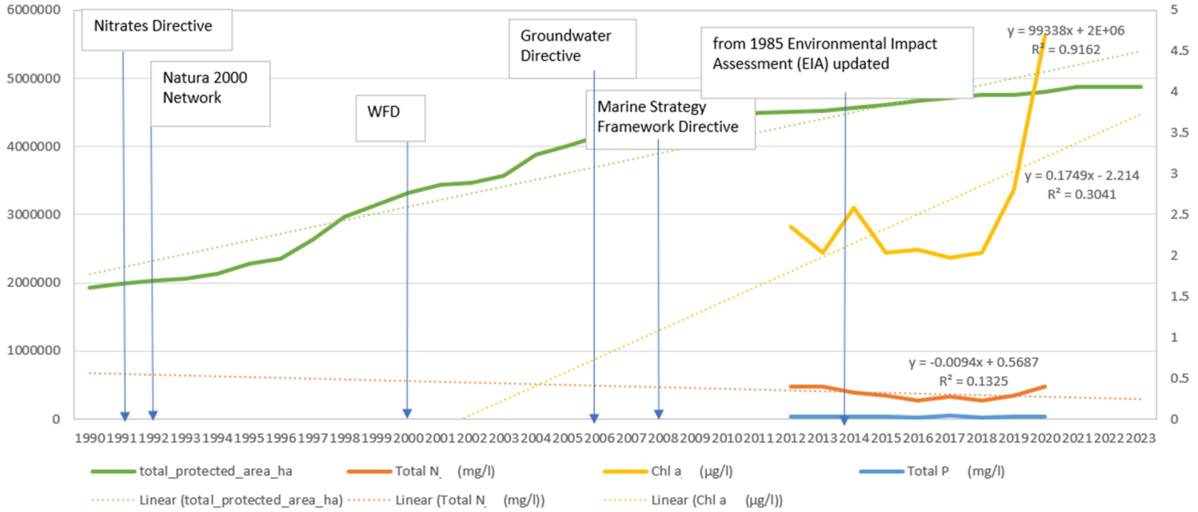


***Figure 19**. Trends in the surface area of protected zones within the Elbe basin (ha), aligned with the enactment of major legislation on protected areas, as well as key water conservation and protection directives (e.g., Water Framework Directive, Nitrates Directive, Groundwater Directive, updated Environmental Impact Assessment Directive, and Marine Strategy Framework Directive), analyzed alongside the dynamics of Total Nitrogen, Total Phosphorus and chlorophyll-a (chl-a) in the North Sea.*

Nitrogen and phosphorus patterns in the Elbe basin show persistent nutrient pressures with spatial hotspots, despite gradual long-term improvements (figure 20 and 21). The maps reveal extensive areas dominated by moderate to high nitrogen concentrations (1–5 mgN/l), with critical hotspots (≥5 mgN/l) particularly in the north and east, while the stacked-area charts show that, although the proportion of extremely high-N areas fluctuates, most of the basin remains in the 1–5 mgN/l range throughout 1990–2018. Phosphorus shows a more favourable distribution, with large parts of the basin in low or moderate classes (<0.1 mgP/l), though high-P hotspots (≥0.5 mgP/l) remain scattered in several sub-catchments. Over time, the basin-wide share of the highest P classes decreases slightly, but the 1–0.5 mgP/l category remains dominant, indicating that diffuse agricultural inputs continue to constrain full improvement. Overall, the Elbe basin exhibits clear spatial heterogeneity, stable nutrient hotspots, and only partial long-term reductions, reflecting the combined influence of land use, legacy pollution, and variable hydrological conditions.

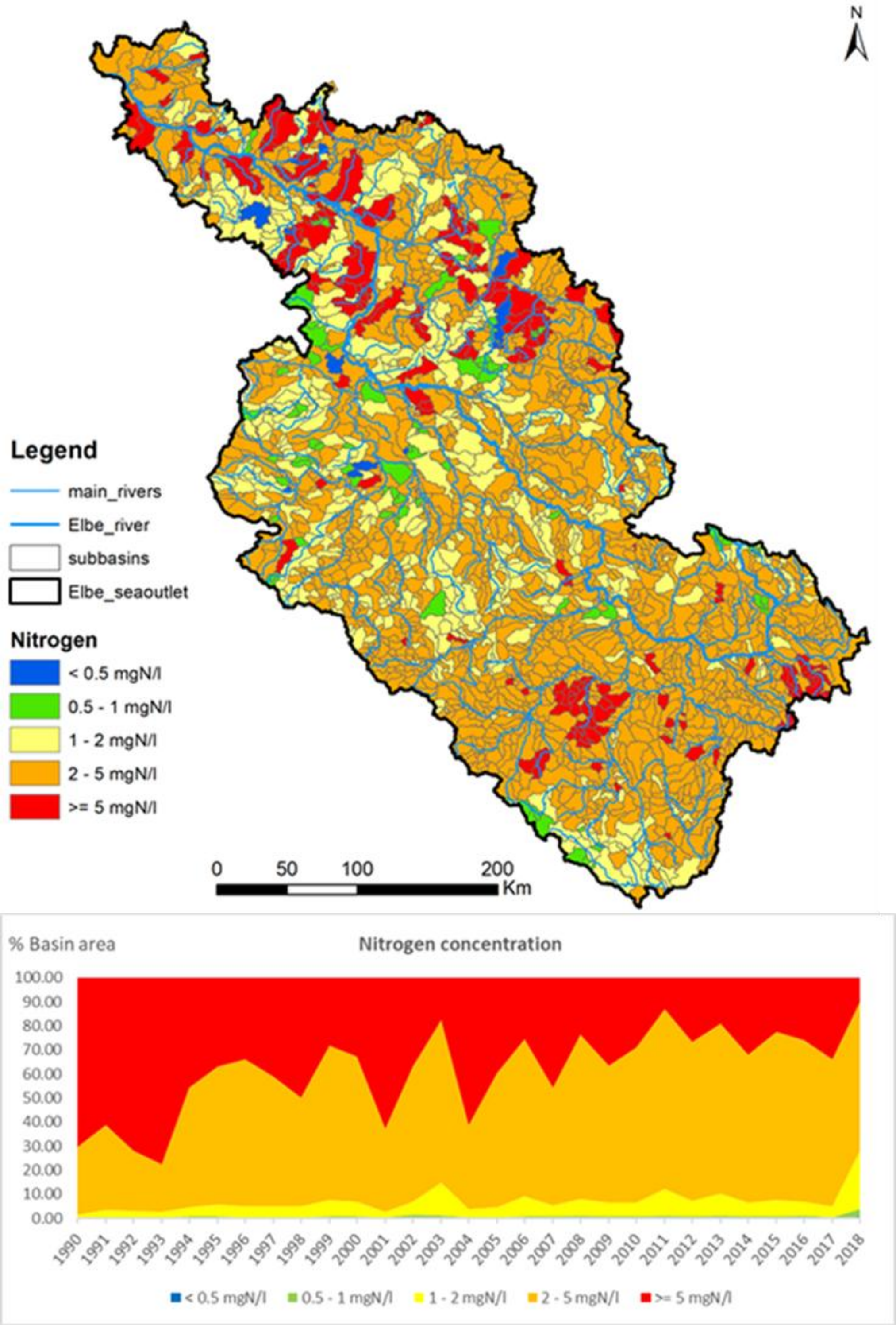


Figure 20. *Classes of mean annual Nitrogen concentrations in Elbe basin estimated at the outlets of freshwater functional elementary catchments (data source Grizzetti et al., 2022; dataset v. nov.2021)*

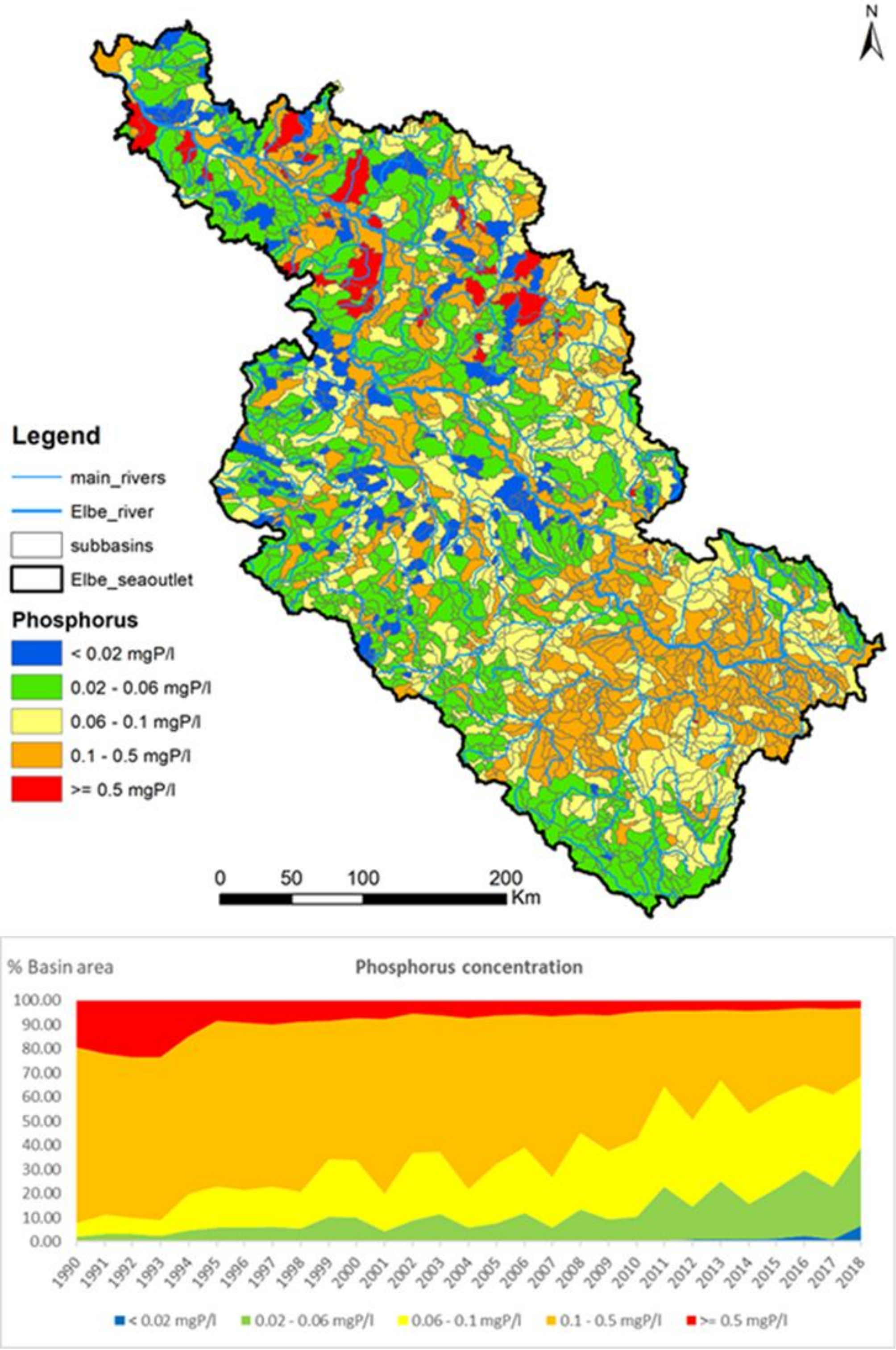


Figure 21. *Classes of mean annual Phosphorus concentrations in Elbe basin estimated at the outlets of freshwater functional elementary catchments (data source Grizzetti et al., 2022; dataset v. nov.2021)*

To test the hypothesis that greater upstream protection in the Elbe basin leads to improved biodiversity by lowering nutrient export and creating better habitat conditions along land-to-North Sea continuum the spatially distributed relationships between protected area coverage (PA%), nutrient concentrations (nitrogen and phosphorus) and water ecological quality classes (EQC) based on biology EQR values as reported under WFD were examined.

Associations tests between protected area coverage, nutrients and water ecological quality classes

The Chi-square test statistics demonstrate significant relationships between protected area coverage and water EQC (based on EQRs) and highly significant relationships between protected area (PA) coverage and nutrient concentrations (N, P) (table 8). Better water ecological quality is expected to co-occur with higher PA coverage and lower N and P concentrations to occur more frequently where PA coverage is higher. Cramér’s V values (~0.24–0.34) indicate moderate associations.

Table 8. Association tests between protected area coverage, water ecological quality classes (EQC) and nutrient concentrations in Elbe basin

Variable Pair	Chi-square	df	p-value	Cramér’s V
Protected Area vs water EQC	26.453	12	**< .05**	0.249
Protected Area vs Nitrogen	39.312	9	**< .0001**	0.339
Protected Area vs Phosphorus	34.349	9	**< .0001**	0.317

p < .05 - significant, p < .0001 - very strong statistical significance

To further assess the relationship between protected area coverage (PA) and water EQC, additional non-parametric tests were applied to compare distributions and detect if there are ordered trends.

