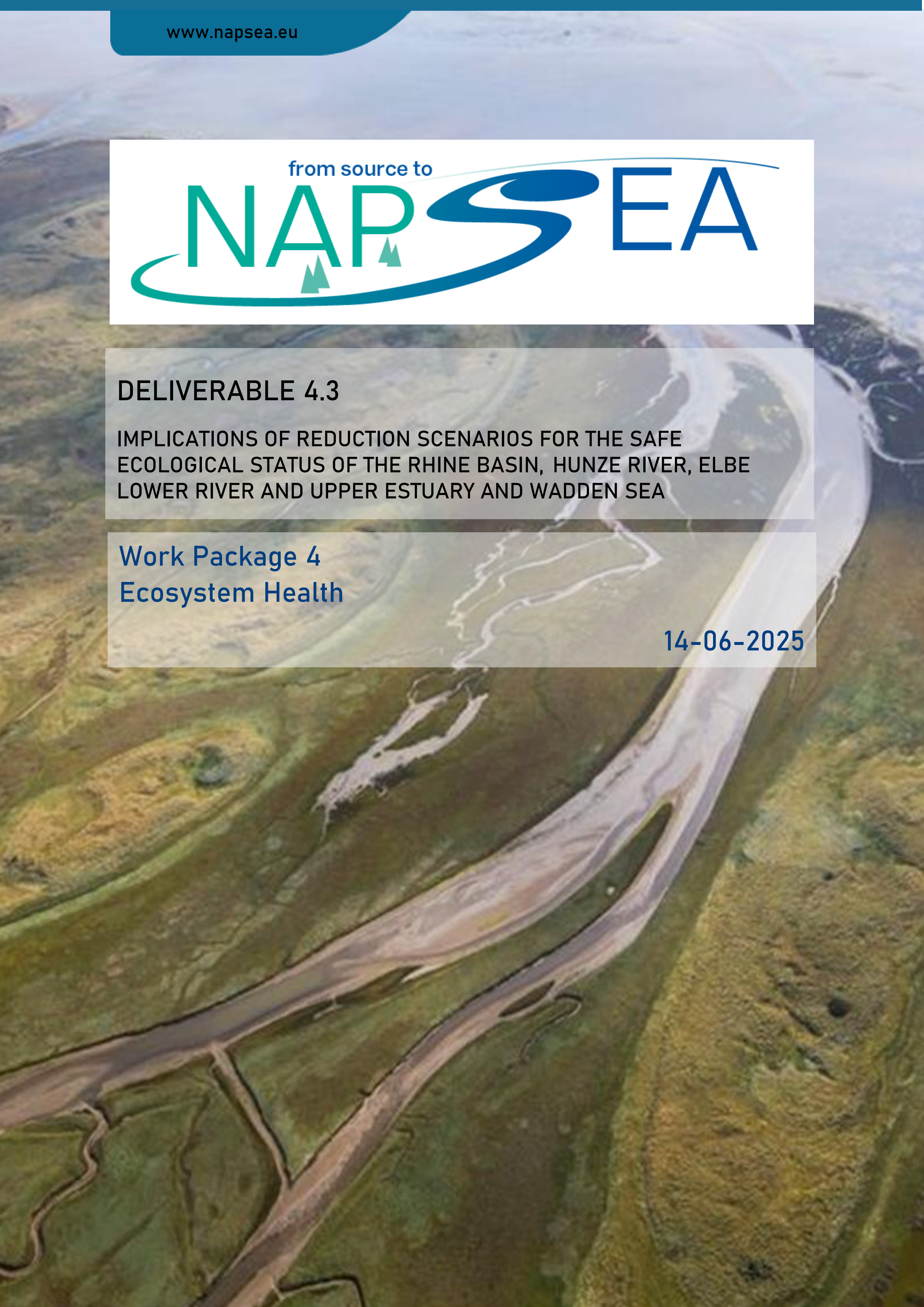

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DELIVERABLE 4.3

IMPLICATIONS OF REDUCTION SCENARIOS FOR THE SAFE ECOLOGICAL STATUS OF THE RHINE BASIN, HUNZE RIVER, ELBE LOWER RIVER AND UPPER ESTUARY AND WADDEN SEA