Table 9. Tests to evaluate how water ecological quality classes (EQC) with protected area coverage (PA%) in Elbe basin

Test	Statistic	p-value	Interpretation
Kruskal–Wallis Test (4 PA categories*)	1.8095	.6129	No significant difference in water EQC between PA categories
Mann–Whitney U (Low vs Very high PA)	802.0	.7173	No significant Low PA (0–25%) vs Very High PA (75–100%) difference in water EQC
Jonckheere–Terpstra (trend, Z)	-0.008	.9101	No significant trend

**PA categories: Low (0–25%); Moderate (25–50%); High (50–75%); Very high (75–100%)*

The Kruskal–Wallis nor the Mann–Whitney U tests did not detect a significant difference in ecological status among PA categories, likely due to higher within-group variability, and no significant trend was detected (table 9), although the previous chi-square test indicated moderate associations — this suggests that protection likely exerts an **indirect effect** (through nutrient reduction) rather than producing a clear shift in the overall status distribution. Association tests between nutrient concentrations and water ecological quality classes (EQC) show that low Nitrogen and Phosphorus concentrations were predominantly associated with High and Good ecological status, while high N and P concentrations were associated with Moderate to Poor ecological status. Chi-square tests confirmed statistically highly significant associations ($p < .001$) (table 10).

Table 10. Association tests between nutrient concentrations and water ecological quality classes (EQC) in Elbe Basin

Variable Pair	Chi-square	df	p-value	Cramér's V
Nitrogen vs water EQC	80.48	12	.001	0.49
Phosphorus vs water EQC	64.15	12	.001	0.43

p < .001 - strong statistical significance

4.3.3. Conclusions

In the case of Elbe the spatially distributed relationship between protected areas (PA) and water EQC is not direct, but rather the higher protection levels are associated with lower nutrient concentrations in sub-catchments, which in turn support better ecological status.

4.4. Guadalquivir – Atlantic Ocean

4.4.1. Introduction

The Guadalquivir river, one of Spain's most significant waterways, flows across the southern region of Andalusia before meeting the Atlantic Ocean near the town of Sanlúcar de Barrameda. This convergence creates a dynamic and complex interaction between fluvial and marine environments. As the river approaches the ocean, it slows and broadens, depositing sediments that contribute to the formation of fertile marshlands and estuarine ecosystems. This transitional zone, known as the Guadalquivir estuary, serves as a vital ecological interface where freshwater from the river mixes with the saline waters of the Atlantic.

The interaction between the Guadalquivir and the Atlantic also has important climatic, economic, and cultural implications. Tidal influences from the ocean reach far inland, affecting navigation, salinity levels, and agricultural practices along the riverbanks. Historically, this connection enabled the city of Seville, located more than 80 kilometres from the coast, to flourish as a major inland port during the Age of Exploration. Today, the river-ocean interface continues to shape local livelihoods, support biodiversity, and highlight the interdependence between inland and coastal environments. The Guadalquivir river is the only major waterway navigable in Spain spanning some 657 km. Thanks to an inland port 80 km upstream, the river has played a key role in Seville's history allowing Seville to become the economic centre of the Spanish Empire in the 16th century but also imposing its chaotic behavior, flooding the city on many occasions.

The Guadalquivir catchment, located in southern Spain, is a region of remarkable biodiversity due to its varied landscapes, which include wetlands, forests, mountains, and agricultural lands. This diversity of habitats supports a wide range of flora and fauna, including endemic plant species and numerous bird species, many of which migrate along the East Atlantic Flyway. The Doñana National Park, located at the river's delta, is a key ecological zone, serving as a critical refuge for endangered species such as the Iberian lynx (*Lynx pardinus*) and the Spanish imperial eagle (*Aquila adalberti*). The catchment also hosts rich aquatic ecosystems, which are vital for both biodiversity conservation and local livelihoods.

The Guadalquivir river basin is among the most heavily regulated in Spain and in the world, featuring an extensive network of dams and reservoirs. According to recent data, the basin encompasses a total of 118 dams, with 11 situated directly on the main course of the Guadalquivir River. These structures have been constructed primarily for purposes such as irrigation, hydroelectric power generation, and flood control. Additionally, the regulation of water flow has implications for water quality and availability, particularly in the estuarine regions where the Guadalquivir meets the Atlantic Ocean.

Main degradations processes in the Guadalquivir Catchment

- **Water Abstraction and Hydrological Alteration:** The proliferation of dams has significantly altered the river's natural flow regime, impacting sediment transport and disrupting ecological processes (11 dams on the Guadalquivir river for 600km of river, 118 in its basin). These dams, primarily built for irrigation, hydroelectric power, and flood control, have reduced the river’s sediment transport and disrupted the natural seasonal flow patterns essential for wetland and estuarine ecosystems. As a result, areas like the Doñana National Park—a UNESCO World Heritage site dependent on periodic flooding—face threats from reduced freshwater input and altered hydrological cycles, but also from illegal watering practices from surrounding agriculture. Furthermore, the regulation of the river’s flow impacts fish migration, water quality, and the overall health of downstream habitats, intensifying the pressure on both biodiversity and traditional agricultural systems that rely on the natural rhythms of the river. Large-scale irrigation and dam construction alter natural flow regimes, affecting aquatic species and wetland ecosystems. Use of water in the Guadalquivir River basin is dominated by irrigated agriculture, which accounts for approximately 80% of water consumption (figure 22). With drought situations becoming more and more frequent with climate change, the Guadalquivir river will face reduced navigability and shortage in water supplies with multiple consequences for agriculture, the environment and the economy.

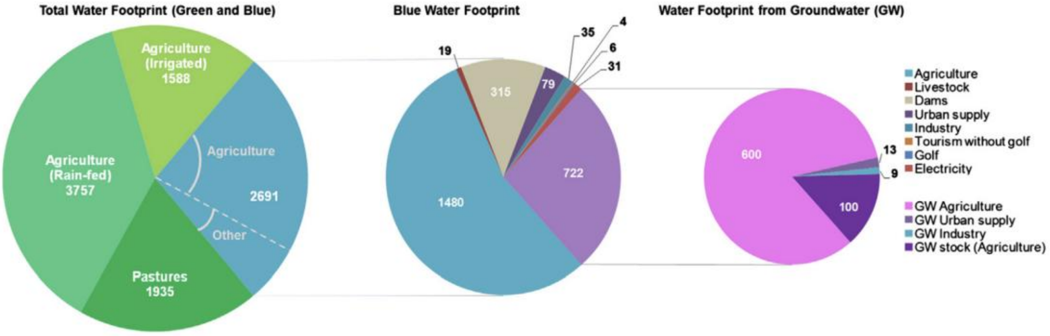


Figure 22. *The total water footprint (Mm³) of the Guadalquivir basin, distinguishing green and blue (surface and ground water) water footprints (Dumont et al., 2013)*

- **Pollution (agricultural and industrial):** Runoff containing fertilizers, pesticides, and industrial waste affects water quality and species survival, particularly in aquatic habitats. Water quality in the Guadalquivir basin is a significant environmental concern due to pressures from agriculture, urban development, and industrial activity. In 1998 there was a major case of industrial pollution, when a holding mine dam near Aznalcóllar burst, releasing toxic sludge and acidic water causing widespread ecological damage. High levels of nutrients, mainly nitrates and phosphates, enter the river system through runoff from intensive farming, leading to eutrophication and the degradation of aquatic habitats. In some areas, pollution from untreated or insufficiently treated wastewater further exacerbates the problem, particularly during low-flow periods when dilution is minimal. Despite ongoing monitoring and management efforts, improving water quality remains a challenge, requiring stricter regulation, better wastewater treatment, and more sustainable land-use practices.

Protected areas in Guadalquivir basin

The Guadalquivir River Basin contains one of the largest and most diverse protected-area networks in Spain, spanning mountain headwaters, Mediterranean forests, dehesa landscapes, wetlands, lagoons, and the estuarine marshes at the river mouth. Doñana National Park is one of Europe's most important and biologically diverse wetlands, located at the estuary of the Guadalquivir River, where it meets the Atlantic Ocean in southwestern Spain. Doñana holds multiple conservation level designations: National Park (1969), UNESCO Biosphere Reserve (1980), Ramsar Wetland of International Importance (1982), UNESCO World Heritage Site (1994) and is part of the Natura 2000 Network (EU Habitats & Birds Directives). Since 1990 protected area coverage in the basin has increased from 15.22% to 29.85% (figure 23).

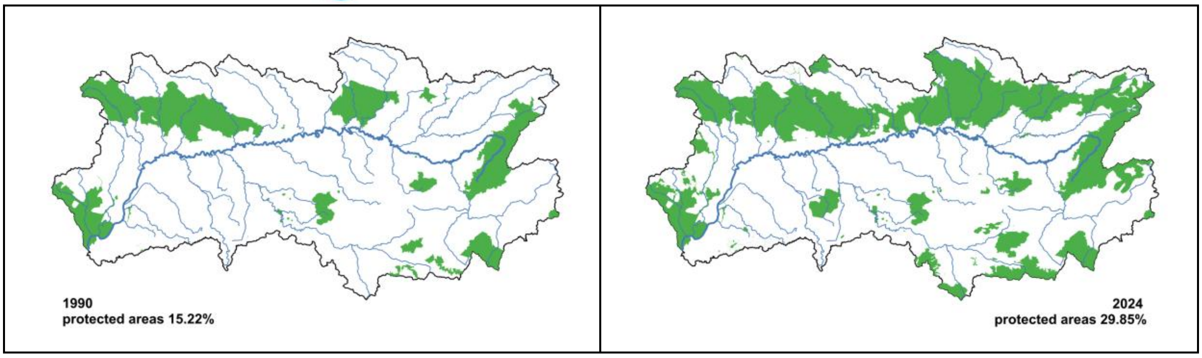


Figure 23. *Protected area in the Guadalquivir basin (green) in 1990 and 2024 (dataset source WDPA)*

The Atlantic Ocean, Guadalquivir estuary region and the ecosystem services (ES)

The Atlantic Ocean in the Guadalquivir estuary region provides a wide range of essential ES that support both the environment and human societies (figure 24). Through their combined hydrological and ecological dynamics, they generate provisioning services (e.g., fisheries, aquaculture, rice production, and maritime transport), regulating services (including water purification, climate regulation, and coastal protection), cultural services (tourism, recreation, and symbolic value), and supporting services such as nutrient cycling, primary production, and habitat provision.

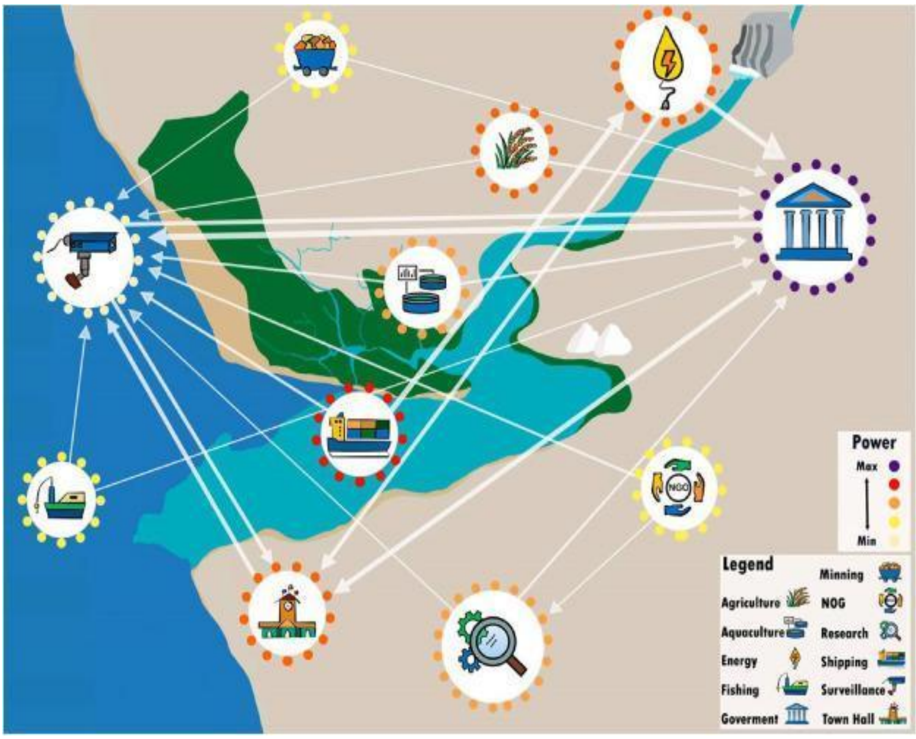


Figure 24. *The Guadalquivir estuary-Gulf of Cadiz coupled socio-ecological system (Garcia-de-Vinuesa et.al., 2025)*

This Atlantic-estuarine interface is particularly observed in the functioning of reconstructed wetlands such as Veta la Palma, located between the Guadalquivir River and Doñana National Park. Estuarine inflows supply nutrient-rich brackish water that fuels high primary productivity, enabling the wetland to remove approximately 377 tonnes of dissolved inorganic nitrogen per year and to sequester substantial amounts of carbon. These processes underpin key regulating services such as water purification and climate mitigation. At the same time, the wetland supports extensive and semi-extensive aquaculture and provides habitat for more than 94 wetland bird species and 21 fish species, illustrating how provisioning, supporting, and biodiversity-related services are tightly coupled in this system (Walton et al., 2015).

Across the broader Doñana marshes, the influence of Atlantic-driven hydrology interacts with seasonal flooding and groundwater inputs to create a mosaic of clear- and turbid-water patches. This fine-scale spatial heterogeneity shapes the performance of critical ecosystem services. Clear-water, macrophyte-dominated areas, for instance, exhibit greater efficiency in water purification, soil stabilization, and flood regulation—regulating services that directly support high biodiversity and overall ecosystem functioning (Gómez-Baggethun et al., 2011). Although clear and turbid states coexist, the enhanced ecological service provision of clear-water patches highlights the importance of maintaining natural hydrological regimes and controlling nutrient inputs across the Guadalquivir–Atlantic wetland gradient.

At the landscape scale, the delivery of ecosystem services within the Doñana social-ecological system is increasingly constrained by land-use change in the surrounding areas. From 1956 to 2007, rapid expansion of irrigated agriculture and urban development outside the protected zones coincided with a marked decline in wetland extent and increased isolation of the National and Natural Parks. As a result, high-value regulating and cultural services, such as water regulation, habitat provision, recreation, aesthetic appreciation and environmental education, remain predominantly concentrated within the protected areas, while provisioning services, particularly agricultural production, dominate the transformed landscapes beyond (Palomo et al., 2014).

Together, the Atlantic Ocean, the Guadalquivir estuary, and the Doñana marshes form an interconnected ecological continuum, whose ability to provide ecosystem services, ranging from nutrient retention and carbon storage to biodiversity support and cultural value, relies on intact hydrological and ecological connections. Protecting these linkages is vital for maintaining the resilience of the region and ensuring the continued flow of ecosystem services to both local communities and the wider European landscape.

4.4.2. Results

Exploratory analysis

Nitrogen and phosphorus patterns in the Guadalquivir basin reveal widespread and persistent nutrient pollution (figure 25 and 26), with far more severe conditions than in the other case studies.

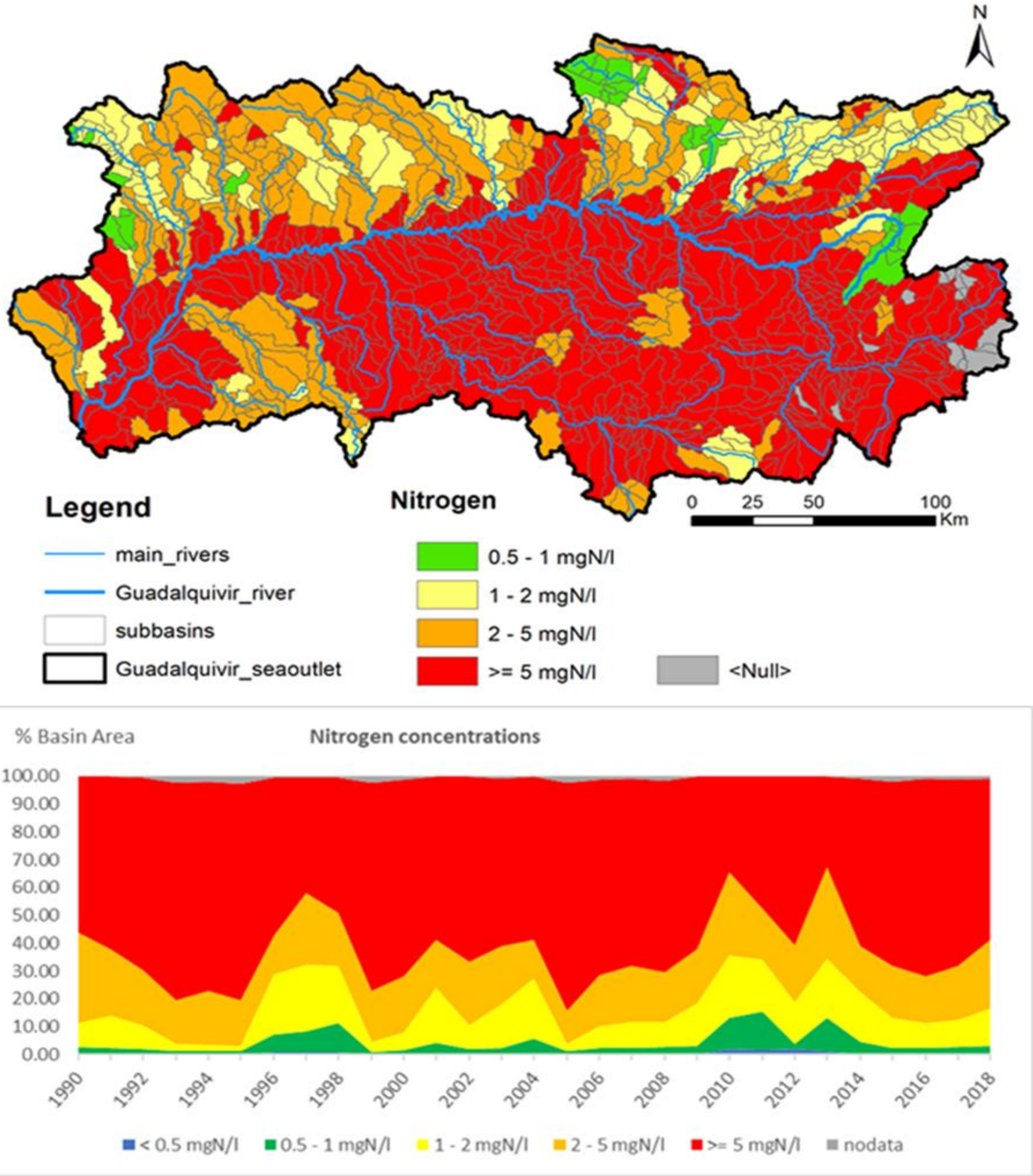


Figure 25. *Classes of mean annual Nitrogen concentrations in Guadalquivir basin basin estimated at the outlets of freshwater functional elementary catchments (data source Grizzetti et al., 2022; dataset v. nov.2021)*

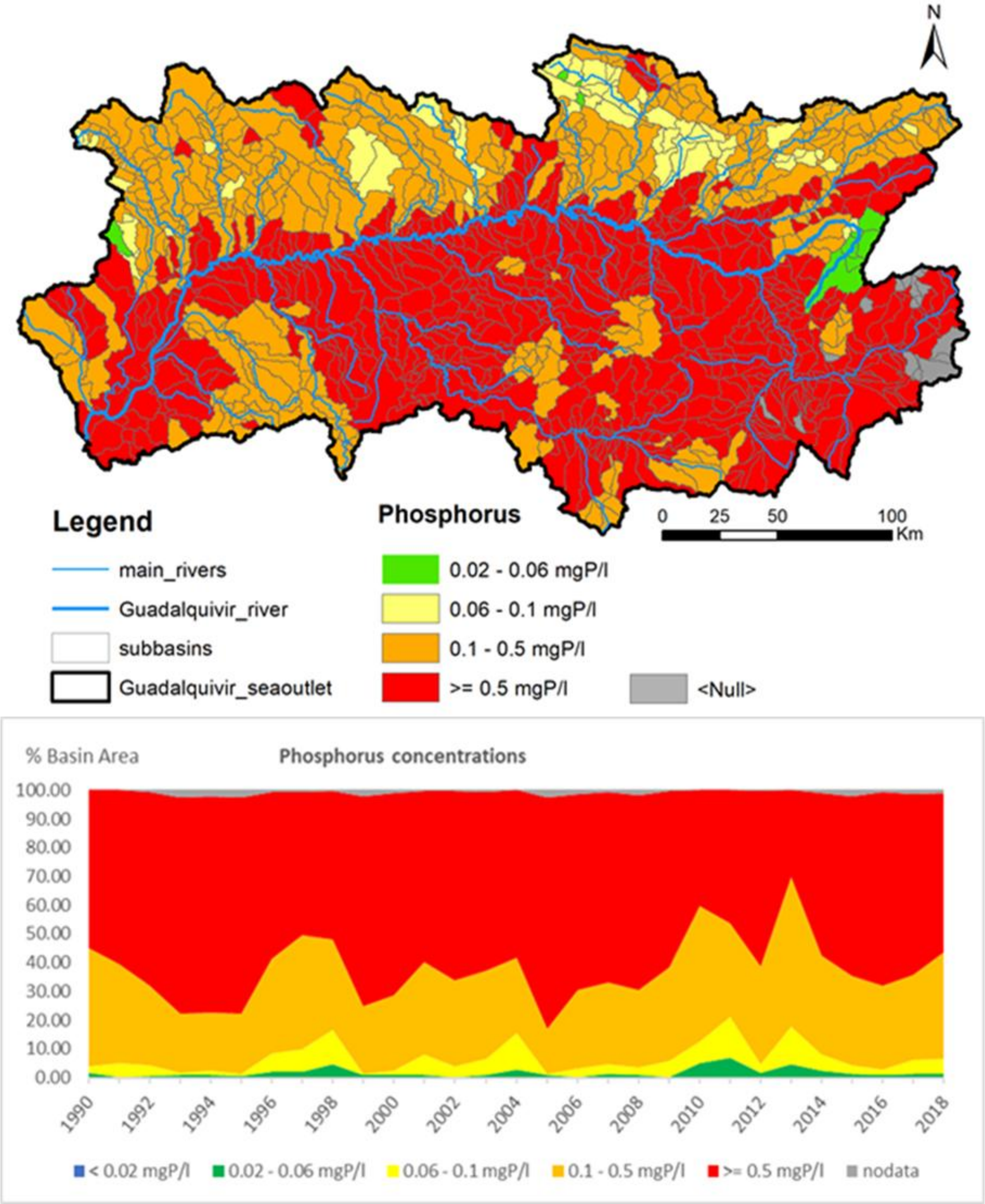


Figure 26. *Classes of mean annual Phosphorus concentrations in Guadalquivir basin basin estimated at the outlets of freshwater functional elementary catchments (data source Grizzetti et al., 2022; dataset v. nov.2021)*

The nitrogen map is dominated by high to very high concentrations (2–5 mgN/l and ≥5 mgN/l) across most sub-catchments, and the temporal plot confirms that over 80–90% of the basin consistently falls in these two highest classes from 1990 to 2018. Phosphorus shows an even more critical situation: the map reveals extensive areas with extremely high P levels (≥0.5 mgP/l), and the stacked-area charts indicate that this class occupies the vast majority of basin area throughout the entire period, with only small fluctuations and very limited representation of low-P waters. This pattern reflects strong and sustained pressures from intensive agriculture, livestock production, and hydrological regulation, resulting in chronic nutrient enrichment and high ecological vulnerability throughout the Guadalquivir basin.

To test the hypothesis that greater upstream protection in the Guadalquivir basin leads to improved biodiversity by lowering nutrient export and creating better habitat conditions along land-to-Atlantic Ocean continuum the spatially distributed relationships between protected area coverage (PA%), nutrient concentrations (nitrogen and phosphorus) and water ecological quality classes (EQC) based on biology EQR values as reported under WFD were examined.

Associations tests between protected area coverage, nutrients and water ecological quality classes

The Chi-square test statistics demonstrate that all associations are statistically significant ($p < .001$) (table 11). Moderate relationships are observed between protected area coverage and nutrient concentrations (N and P), with Cramér's V values of approximately 0.34–0.35. Sites with higher PA coverage tend to have better water ecological quality, while low protection areas are associated with poorer ecological conditions. The Cramér's V of 0.26 indicates a moderate strength of association.

Table 11. Association tests between protected area coverage, water ecological quality classes (EQC) and nutrient levels in Guadalquivir basin

Variable Pair	Chi-square	df	**p-value**	Cramér's V
Protected Area vs water EQC	213.521	12	**< .001**	0.257
Protected Area vs Nitrogen	262.444	9	**< .001**	0.346
Protected Area vs Phosphorus	254.966	9	**< .001**	0.341

p < .001 - strong statistical significance

To further assess the relationship between protected area coverage (PA%) and water ecological quality classes (EQC), non-parametric tests were applied to compare distributions and detect ordered trends across PA categories (table 12). The Kruskal–Wallis test detected significant differences between PA categories, indicating that water ecological quality varies across protection levels. The Mann–Whitney U test further confirmed a significant difference between sites with low and very high protection levels. Finally, the Jonckheere–Terpstra test revealed a significant monotonic trend, with ecological status improving as PA coverage increases. This pattern supports the hypothesis that protected areas contribute to better ecological conditions.

Table 12. Tests to evaluate how water ecological quality classes (EQC) changes with protected area coverage (PA%) in Guadalquivir basin

Test	Statistic	p-value	Interpretation
Kruskal–Wallis (4 PA categories*)	98.930	**< .001**	Significant differences difference in water EQC between PA categories
Mann–Whitney U (Low vs Very high PA)	119 791.500	**< .001**	Significant difference Low PA (0–25%) vs Very High PA (75–100%) difference in water EQC
Jonckheere–Terpstra (trend)	−14.364 (Z)	**< .001**	Significant monotonic trend (higher PA → water EQC)

4.4.3. Conclusions

In the Guadalquivir basin the spatially distributed analysis showed significant relationships between protected area (PA) coverage and water EQC (based on EQRs), with a moderate strength of association. Sites with higher PA coverage tend to have better water ecological quality, while low protection areas are associated with poorer ecological conditions. EQC is improving as PA coverage increases

4.5. Analysis of nutrient and chlorophyll dynamics in freshwater-marine continuum

Danube-Black Sea analysis (figure 27)

Freshwater:

In freshwater sites, a clear and consistent pattern emerges where increasing percentages of protected area correlate with declining concentrations of Total Nitrogen (TN) (R^2 = **0.46**, N = **143**). This negative trend is strong and statistically significant, indicating that protection may contribute to reducing nitrogen pollution. For Total Phosphorus (TP), the trend is weaker but still significant, suggesting modest benefits from protected area coverage (R^2 = **0.14**, N = **173**). Chlorophyll-a (chl-a) levels also appear to decrease with increasing protection, supporting the idea of improved ecological conditions.

The insets with annual averages reinforce these observations by showing smoothed, year-to-year improvements. Overall, freshwater systems show the most robust response to protection, especially for nitrogen reduction. The inset plots of annual averages reinforce these findings, showing consistent year-over-year improvements in nutrient levels as protection increases. This indicates a likely ecological benefit of protected areas in mitigating nutrient pollution.