Work Package 4
Ecosystem Health

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Abstract	In this deliverable, the results of the reduction scenarios are discussed in relation to reductions needed to reach the Safe Ecological Limits in the four case studies. By carrying out all planned measures, the reductions are close to what is needed, but additional measures must be implemented. The impact of climate change is discussed. The importance of reducing both N and P in concert to prevent a further increase in N/P ratios is underlined.
Keywords	Scenario evaluation; Safe Ecological Limits; reduction scenarios; Wadden Sea; Elbe estuary; Rhine basin; Hunze

Contents

1. ACRONYMES

DuV	Düngerverordnung (German Fertilizer regulation)
CnANDY	Coupled Complex Algal-Nutrient Dynamics
RCP	Representative Concentration Pathways
NECD	National Emissions Reduction Commitments Directive
LAWA	Bund/Länder-Arbeitsgemeinschaft Wasser (German federal/state working group on water)
DIN	Dissolved Inorganic Nitrogen
PO_4	Orthophosphate
Chl-a	Chlorophyll-a

2. EXECUTIVE SUMMARY

This deliverable (Deliverable 4.3) evaluates the implications of various nutrient reduction scenarios on achieving safe ecological limits in the Rhine basin, Hunze river, Elbe lower river and upper estuary, and Wadden Sea. Despite extensive measures to combat eutrophication since the 1970s, nutrient enrichment remains a significant environmental issue in Europe. This report, part of the NAPSEA project, assesses the effectiveness of different strategies to reduce nitrogen (N) and phosphorus (P) loads in these regions.

The analysis focuses on four case studies, each with specific ecological indicators and reduction needs. For the Wadden Sea, the recovery of seagrass and the management of dissolved nitrogen/silicate (N/Si) ratios are critical. In the Elbe estuary, reducing nutrient loads is essential to alleviate oxygen deficits and improve ecological conditions. The Rhine basin requires additional measures to meet N concentration thresholds, while the Hunze catchment needs a combination of local measures to achieve both local and downstream targets.

The study highlights the importance of addressing both N and P reductions to prevent imbalances that could negatively impact ecosystems. The scenarios modelled include improved wastewater treatment, agricultural practices, and nature-based solutions, with evaluations for short-term (2030) and long-term (2050) impacts. The findings indicate that while planned measures bring reductions close to necessary levels, additional actions are required to achieve safe ecological limits.

Climate change is identified as a significant factor influencing nutrient retention and mobilization, with contrasting effects on N and P. The report advocates for a holistic approach to nutrient management from source to sea, emphasizing the need for comprehensive and adaptive strategies to protect Europe's water bodies.

3. INTRODUCTION

Eutrophication still is a wide-spread environmental problem in Europe (e.g. Poikane et al., 2019; van Beusekom et al., 2024). Manifold measures have been taken since the 1970s to combat eutrophication, including wastewater treatment and better agricultural practices (e.g. de Jong et al., 2007). As part of the NAPSEA project, we selected four case study within which we further tackle the issues related to eutrophication:

1) The Wadden Sea as the ultimate receiver of terrestrial (European-scale) nutrient loads;

2) the Rhine river basin, being the largest European river basin receiving a significant water load from glaciers;

3) the Elbe Estuary, receiving nutrient mainly form central Europe, water mainly from rain and is characterized by intense algae blooms and;

4) the Hunze catchment as an example of a small catchment area near the Wadden Sea strongly impacted by agriculture and directly draining into the shallow freshwater lake called Zuidlaardermeer.

For these case studies, Safe Ecological Limits were derived (van Beusekom et al, 2024) which depended on and related to the system targeted, but were all linked to nutrient reductions. The scenarios to reduce nutrient input into surface waters are described in Gericke and Leujak (2024). In Musolff et al. (2024 updated) the effects of these scenarios on the riverine nutrient loads were estimated with hydrological waterquality models.

In this Deliverable (4.3), we discuss to what extent the reduction scenarios enable the environment to reach Safe Ecological Limits (Figure 1). First, an overview of the Safe Ecological Limits and of the Reduction Scenarios will be given. Based on this, we will discuss the effects of the reduction scenarios on the Ecological Status of the four study areas.