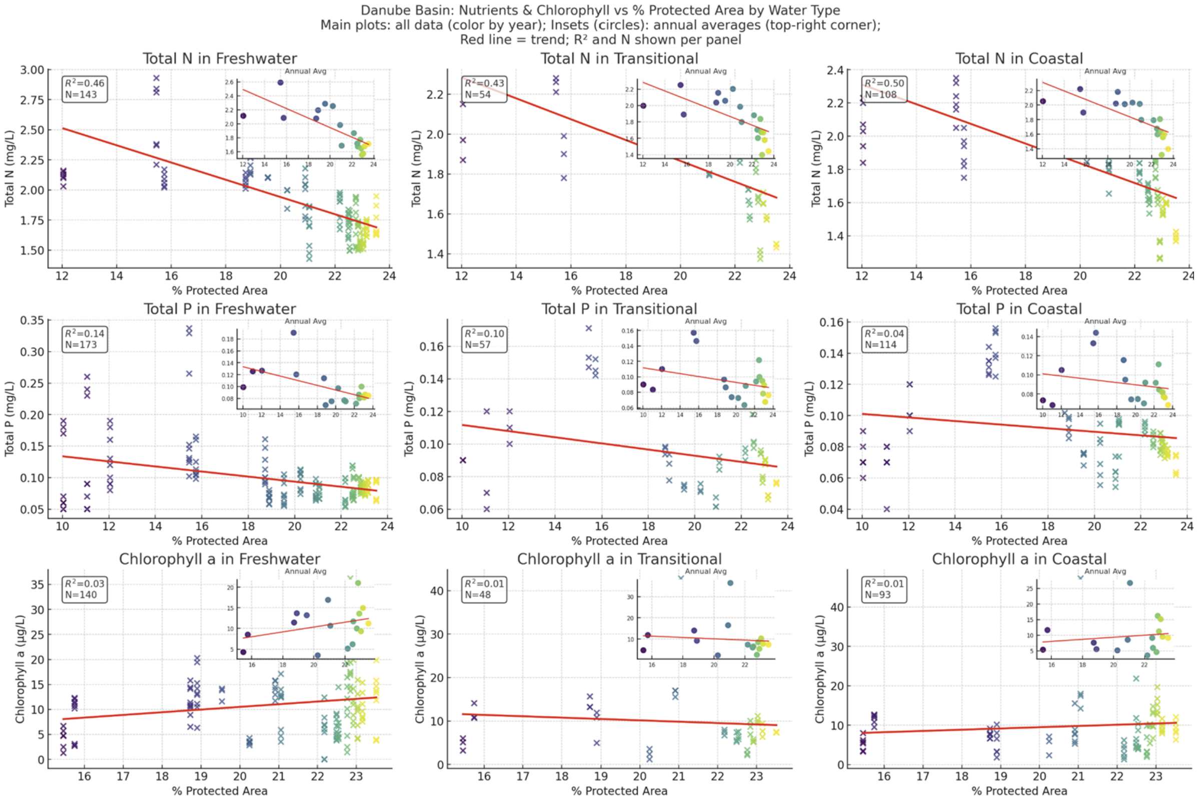


__Figure 27.__ Relationship between % protected area and nutrient and chlorophyll concentrations in the Danube-Black Sea across water body types

*Each main panel displays all available monitoring data points (coloured by year), while inset panels show annual average values. Trend lines (red) and corresponding **R²** values and **sample sizes (N)** are included for each relationship. The trends are summarized and interpreted below by water body type.*

Transitional waters:

In transitional water bodies, similar patterns are observed, though slightly less pronounced than in freshwater. TN still shows a meaningful decline with increasing protection (R² = **0.43**, N = **54**), suggesting benefits extend beyond purely freshwater environments. The reduction in TP is smaller, but the trend remains significant (R² = **0.10**, N = **57**). Variability in these environments, due to mixing zones and fluctuating hydrology, may dampen the strength of the trends. Chlorophyll-a data for transitional waters show a downward trajectory but require further data for strong conclusions. Still, transitional waters reflect a measurable improvement in water quality as protection increases.

Coastal waters:

Coastal sites show a strong and statistically significant reduction in TN concentrations with increased protection (R² = **0.50**, N = **108**). Despite the complexity of coastal systems and influences from both land and sea, the signal for nitrogen reduction is still evident. There is insufficient data for TP and chl-a in coastal sites in this analysis, highlighting a gap in monitoring or reporting. Nevertheless, the observed trend in nitrogen suggests that even coastal water quality may benefit from upstream freshwater protection. Continued monitoring and expanded nutrient datasets would strengthen the understanding of coastal response to protection.

Po-Adriatic Sea data analysis (figure 28)

Freshwater:

TN exhibits a small but statistically significant decreasing trend with increasing percentage of protected area (R² = **0.01**, N = **604**), supporting the potential effectiveness of freshwater conservation efforts. The absence of trends for TP (R² = **NaN**, N = **604**) and no available data for chl-a reflects data limitations or influences from unmeasured factors.

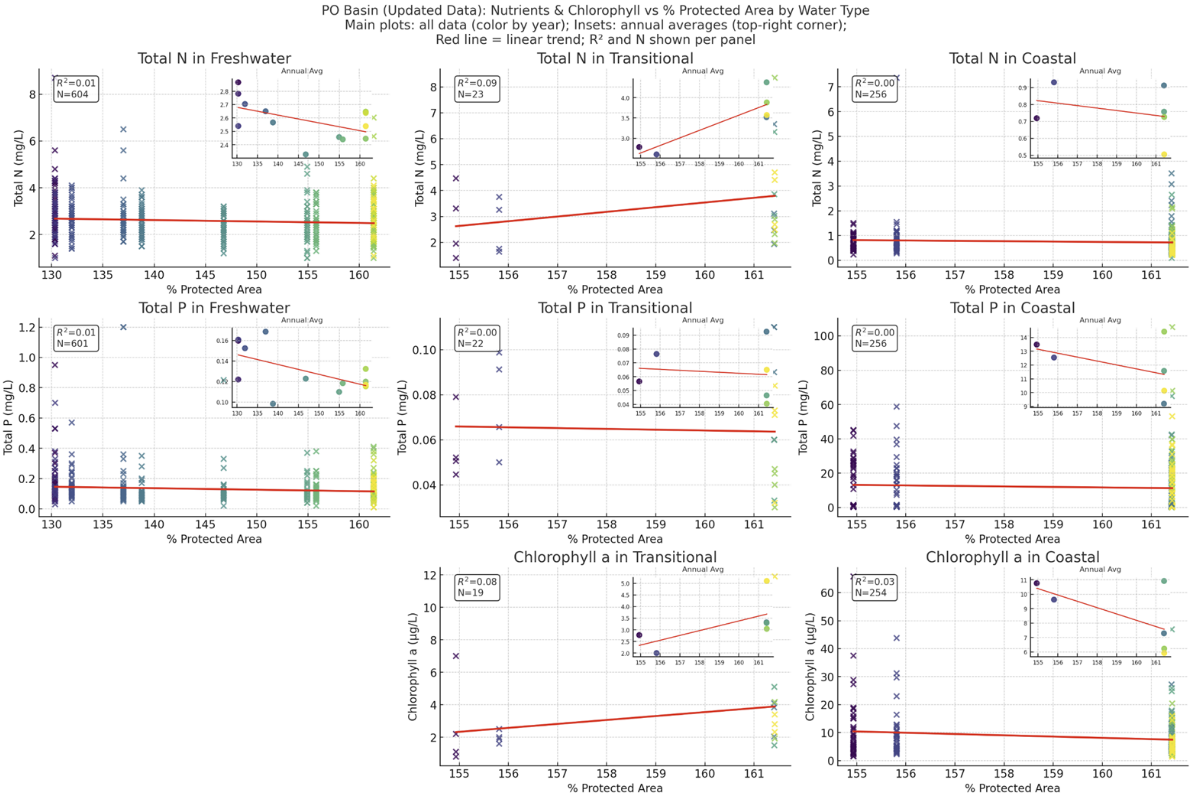


Figure 28. *Relationship between % protected area and nutrient and chlorophyll concentrations in the Po-Adriatic Sea across water body types*

*Each main panel displays all available monitoring data points (coloured by year), while inset panels show annual average values. Trend lines (red) and corresponding **R²** values and **sample sizes (N)** are included for each relationship. The trends are summarized and interpreted below by water body type.*

Transitional waters:

Transitional systems present limited data, making it challenging to derive firm conclusions. A non-significant increasing trend for TN (R^2 = **0.09**, N = **23**) was observed but is likely influenced by small sample size. Due to low sampling frequency, observed patterns in transitional areas should be interpreted cautiously. Expanded monitoring is essential to evaluate protection impacts in these complex systems.

Coastal Waters:

In coastal areas of the Po basin, no statistically significant trends were found for TN (R^2 = **0.01**, N = **256**), despite a moderately large dataset. The absence of trends could reflect complex coastal dynamics, such as dilution, tidal mixing, or legacy nutrient loads. Continued and expanded monitoring remains crucial to assess long-term impacts of upstream protection.

Elbe-North Sea data analysis (figure 29)

Freshwater:

In Elbe freshwater systems, strong and statistically significant trends indicate clear water quality improvements with increased protection. Both TN (R^2 = **0.63**, N = **892**) and TP concentrations (R^2 = **0.57**, N = **896**) decline markedly with rising percentages of protected areas, affirming the role of freshwater conservation in nutrient reduction.

While nutrient trends are robust, chl-a levels show no clear pattern (R^2 = **0.00**, N = **476**), possibly due to confounding factors like light availability or grazing pressure.

Transitional waters:

Elbe's transitional waters show nutrient improvements with protection, although patterns are more variable due to the dynamic nature of these systems. TN displays a well-supported downward trend (R^2 = **0.44**, N = **2,275**), while TP shows a weaker but still statistically significant relationship (R^2 = **0.11**, N = **2,271**). Chl-a levels show no clear pattern (R^2 = **0.00**, N = **715**).

Annual average values from inset panels support these observations, showing year-on-year declines in nutrient levels aligned with growing protection. Despite ecological complexity, transitional zones appear to be benefiting from upstream conservation.

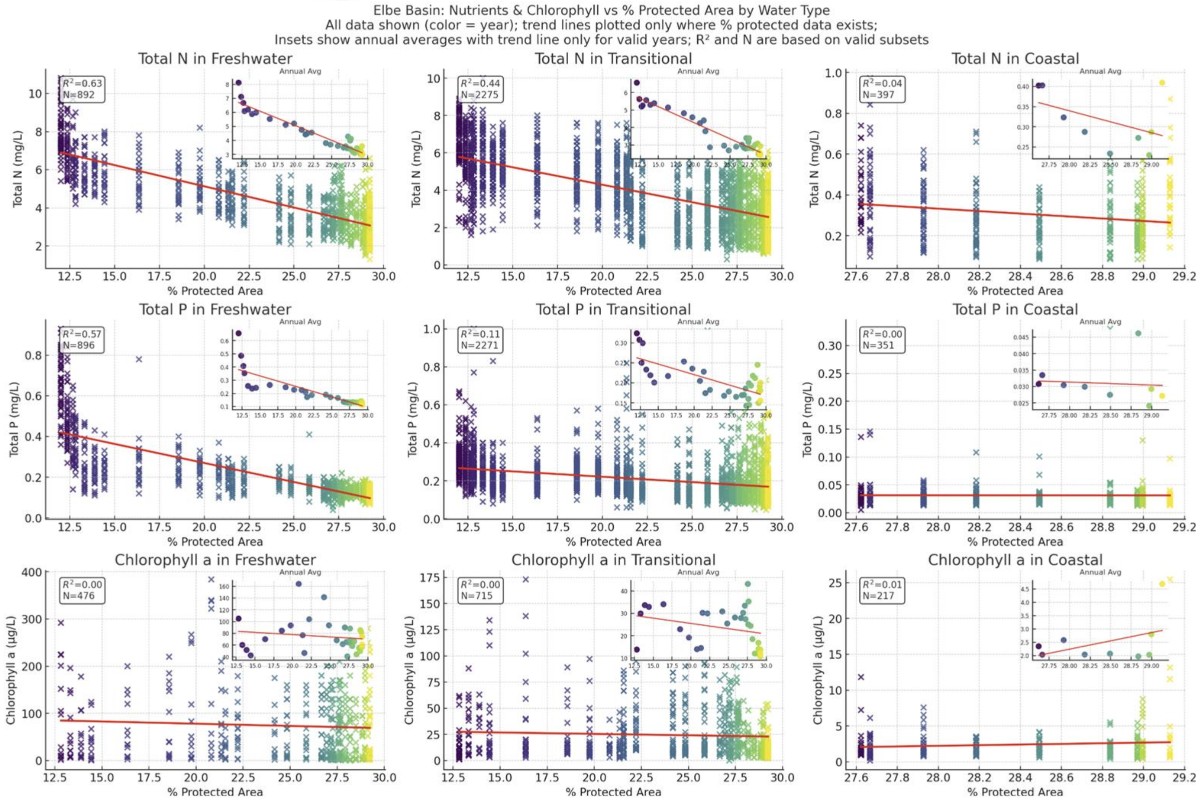


Figure 29. *Relationship between % protected area and nutrient and chlorophyll concentrations in the Elbe-North Sea across water body types*

Each main panel displays all available monitoring data points (coloured by year), while inset panels show annual average values. Trend lines (red) and corresponding ***R²*** *values and* ***sample sizes (N)*** *are included for each relationship. The trends are summarized and interpreted below by water body type.*

Coastal waters:

While the TN signal is weaker in coastal areas (R^2 = **0.04**, N = **397**), it is still detectable, suggesting that even distant downstream environments may benefit from inland protection efforts. Expanding monitoring coverage for TP (R^2 = **0.00**, N = **351**) and chl-a (R^2 = **0.00**, N = **217**) would be critical for a more complete assessment of coastal system responses.

Guadalquivir-Atlantic Ocean data analysis

No results could be presented for Guadalquivir due to the lack of data.

5. Ecosystem Services (ES), Nutrient Dynamics and Data Limitations

Understanding how protected areas influence nutrient dynamics across large European river basins requires integrating ecological function, hydromorphological condition, and data availability. The four basins analysed—Danube, Elbe, Po, and Guadalquivir—differ substantially in their floodplain connectivity, land-use pressures, monitoring intensity, and estuarine complexity. These differences shape both the actual expression of nutrient-regulating ES and the capacity to detect them empirically. The Danube-Black Sea and Elbe-North Sea systems exhibit clear and statistically significant nutrient declines with increasing protected-area extent, particularly for nitrogen in freshwater and transitional systems. These patterns reflect both functional floodplains capable of nutrient retention and robust monitoring infrastructure. In contrast, the Po-Adriatic Sea system shows only weak or absent nutrient–protection signals, consistent with extensive hydromorphological alteration and limited connectivity. For the Guadalquivir-Atlantic Ocean, insufficient data prevent quantitative assessment, but known pressures and estuarine dynamics suggest substantial challenges in isolating protection effects. Together, these comparisons highlight how ecological processes and data limitations jointly determine the detectability of ES benefits at basin scale (table 13).

Danube-Black Sea

In the Danube-Black Sea system, nutrient-regulating ES remain among the strongest of the three case studies where data availability permitted the analysis in subchapter 4.5. Historically, extensive floodplains and riparian corridors have supported key regulating functions such as nitrogen and phosphorus retention, denitrification, sediment trapping, and water purification (Stammel et al., 2018). Recent modelling shows that restoring lateral connectivity significantly enhances these services by increasing nutrient retention capacity (Natho et al., 2020). The new results align strongly with these expectations. Across all water body types, **statistically significant reductions in TN** with increasing protected-area extent were observed, with particularly **strong responses in freshwater and transitional waters**, and a similarly **strong decline in the coastal zone**. TP also shows a measurable decrease in freshwater and transitional systems, though weaker in magnitude, while chl-a decreases visually where data are available. These findings confirm that protected floodplains and riparian zones continue to deliver substantial nutrient-regulation benefits. As waters move downstream—into transitional and coastal Black Sea environments—the strength of ES expression naturally attenuates due to hydrodynamic mixing, legacy nutrient accumulation, and complex multi-source inputs. Despite this, the persistence of a strong TN signal even in coastal waters indicates that basin-wide protective measures have measurable downstream impacts. The Danube’s comparatively strong correlations are also supported by robust monitoring infrastructure, including consistent nutrient records, detailed geospatial datasets on floodplains and connectivity, and long-term sampling across jurisdictions (Borja et al., 2023). However, data gaps remain, particularly concerning diffuse-source contributions and nutrient export to the sea. These limitations imply that the actual magnitude of the nutrient-regulating services may still be underestimated.

Po-Adriatic Sea

In the Po-Adriatic Sea system, nutrient-retention ES are comparatively weak and less detectable. Long-term analyses indicate declines in nutrient loads to the northern Adriatic Sea, but these are driven largely by hydrological variability rather than by protected-area expansion or large-scale floodplain restoration (Soana et al., 2024; Cavallini et al., 2024). The basin's extensive agricultural activity, drainage infrastructure, hydromorphological modifications, and limited floodplain connectivity substantially reduce the capacity of protected areas to function as nutrient sinks. Freshwater systems show **only a very weak negative TN trend**, with no detectable patterns for TP or chl-a. Transitional waters are represented by extremely small datasets, preventing meaningful interpretation, while coastal waters show no significant nutrient trends despite a moderate number of observations. These findings highlight structural limitations in the Po basin: even if local wetland pockets exhibit strong denitrification (e.g., >30% in specific Po Delta sites; Gervasio et al., 2022), such effects are highly localized and do not scale to detectable basin-level improvements. Monitoring coverage in both transitional and coastal zones is sparse and inconsistent, complicating attempts to link protected-area extent with nutrient-regulation outcomes.

Thus, while nutrient-regulating ES may exist in isolated parts of the Po basin, their basin-wide manifestation is weak, and the limited spatial–temporal resolution of monitoring reduces the likelihood of detecting correlations in large-scale analyses.

Elbe-North Sea

In the Elbe river basin, nutrient-regulation ES are present but expressed differently compared to the Danube. Floodplain and wetland restoration studies identify measurable nitrogen-retention and denitrification benefits (Lautenbach et al., 2012; Grossmann, 2012), yet the extent to which these services translate into basin-scale water quality improvements depends on both ecological pressures and data quality. The analysis shows **strong and statistically significant declines in TN and TP in freshwater systems**, indicating that ES benefits are more pronounced upstream than previously assumed. Transitional waters also exhibit significant, though weaker, negative trends. In contrast, **coastal waters display only a very weak decline in TN**, and no detectable trends for phosphorus or chl-a. These patterns reflect the cumulative influence of agricultural nutrient loads, industrial discharges, and urban effluents, which constrain the detectability of protection effects—particularly in the estuarine and marine zones. Hydrological complexity, variable sampling frequency, and inconsistent spatial coverage further complicate trend detection in downstream segments (Schulz et al., 2023). Overall, while protected areas and floodplain reconnection do contribute to nutrient mitigation in the Elbe basin, their measurable influence diminishes toward the coast due to both external nutrient pressures (van Beusekom et al., 2019; BMEL, 2022) and monitoring limitations. The strong freshwater response suggests local effectiveness, whereas downstream detectability is strongly mediated by data constraints and mixed-source inputs.

Guadalquivir-Atlantic Ocean

In the Guadalquivir-Atlantic Ocean case, the assessment of nutrient-regulating ES is strongly constrained by limited monitoring data across freshwater, transitional, and coastal systems. Unlike the Danube, Elbe, or Po, the Guadalquivir is characterised by **shorter hydrological gradients**, a **heavily regulated river network**, and **strong estuarine salinity dynamics**, all of which complicate the detection of nutrient trends and ES signals. Existing studies document that the basin is subject to high agricultural nutrient inputs—particularly from intensive olive and irrigated crop systems—combined with hydrological modifications such as dams, water diversions, and flow regulation (Picó, Y., & Navarro-Ortega, A., 2013). These pressures significantly alter nutrient transport, retention, and denitrification processes along the river.

Data availability and its implications: The absence of consistent monitoring data available across water body types—especially for TN, TP, and chl-a—precludes the statistical evaluation of nutrient–protection relationships in the Guadalquivir. Transitional and coastal monitoring is particularly discontinuous, with sparse measurements in the estuary and limited long-term nutrient time series for the Gulf of Cádiz. This gap is critical because the Guadalquivir estuary is known to exhibit:

- strong **stratification–mixing cycles**,
- high **sediment resuspension**,
- significant **tidal influence**, and
- complex **biogeochemical transformations**,
  all of which modify nutrient concentrations independently of upstream protection measures.

Ecosystem service (ES) context: Although wetlands and riparian zones in the upper and middle basin can provide nutrient-retention services, these areas are highly fragmented and hydrologically disconnected due to centuries of land reclamation and river engineering. As a result:

- nutrient processing capacity is spatially constrained,
- retention signals may be highly localized, and
- downstream detectability is extremely low even under good monitoring conditions.

Available research on the Doñana wetlands and marshes highlights their potential for nitrogen removal and ecological buffering (Serrano et al., 2006), but these effects are local and not captured in basin-wide datasets.

Interpretation: Given the **data gaps**, **hydrological regulation**, and **complex estuarine processes**, the Guadalquivir Basin currently lacks the empirical basis needed to evaluate the relationship between protected-area extent and nutrient concentrations. This does not imply the absence of nutrient-regulating ES - rather, their manifestation is likely diffuse, fragmented, and statistically undetectable with current monitoring coverage.

A future assessment would require:

- harmonised freshwater–transitional–coastal nutrient monitoring,
- higher temporal resolution in the estuary,
- spatially explicit mapping of protected floodplains and wetlands, and
- hydrological modelling to trace nutrient retention pathways.

Such improvements would allow a more complete evaluation of ES expression and the potential role of protected areas in mitigating nutrient loads in the Guadalquivir system.

Report Edit

Table 13. Comparative summary across the Danube-Black Sea, Elbe-North Sea, Po-Adriatic Sea, and Guadalquivir-Atlantic Ocean systems

System	Ecosystem Service Potential (N/P retention, denitrification, floodplain function)	Observed Nutrient Trends vs. Protection (%)	Strength of Evidence	Key Pressures Affecting Outcomes	Data & Monitoring Limitations
Danube - Black Sea	Very high potential; extensive floodplains, strong N and P retention documented; restored connectivity enhances services.	**Strong declines in TN** across freshwater (R^2 = 0.46), transitional (R^2 = 0.43), and coastal (R^2 = 0.50). Moderate decline for TP in freshwater and transitional waters. chl-a decreasing where data exist.	**High** — robust, consistent, multi-sector datasets; trends statistically significant across all water types.	Agricultural inputs, legacy loads in delta, hydrodynamic mixing in coastal zone.	Generally strong datasets but gaps in diffuse-source loads and coastal TP/chl-a measurements.
Elbe - North Sea	Moderate to high potential; floodplain restoration shown to provide N retention; services partly fragmented by river engineering.	**Strong declines (freshwater)** TN R^2 = 0.63; TP R^2 = 0.57. **Moderate declines (transitional)** TN R^2 = 0.44; weak TP R^2 = 0.11. **Weak coastal TN decline** (R^2 = 0.04). No trends for chl-a.	**High–Moderate** — good freshwater and transitional coverage; weaker coastal evidence.	Intensive agriculture, industrial discharges, urban effluents, estuarine mixing.	Spatial heterogeneity, inconsistent coastal sampling, variable estuarine monitoring.
Po - Adriatic Sea	Low to moderate potential; highly modified system with limited floodplain connectivity; episodic local denitrification.	**Very weak TN decline** in freshwater (R^2 = 0.01). No trends for TP or chl-a. No significant trends in transitional or coastal waters.	**Low** — minimal signals detectable; ecosystem service effects strongly masked.	Intensive agriculture, drainage canals, strong hydromorphological modification, Adriatic mixing.	Poor coverage in transitional/coastal zones; inconsistent long-term nutrient data; episodic measurements.
Guadalquivir-Atlantic Ocean	Localised nutrient-retention potential (wetlands, marshes), but fragmented and hydrologically disconnected.	**No analysable trends** (insufficient nutrient datasets across water types).	**Very low** — monitoring gaps prevent detection.	High agricultural inputs, regulated river system, strong salinity and tidal dynamics in estuary.	Major gaps in freshwater–transitional–coastal continuity; limited long-term nutrient and chl-a records; sparse estuarine monitoring.

5.1. Linking nutrient indicators and chlorophyll-a to ecosystem services (CICES Framework)

Understanding the relationships between protected areas, nutrient concentrations, and ecological responses requires situating biophysical indicators within a wider **ecosystem service (ES) framework**. Nutrient concentrations (TN, TP) and phytoplankton biomass (chlorophyll-a) are not only chemical or ecological variables - they are **entry points into an entire cascade of ecosystem functions and societal benefits**. When these indicators improve, the benefits extend far beyond the upstream river reaches, propagating downstream into transitional waters and ultimately shaping estuarine and coastal ES. This framework provides the ecological and societal rationale for associating observed declines in TN, TP, and chl-a with broader benefits reflected in the CICES ES1–ES16 categories (Table 14).