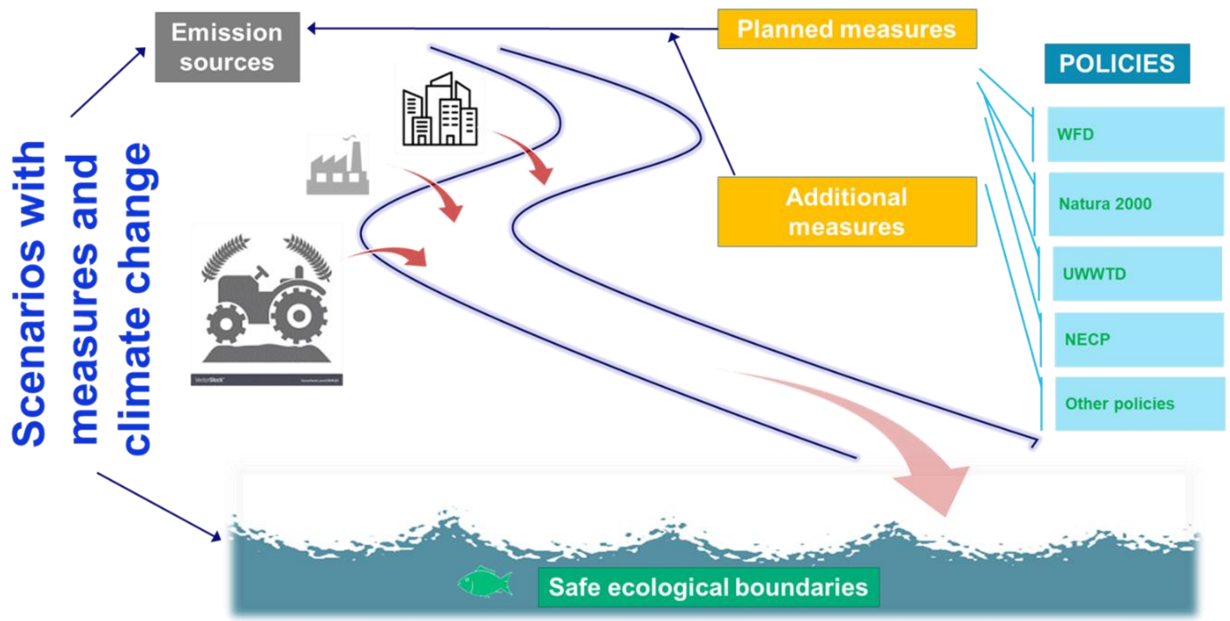


Figure 1. A conceptual overview of NAPSEA method, including the different work packages and focus areas.

3.1 Safe Ecological Limits: an overview

This chapter summarizes the Safe Ecological Limits as described in Deliverable 4.2 (van Beusekom et al., 2024). For the four case studies, different indicators were selected that were tied to the local issues: For the Wadden Sea, we focused on two ecological aspects: seagrass recovery and shifts in phytoplankton species composition due to Si limitation. For the Elbe, we focused on the O_2 problems in the upper estuary due to massive algae blooms in the lower Elbe River. For the Hunze we focused on recovery of the submersed vegetation in the receiving Zuidlaardermeer and the reduction needs to protect the Wadden Sea further downstream. For the Rhine catchment, we estimated which share of the catchment reaches nitrate concentrations below 1.9 mg/L and PO_4 concentrations below 0.055 mg/l as proposed by Poikane et al (2019) and the German Working Group on Water Issues (LAWA, see Musolff et al., 2024).

Table 1 presents an overview of the reduction needs for N and/or P to reach the case-specific Safe Ecological Limits developed in NAPSEA. As the reference period, 2010-2020 was used. The reduction needs and indicators vary between the four case studies. Both the maximum and minimum values were observed for the Elbe River and Estuary (a minimum of 30% (N/Si ratio of 1 in the lower Elbe River and a maximum of 63% for phytoplankton blooms in the Elbe River).