Table 14. Ecosystem services linked to nutrient and chlorophyll-a dynamics, and level of empirical support by case study. ***Legend: TN*** *- Total Nitrogen,* ***TP*** *- Total Phosphorus,* ***chl-a*** *- chlorophyll a,* ***PA*** *- protected areas,* ***HAB*** *- Harmful Algal Blooms,* ***F*** *- freshwater,* ***T*** *- transitional waters,* ***C*** *- coastal waters;* ***evidence by case study: S*** *– Strong support from current data,* ***M*** *– Moderate / inferential support,* ***W*** *– Weak / local or only partially supported,* ***NA*** *– Not assessed or no empirical basis with current indicators*

Code	Ecosystem Service (short label)	CICES section / type	Main proxy in this study	Danube - Black Sea	Po – Adriatic Sea	Elbe – North Sea	Guadalquivir – Atlantic Ocean
ES1	Reduced sediment loading to estuaries/coast	Regulation & Maintenance – Mediation of mass flows / erosion control	*Not directly measured* (would need sediment/turbidity)	NA	NA	NA	NA
ES2	Improved water clarity / lower turbidity	Regulation & Maintenance – Filtration / sequestration / accumulation	↓TN, ↓TP, ↓chl-a (mainly freshwater)	**M–S**	NA	**M** (via nutrients only)	NA
ES3	Reduced nutrient / pollutant flux downstream	Regulation & Maintenance – Mediation by biota / ecosystems	↓TN, ↓TP across F–T–C	**S**	**W** (F only)	**S**	NA
ES4	More stable flow regime / reduced extremes	Regulation & Maintenance – Hydrological flow regulation	*Not analysed here* (needs discharge/flood metrics)	NA	NA	NA	NA

ES5	Maintaining salinity gradients / limiting saline intrusion	Regulation & Maintenance – Water quality / chemical conditions	*Not analysed* (needs salinity & flow)	NA	NA	NA	NA
ES6	Better nursery habitat quality (fish, shellfish)	Reg. & Maint. / Provisioning – Habitat & lifecycle maintenance	↓TN, ↓TP (less eutrophication stress)	**S**	**W**	**M**	NA
ES7	Enhanced catch yield / fishery robustness	Provisioning – Wild/reared aquatic animals	↓TN, ↓TP (and ↓chl-a where present) reducing extreme events	**M**	**W**	**M**	NA
ES8	Better water supply / water quality for human use	Provisioning – Surface water for drinking / non-drinking	↓TN, ↓TP (F, T)	**S**	**W**	**S**	NA
ES9	Increased recreation, tourism, aesthetic value	Cultural – Physical & experiential interactions	↓TN, ↓TP, ↓chl-a → fewer blooms, better aesthetics	**M–S** (delta & Black Sea)	**W**	**M**	NA
ES10	Climate regulation / carbon sequestration	Regulation & Maintenance – Atmospheric composition	*Not measured* (needs carbon/biomass/soil carbon)	NA	NA	NA	NA
ES11	Lower coastal erosion / shoreline protection	Regulation & Maintenance – Buffering / storm protection	*Not measured* (needs shoreline, habitat & wave data)	NA	NA	NA	NA
ES12	Avoidance of harmful algal blooms / hypoxia	Regulation & Maintenance – Mediation of water quality / chemical conditions	↓TN, ↓TP and ↓chl-a reducing eutrophication	**S**	**W**	**M**	NA
ES13	Greater biodiversity / species richness (condition)	Underlying ecological condition – habitat & lifecycle support	Combined ↓TN, ↓TP, ↓chl-a	**S**	**W**	**M**	NA

ES14	Food-web & secondary production support	Reg. & Maint. / Supporting – Maintenance of biological conditions	Shape of TN, TP, chl-a response (from high to moderate)	**M**	**W**	**M** (via nutrients)	NA
ES15	Health risk reduction (HAB, bathing water)	Regulation & Maintenance – Water quality mediation (health-oriented)	↓TN, ↓TP, ↓chl-a → lower HAB & toxin risk	**M–S**	**W**	**M**	NA
ES16	Scientific, monitoring & educational services	Cultural – Intellectual & representational interactions	Existence/quality of TN, TP, chl-a time series along PA gradients	**S**	**M**	**S**	**W**

In rivers–floodplain systems, protected areas conserve or restore key ecological structures—connected floodplains, wetlands, riparian forests—that perform **critical regulating services** such as nutrient retention, denitrification, sediment trapping, and water purification. These functions correspond directly to the CICES "Regulation & Maintenance" group (ES1–ES5, ES10–ES12). Where connectivity is strong, these natural systems slow water, increase residence time, and enhance biological transformation of nutrients, thereby reducing TN and TP loads exported to downstream waters. As nutrient loads decline, the risk of eutrophication diminishes, harmful algal blooms become less frequent, and water clarity increases. These changes directly affect other ES categories, including provisioning services (ES6–ES8) and cultural services (ES9). Chlorophyll-a, representing phytoplankton biomass, is an especially important proxy for ecosystem functioning along the river–estuary–coastal continuum. High Chl-a indicates nutrient oversupply and elevated primary production, often associated with reduced water clarity, higher organic oxygen demand, and increased likelihood of hypoxia or harmful algal blooms. When Chl-a decreases in response to reduced nutrient loads, this signals a shift toward **healthier, less eutrophic, more resilient ecosystems**. The implications span multiple ES dimensions: improved water quality for human consumption (ES8), better conditions for fish nursery grounds (ES6), less risk to coastal fisheries (ES7), enhanced recreational and aesthetic value of coastal waters (ES9), and increased habitat suitability for diverse marine and estuarine species (ES13).

In this context, the biophysical indicators examined in this study - TN, TP, and Chl-a - represent **quantifiable, policy-relevant entry points** for assessing ES performance. Each decline in nutrient concentrations or phytoplankton biomass can be directly linked to a set of ES outcomes in the CICES typology:

- *Lower nutrient concentrations (TN, TP → ↓) map to CICES categories of water purification, pollutant removal, and biogeochemical regulation (ES3, ES12).*
- *Reduced phytoplankton biomass (Chl-a → ↓) corresponds to improved water clarity, reduced eutrophication, and avoidance of hypoxic events (ES2, ES12).*
- *The combination of nutrient and phytoplankton reductions underpins improved nursery habitat quality, strengthened fisheries, and enhanced recreation (ES6–ES9).*
- *These processes are embedded within broader regulating, supporting, and cultural benefits that structure coastal socio-ecological systems.*

Framing nutrient and chlorophyll patterns in terms of ES also highlights why **upstream protected areas have far-reaching downstream impacts**. Floodplains and wetlands act as natural biogeochemical reactors: by filtering sediments, storing organic matter, facilitating microbial denitrification, and stabilising flow regimes, they influence the delivery, timing, and form of nutrients entering transitional and coastal waters. These processes exemplify CICES codes such as “Mediation of mass flows,” “Maintenance of chemical and physical conditions,” and “Hydrological regulation” (ES1–ES5), and they are the mechanisms through which protected-area expansion or improved floodplain connectivity translate into ES gains downstream.

At the same time, recognising nutrients and Chl-a as ES proxies helps clarify why differences across basins emerge. Systems with extensive, well-connected floodplains and strong ecological integrity (e.g., the Danube) show clear declines in TN, TP, and Chl-a with increasing protected-area coverage. In contrast, heavily modified or regulated systems with fragmented wetlands (e.g., the Po, parts of the Guadalquivir) exhibit attenuated or absent signals because the upstream processes that generate ES have been weakened, disconnected, or compressed by anthropogenic pressures. Thus, the nutrient dynamics observed in each basin can be interpreted as **expressions of the strength - or absence - of underlying ES.** This conceptual framing strengthens the policy relevance of your findings. By linking concrete, measurable indicators (nutrients, Chl-a) to CICES service categories (ES1–ES16), the analysis provides a structured way to articulate how protected-area expansion, floodplain restoration, and integrated basin management generate cascading benefits that reach all the way to coastal economies, fisheries, tourism, and human well-being. Moreover, the framework clarifies where monitoring gaps limit our capacity to detect these services, underscoring the need for harmonised river–estuary–coastal nutrient time series. In summary, interpreting nutrient and chlorophyll dynamics through the lens of ES reveals a complex, yet coherent, cascade: **protected**

areas → restored ecosystem functions → reduced nutrient export → improved ecological quality → enhanced provisioning, regulating and cultural services.

5.2. System-specific interpretation of ecosystem services (ES) based on nutrient and chlorophyll dynamics

Danube-Black Sea: The most complete and coherent ecosystem service profile (Strong–Moderate across all relevant ES)

Among all case-studies analysed, the Danube-Black Sea exhibits the strongest and most coherent expression of water-quality–related ES. The consistent and significant reductions in TN and TP across freshwater, transitional, and even coastal sites create a clear cascade linking increased protected-area coverage with enhanced ES delivery. These patterns directly support **ES3 (reduced downstream nutrient flux)**, **ES12 (avoidance of harmful algal blooms and hypoxia)**, **A8 (improved water supply and downstream water quality)**, and **ES6 (enhanced nursery habitat conditions)**. In freshwater systems, the visual decline in Chl-a further strengthens support for **ES2 (improved water clarity)**, **ES9 (recreational and aesthetic value)**, and **ES13 (better ecological conditions for biodiversity)**. The Danube is the only basin where nutrient declines carry through the entire river–delta–coast continuum, making plausible the link to additional ES such as **ES14 (support for food webs and secondary production)** and **ES15 (reduced health risks related to eutrophication and HABs)**. This basin also shows strong alignment with **ES16 (scientific, monitoring and educational services)** due to long-term, continuous monitoring networks.

The diagram presented in figure 30 illustrates the interconnected nutrient dynamics and ES across the **Danube–Black Sea continuum**, progressing **diagonally from the freshwater Danube River (upper left)** through the **transitional Danube Delta (center)** to the **marine Black Sea zone (bottom right)**. It visualizes how **nutrients (TN, TP)** drive **Chlorophyll-a responses** and influence key **ES** — including regulation (e.g., nutrient flux control, HAB prevention), provisioning (e.g., fisheries), and cultural (e.g., recreation, aesthetics). Reinforcing (R) and balancing (B) loops highlight feedbacks maintaining or destabilizing water quality and ecosystem health along the land–sea gradient. Overall, the Danube represents the best-case example in which protected-area expansion translates into measurable ES benefits at multiple spatial scales.

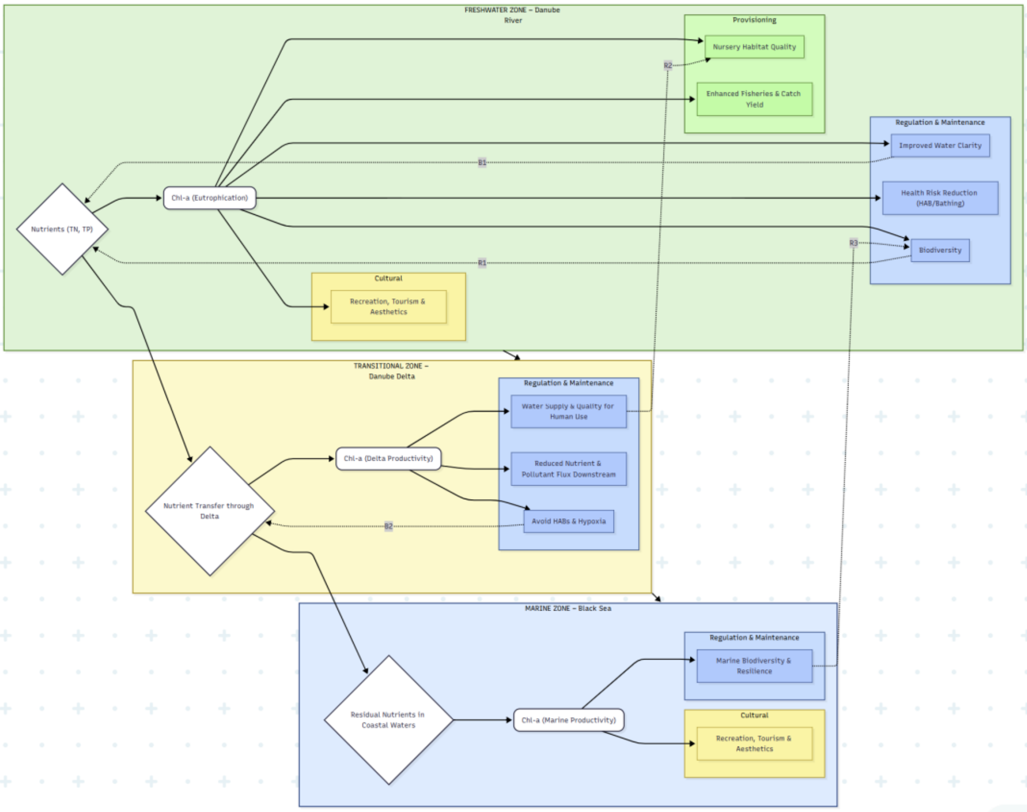


Figure 30. *Causal loop diagrams for the Danube Basin linking the nutrients (TN, TP) with chlorophyll-a (chl-a) and ecosystem services (ES)*

Po-Adriatic Sea: A fragmented ES profile with weak or localized signals (Weak across most ES)

The Po-Adratic Sea case study presents a markedly weaker and highly fragmented ES profile. The only detectable trend at basin scale is a very small decline in TN in freshwater, which translates into **weak support** for **ES3**, **ES8**, and **ES12**, and **only in upstream areas**. The absence of meaningful TP or Chl-a trends prevents linking the data to ES such as **ES2**, **ES6**, **ES7**, or **ES9** at basin scale. This weak ES expression is consistent with extensive hydromorphological modification, reduced floodplain connectivity, high agricultural nutrient loads, rapid water transport through drainage canals, and strong coastal mixing in the northern Adriatic Sea. Although small wetland patches in the Po Delta may locally support nutrient retention (ES3), eutrophication control (ES12), or nursery habitats (ES6), these effects are not detectable at the scale of the entire basin. Therefore, most ES codes appear as **Weak** or **Not Assessable** for Po in the synthetic table. This basin is the clearest example of how river engineering, land-use intensity, and monitoring gaps suppress the capacity of protected areas to deliver detectable ES benefits at large spatial scales.

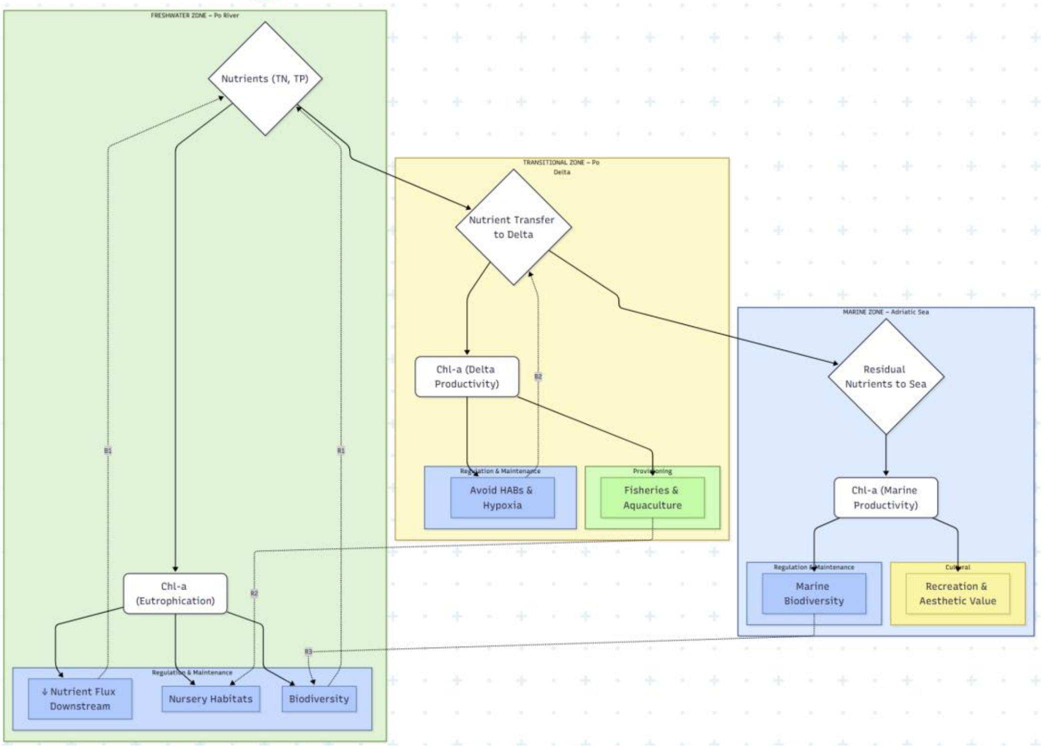


***Figure 31.** Causal loop diagrams for the Po-Adriatic Sea linking the nutrients (TN, TP) with with chlorophyll-a (chl-a) and ecosystem services (ES)*

The diagram presented in figure 31 visualizes the **Po River–Adriatic Sea continuum**, progressing **from freshwater (Po River, left)** through **transitional (Po Delta, center)** to **marine (Adriatic Sea, right)** zones. It depicts how **nutrient concentrations (TN, TP)** influence **Chlorophyll-a dynamics** and shape key **ES** across the land–sea gradient. The **freshwater zone** emphasizes nutrient flux reduction and biodiversity regulation; the **transitional zone** highlights nutrient transfer, aquaculture productivity, and mitigation of harmful algal blooms; and the **marine zone** focuses on recreation, aesthetic value, and marine biodiversity. Reinforcing (R) and balancing (B) feedback loops illustrate interactions that sustain or regulate ecosystem functioning within and between these zones.

Elbe-North Sea: Strong upstream ES expression with moderate estuarine propagation (Strong–Moderate for most ES)

The Elbe-North Sea displays a favourable ES profile, especially in freshwater sections where nutrient declines are strong for both TN and TP. These findings support **ES3**, **ES8**, **ES12**, and **ES6**, indicating effective nutrient mediation and improvement in water quality and ecological conditions upstream. Transitional waters also show moderate support for these services, although with reduced intensity. In coastal and estuarine waters, only weak TN declines persist, leading to partial support for **ES3**, while the absence of chl-a trends limits evidence for **ES2**, **ES9**, and **ES12** in the estuary. Strong tidal mixing, saline intrusion, port dredging, and high turbidity disrupt the downstream propagation of ES generated upstream—an expected pattern for engineered estuarine systems. Nevertheless, the Elbe still demonstrates moderate support for **ES14** (food-web and secondary production stability) and **ES15** (lower eutrophication-related health risks), inferred from strong upstream nutrient improvements. The basin also stands out for **ES16**, with well-developed monitoring systems and long-term datasets, similar to the Danube. Overall, the Elbe provides strong ES delivery upstream, with diminishing—but still discernible—signals toward the coast.

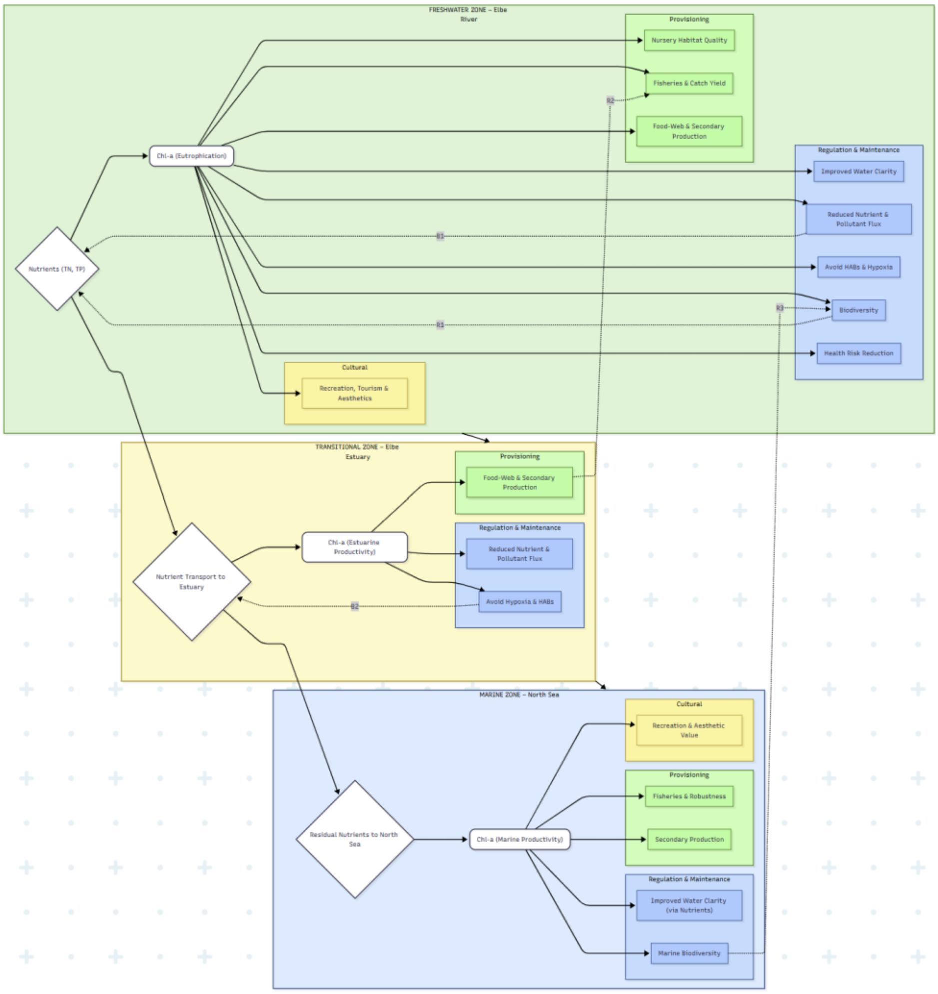


***Figure 32.** Causal loop diagrams for the Elbe-North Sea linking the nutrients (TN, TP) with chlorophyll-a (chl-a) and ecosystem services (ES)*

The diagram presented in figure 32 illustrates the **Elbe River–North Sea continuum**, showing the progression **from freshwater (Elbe River, left)** through **transitional (Elbe Estuary, center)** to **marine (North Sea, right)** ecosystems. It represents how **nutrient dynamics (TN, TP)** and **Chlorophyll-a concentrations** influence key **ES** across this land–sea gradient. The **freshwater zone** emphasizes nutrient and pollutant flux reduction, improved water clarity, and biodiversity; the **transitional zone** highlights nutrient transport, food-web productivity, and hypoxia control; while the **marine zone** focuses on recreation, fisheries robustness, and marine biodiversity. Reinforcing (R) and balancing (B) feedback loops capture the dynamic interactions that regulate eutrophication and ecosystem resilience in the Elbe–North Sea system.

Guadalquivir-Atlantic Ocean: Data limitations prevent ES assessment (Weak–NA across all ES)

The Guadalquivir-Atlantic Ocean case study stands out due to severe monitoring gaps *(or the data were not available to us)*, with insufficient TN, TP, and Chl-a data in freshwater, transitional, and coastal waters. As a result, all water-quality-related ES (ES2, ES3, ES6, ES7, ES8, ES9, ES12, ES13) remain **not assessable**, even though ecologically meaningful processes may exist in key areas such as the Doñana wetlands. The strong hydrological regulation of the river, together with complex estuarine dynamics (salt-wedge structure, turbidity maxima), makes it nearly impossible to infer downstream ES without reliable biogeochemical time series. Because of this, **ES14** (food-web support) and **ES15** (health risk reduction) cannot be quantitatively evaluated, and **ES16** (scientific/educational services) is rated as **Weak**, reflecting the fragmented nature of existing monitoring programs.

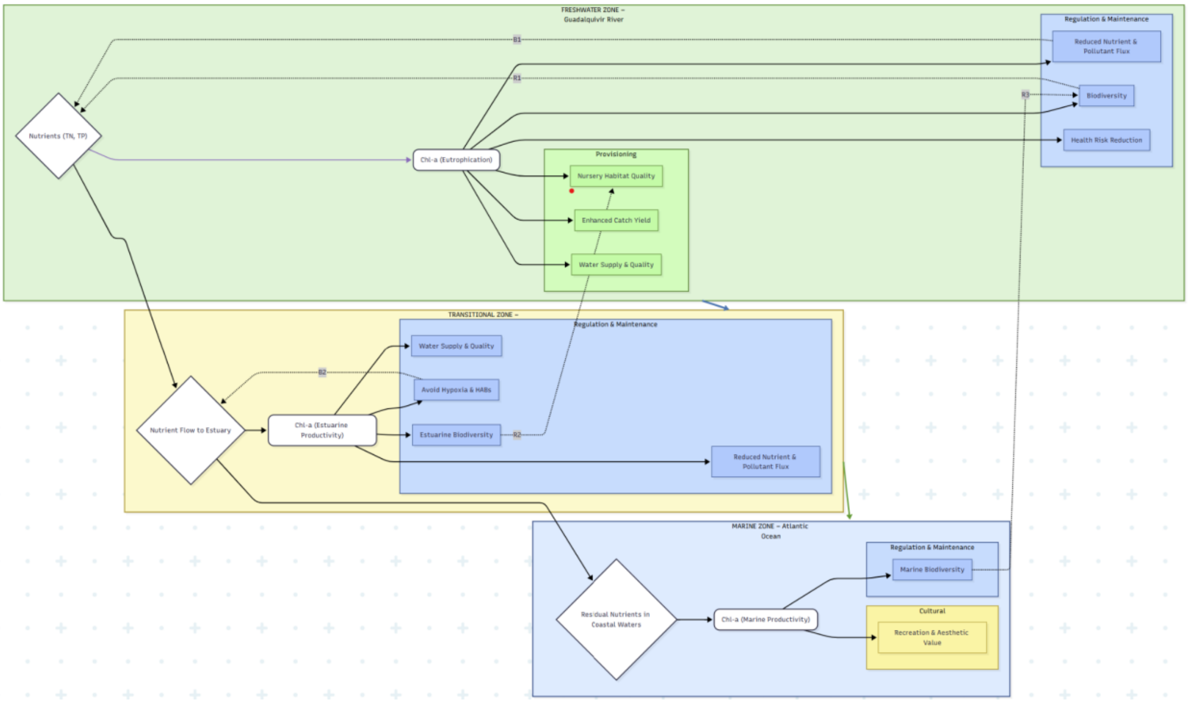


Figure 33. *Causal loop diagrams for the Guadalquivir-Atlantic Ocean linking the nutrients (TN, TP) with chlorophyll-a (chl-a) and ecosystem services (ES)*

The diagram presented in figure 33 represents the Guadalquivir–Atlantic continuum, progressing from freshwater (Guadalquivir River, left) through transitional (estuarine, center) to marine (Atlantic coast, right) zones. It illustrates the conceptual relationships between nutrient concentrations (TN, TP), chl-a, and associated ES, although direct empirical data are largely missing for this basin. Most interpretations are inferred from ecological analogues in other European basins (e.g., Po, Danube, Elbe), using general knowledge of nutrient attenuation, estuarine productivity, and habitat quality patterns. Consequently, the diagram emphasizes conceptual linkages—such as nutrient control, habitat support, and biodiversity maintenance—rather than quantified interactions. This highlights the need for future monitoring and data collection to better quantify nutrient–ecosystem dynamics in the Guadalquivir system.

5.3. Structural data gaps along the freshwater–marine continuum

A central result emerging from our case-study comparison is that the **ability to detect ecosystem service (ES) benefits is constrained by the data availability (a platform that will provide easy access to data, harmonization methods, variables, metadata).** Even where protected areas and floodplain restoration are likely to provide nutrient-regulating services, fragmented and inconsistent monitoring severely limits our capacity to quantify these effects from headwaters to the sea.

5.3.1. Fragmentation across water domains (freshwater, transitional, coastal)

Monitoring of **rivers, transitional waters and coastal seas is organised in separate institutional and legal silos**. Freshwater stations are typically designed under river-basin frameworks, while marine networks respond to marine or coastal policies. The result is:

- Different **station locations**, with gaps precisely at the points where riverine signals meet marine dynamics.
- A lack of **overlapping time series** where the same water mass can be followed as it moves from river to estuary to coastal zone.
- In our analysis, this is evident in the strong riverine signals in the Danube and Elbe, contrasted with much weaker or non-existent evidence in the estuarine and coastal parts of Po and Guadalquivir, where data are sparse or discontinuous.

Thus, the **river–sea continuum is broken in the data**, even when it may be physically connected in reality.

5.3.2. Lack of harmonisation and standardisation of variables and methods

Where data do exist, they are rarely **methodologically harmonised** across domains or basins:

- Rivers may report **TN and TP**, while coastal programmes focus on **dissolved inorganic nitrogen and phosphorus**, or use different fractionation schemes.
- Laboratories use different **analytical methods, detection limits, and quality-control procedures**, so combining time series across jurisdictions introduces uncontrolled methodological trends.
- Chlorophyll-a measurements differ in **depth integration (surface vs integrated), filtration, extraction solvents, and fluorometric vs spectrophotometric techniques**, making them only partially comparable.
- Sampling frequencies and timings are not aligned: some stations provide monthly data, others only a few samples per year, often biased towards specific seasons.

These inconsistencies mean that, even when data appear abundant, they do not form a **coherent, statistically robust basin-scale dataset**. Trends in TN, TP or chl-a may reflect **method changes rather than real ecological change**, or may simply be incomparable between freshwater and marine segments.

5.3.3. Absence of integrated basin-to-coast data repositories

Data are typically stored in **separate databases**: national river-basin systems, marine monitoring archives, research project servers, consultancy reports, etc. There is often **no single basin-scale repository** that:

- brings together river, transitional and coastal time series;
- links nutrient and chlorophyll data with protected-area boundaries, floodplain extent, or restoration measures;
- provides consistent metadata (methods, QA/QC, station history) to support long-term analyses.

For this study, assembling data for the Danube required substantial manual integration, while for the Po and Guadalquivir many potentially relevant datasets could not be used because they were either inaccessible, undocumented, or not clearly linkable to specific water bodies and protected areas. The **lack of a curated basin-to-coast repository** therefore directly translates into **biased ES assessments**, where only the best-documented basins (Danube, Elbe) can be analysed in depth.

5.3.4. Project-based, non-systematic data gathering

Another structural limitation is that much monitoring is **short-term and project-driven**:

- Many estuarine and coastal datasets originate from **temporary research campaigns**, not from long-term observing systems.

- When projects end, **stations are discontinued**, methods change, or data are not archived in accessible repositories.
- Transitional waters, in particular, are monitored intermittently, with years or decades between campaigns.

This kind of non-systematic data gathering is **poorly suited to detecting slow trends** in nutrient concentrations or the cumulative effects of protected-area expansion and restoration. ES signals—especially those related to nutrient retention and eutrophication control—are inherently **long-term and cumulative**; they require stable time series to be distinguished from interannual variability and hydrological noise. In the absence of such time series, ES benefits remain largely invisible.

5.3.5. Consequences for ecosystem service (ES) detection and policy

These structural data issues have profound implications:

- They create an **illusion of uneven ES performance**: the Danube and Elbe appear “successful”, while Po and Guadalquivir appear “failing”, but part of this contrast reflects **differences in observation systems rather than differences in ecosystem function**.
- They limit the ability to **attribute improvements to specific measures** (e.g. protected areas, floodplain reconnection), because interventions and monitoring are not co-designed.
- They weaken the evidence base for **basin-to-coast management and restoration policies**, including those aimed at reducing eutrophication, protecting fisheries, and enhancing coastal recreation.

In short, the current monitoring landscape **systematically underestimates ES**, particularly in heavily modified or data-poor basins. Without harmonised, long-term, integrated freshwater–marine datasets, it is impossible to fully quantify how protected areas and restoration measures translate into nutrient regulation, improved ecological status, and downstream benefits for society.

6. Recommendations: building an integrated basin-to-coast evidence base

Addressing these structural data gaps requires more than adding a few monitoring stations; it calls for **re-designing observation systems around the river–estuary/delta–coast continuum** (table 15). First, freshwater, transitional and marine monitoring need to be planned as **one integrated network**, not three separate domains. This implies co-locating key stations along main flow paths, aligning sampling frequencies, and ensuring that core variables (TN, TP, dissolved inorganic nutrients, chl-a, oxygen, salinity, discharge) are measured with **compatible methods and Quality Assurance and Quality Control (QA/QC) protocols**. Transitional waters and estuaries should be treated as **priority connectors**, not blind spots, because they are the critical filters where upstream signals are transformed before reaching the sea. Second, there is a clear need for a **basin-scale data infrastructure** that brings together river, transitional and coastal records with information on protected areas, floodplain connectivity and restoration measures. Instead of dispersing data across fragmented national and project servers, an integrated repository should provide: (i) harmonised time series with full metadata, (ii) spatial linkage to hydrological units and PA polygons, and (iii) versioned, citable products designed explicitly for long-term trend and ES analysis. Establishing such infrastructures at the level of large river basins (e.g. Danube, Elbe, Po, Guadalquivir) would turn currently "one-off" datasets into a **living evidence base** for adaptive management. Third, monitoring must shift from a **project-based to a systematic, policy-anchored approach**. Long-term nutrient and chl-a series should be recognised as essential to evaluating the effectiveness of protected areas, restoration under the Nature Restoration Regulation, the Water Framework Directive and Marine strategies. This implies stable funding, institutional responsibility for continuity, and explicit co-design of monitoring with restoration actions (e.g. new floodplain reconnection projects should always be paired with upstream–downstream monitoring transects). Only under these conditions can we robustly quantify how changes in protected-area extent and floodplain restoration translate into **measurable improvements in ES** along the full freshwater–marine gradient.

Table 15. Proposed future monitoring requirements and *current typical status* in large European river–sea systems

Water domain	**Indicator bundle**	**Core variables (minimum set)**	**Main ecosystem services supported**	**Key design / data requirements**	**Current typical status in large EU basins (Danube, Elbe, Po, Guadalquivir)**
Freshwater (rivers, floodplains, lakes)	**Water-quality bundle**	TN, TP, DIN/DIP, Chl-a, DO, temperature, discharge	ES2, ES3, ES8, ES12, ES16	Harmonised analytical methods and QA/QC; at least monthly sampling; stations aligned along main flow paths and near PAs/restoration sites.	**Routinely monitored under WFD** in all four basins (TN, TP, DO, temperature, discharge); **DIN/DIP and chl-a available but less consistent** (better in Danube & Elbe, patchier in Po & Guadalquivir).
	Biodiversity bundle	Fish index; macroinvertebrate index; macrophytes; phytobenthos/ diatoms; key wetland/ floodplain birds	ES6, ES7, ES9, ES13, ES14, ES16	Co-locate with water-quality stations; WFD-type protocols; repeated surveys (e.g. every 3 years).	**Fish, macroinvertebrates, macrophytes, phytobenthos**: yes, monitored under WFD in Danube, Elbe, Po and (to a lesser degree) Guadalquivir; **birds**: monitored via Natura 2000 / bird schemes, but **not systematically linked** to water-quality networks.

Water domain	Indicator bundle	Core variables (minimum set)	Main ecosystem services supported	Key design / data requirements	Current typical status in large EU basins (Danube, Elbe, Po, Guadalquivir)
	Habitat / landscape bundle	Floodplain & wetland extent; lateral connectivity index; riparian corridor integrity; side-channel/backwater area	ES3, ES4, ES11, ES10 (wetlands/peat), ES13	EO/remote sensing + field validation; mapping every ~5 years; GIS link to PAs/restoration.	**Land cover (CORINE / Copernicus) exists**, some national wetland/floodplain maps for Danube & Elbe; **connectivity indices and riparian conditions are rarely standardised**. Typically **partial and not integrated** with monitoring stations.
Transitional (deltas, estuaries, lagoons)	**Water-quality bundle**	TN, TP, DIN/DIP, chl-a, DO, salinity, turbidity, temperature, river discharge/sea level	ES2, ES3, ES5, ES8, ES12, ES15	Integrate river & marine programmes; higher frequency (bi-weekly/monthly); longitudinal cross-sections.	**Danube Delta & Elbe estuary**: nutrients, salinity, Chl-a, DO are monitored, but **stations are sparse and methods not fully harmonised** with upstream rivers. **Po & Guadalquivir**: more **patchy and project-based**, especially for nutrients and chl-a.
	Biodiversity bundle	Fish (with juveniles), benthic invertebrates (incl. filter feeders), phytoplankton functional groups, marsh/reedbed vegetation	ES6, ES7, ES9, ES13, ES14	Standardised estuarine protocols; co-location with water-quality; seasonal coverage.	**Benthic fauna & fish**: present in some estuaries (Elbe, parts of Danube Delta), often under research/MSFD; **harmful phytoplankton groups**: monitored where HAB risk is known; **marsh/reed vegetation**: mapped, but **not regularly monitored as part of water frameworks**. Overall **fragmented and basin-uneven**.
	Habitat / landscape bundle	Extent/condition of saltmarshes, reedbeds, tidal flats, lagoons; inundation frequency/elevation; tidal creek connectivity	ES3, ES4, ES5, ES11, ES10, ES13	EO habitat mapping + field surveys; include elevation; integrate with hydrodynamic models and PA boundaries.	**Habitats are mapped for Natura 2000/Habitat Directive** (especially in Danube Delta, Elbe estuary, Doñana); **time-series and inundation/connectivity metrics are scarce** and typically **project-based**, not part of routine monitoring.

Water domain	Indicator bundle	Core variables (minimum set)	Main ecosystem services supported	Key design / data requirements	Current typical status in large EU basins (Danube, Elbe, Po, Guadalquivir)
Coastal & marine	**Water-quality bundle**	DIN/DIP, TN, TP, chl-a, DO, temperature, salinity, Secchi depth	ES2, ES3, ES8, ES12, ES15	Long-term fixed stations + ferrybox/remote sensing; harmonised with transitional waters; aligned with MSFD/regional conventions.	**Nutrients and Chl-a are routinely monitored** in regional seas (Black Sea, North Sea, Adriatic, Gulf of Cádiz) under MSFD/Regional Conventions; **linkage to specific river basins is indirect**, and station density near river plumes varies (best for Danube, weakest for Guadalquivir).
	Biodiversity bundle	Fish community indices, benthic macrofauna & habitat-forming species (seagrass, mussel/oyster beds), seabirds/ mammals	ES6, ES7, ES9, ES13, ES14	Fisheries-independent surveys + biodiversity monitoring; integrated with habitat maps; periodic surveys.	**Benthic fauna & fish surveys exist**, but often **not synchronised with nutrient stations** and focused on specific fleets or MSFD descriptors; **seagrass/benthic habitats** mapped irregularly; seabirds/mammals mainly via dedicated surveys, not linked to water-quality networks.
	Habitat / landscape bundle	Extent/condition of seagrass, macroalgal reefs, shellfish reefs, coastal dunes & beaches; blue-carbon habitats	ES4, ES10, ES11, ES9, ES13	EO mapping with in situ validation; standard habitat classes; update every 3–6 years; link to PAs/restoration.	**Some mapping exists** (e.g. seagrass in Adriatic, Black Sea hotspots, coastal dunes), but **coverage is incomplete and inconsistent**; blue-carbon habitats rarely monitored with carbon stocks; **no unified basin-specific series**.
Cross-domain / transversal	**Data infrastructure & integration**	Integrated basin-to-coast repository linking chemical, biological, habitat, PA, hydrological and restoration data	N3; enables robust assessment of all ES	Single basin-scale/multi-basin platform; common IDs; open standards (Darwin Core, INSPIRE); versioned, citable datasets.	**Partially present but fragmented**: WFD databases for rivers, MSFD/marine databases, ICPDR for Danube, EMODnet/ICES/regional seas for marine; **no single integrated basin-to-coast system** for any of the four basins. Integration usually done ad hoc in projects.

Water domain	Indicator bundle	Core variables (minimum set)	Main ecosystem services supported	Key design / data requirements	Current typical status in large EU basins (Danube, Elbe, Po, Guadalquivir)
	Monitoring design principles	Co-location of nutrient & biodiversity/habitat measurements; river–estuary–coast transects; harmonised protocols; stable long-term funding	Underpins all ES (ES3, ES6–A9, ES12–ES16)	Move from project-based to systematic monitoring; co-design with restoration/PA planning; align with WFD, MSFD, NRR, biodiversity strategies.	**Some elements exist** (e.g. Danube–Black Sea transects, Elbe estuary programmes), but generally **not systematic**. Co-location of chemical–biological–habitat data is the exception, not the rule; funding often short-term and project-driven.

Performing a more complete assessment of basin-to-coast ecosystem services requires combining nutrient and chlorophyll indicators with multi-taxa biodiversity and habitat data. Along the river–estuary/delta–coastal continuum this implies, at minimum, integrating standard biological quality elements (fish, benthic invertebrates, macrophytes, phytobenthos) in rivers, fish and benthic fauna and marsh/seagrass habitats in transitional waters, and fish, benthos and habitats in coastal zones. These biodiversity and habitat metrics provide the missing links to provisioning services (fisheries, biomass), regulating services (flood regulation, shoreline protection, carbon sequestration), cultural services (recreation, birdwatching, landscape aesthetics) and supporting services (nursery functions, biodiversity maintenance). A future monitoring design should therefore be organised around indicator bundles that systematically co-locate nutrient, biodiversity, and habitat measurements, and store them in harmonised basin-to-coast repositories, so that ecosystem service outcomes can be quantified in a consistent, multi-variable way across basins and domains.

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Funded by the European Union under the Horizon Europe Programme, Grant Agreement No. 101082021 (MARCO-BOLO). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

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and Innovation

UK participants in MARCO-BOLO are supported by the UKRI's Horizon Europe Guarantee under the Grant No. 10068180 (MS); No. 10063994 (MBA); No. 10048178 (NOC).