Table 1. Safe Ecological Limits with related N and P reductions for the four case studies (Hunze, Rhine basin, Elbe lower river and upper estuary, Wadden Sea).

Case study	Indicator	Mainly impacted by:	Reduction needs for:	N reduction:	P reduction:	Applicability
Wadden Sea	Sea grass recovery	Riverine TN loads	Rhine/ Meuse	34-43%		Local
Wadden Sea	Absence of blooms by non-silicifying algae (e.g. *Phaeocystis*)	Winter riverine Silica:Nitrogen ratio	All four rivers below	30-55%		Generally applicable to all rivers
			Rhine	50%		
			Ems	55%		
			Weser	40%		
			Elbe	30%		
Elbe estuary	O_2 >7 mg/l	Import riverine organic matter (phytoplankton)	Elbe	~45%	~45%	Local
Elbe river	Phytoplankton biomass < 40 µg Chl-a/l	Organic matter loads	Elbe	63%	63%	Local
Hunze	Recovery of submersed vegetation in the Zuidlaardermeer	Incoming Phosphorus load	Hunze		40%	The critical P-load depends on various factors and should thus be derived per system
Hunze	Reduction need for Wadden Sea (sea grass recovery)	TN loads (mainly winter)	Hunze	34-43%		
Rhine catchment	N and P concentrations below thresholds as defined by ordinances		Rhine	44%	50%	Local

3.2 Reduction scenarios: an overview

In Deliverable D3.5, results of predictive modelling of nitrogen (N) and phosphorus (P) concentrations and exports for the Elbe, Rhine and Hunze river basins, were evaluated under different scenarios of measures (Table 2). The evaluation relied on the mQM model for N and the CnANDY model for P, with the parameters calibrated to represent current climatic and nutrient conditions (D3.2). This report follows the set of measures introduced in D3.3 (set of scenarios) and the database of concrete measures provided in D3.4 (model input of selected scenarios). A separate set of more detailed scenarios were defined for the local SWAT model explorations for the Hunze catchment.

Table 2. Summary of reduction scenarios.

Scenario	Target of measures	Narrative
1	Wastewater treatment	The revised Urban Wastewater Treatment Directive is implemented
2	Agricultural input	The Nitrates Directive is implemented as DuV in Germany and 7th AP in The Netherlands
3	Atmospheric deposition	The NECD is implemented, the Dutch atmospheric target for the protection of the Natura 2000 areas is reached
4	Nature-based solutions for nutrient retention	The Biodiversity Strategy 2030 and national regulations related to restoration of riparian areas and floodplains, potentially also fulfilment of water-related goals of the EU Nature Restoration Law
5	All measures	All the scenarios 1-4 are implemented together
6	No measures	None of 1-4 is implemented. The projected hydrological states represent the emission scenario RCP4.5.
7A	Strengthening policies	Urban Wastewater Treatment Plants achieve the technological benchmark set as the median retention and concentration, treatment plants ≥2000 p.e. considered, agricultural and atmospheric inputs are further reduced, nature-based solutions similar to scenario 4
7B	Exploring synergies	Similar to scenario 7A but nature-based solutions are enhanced
7C	Drastic societal changes	Agricultural inputs and atmospheric deposition drastically reduced, e.g. by lower livestock densities and dietary changes

The mQM and CnANDY model results are compared to reference conditions (2010-2020), assessing the effectiveness of each scenario in reducing the N and P concentrations in inland waters and the nutrient fluxes exported to the estuaries and the Wadden Sea. The scenarios include the effects of existing policies and measures like improved wastewater treatment, improved agricultural practices, reduction of atmospheric deposition and the extension of nature-based solutions. Furthermore, scenarios were developed that strengthen existing policies, explore synergies and include more drastic societal changes like a change towards diets with less meat. For each of the scenarios, both the short-term effects (until 2030) and long-term effects (until 2050) were calculated, which include modelled changes in climate and hydrology according to the scenario RCP4.5.

Table 3, and Table 4 summarize the reduction percentages of N and P loads reached for the different scenarios. For N the changes in concentrations at the river outlet were also estimated to evaluate possible effects on the N/P ratio. By implementing all planned measures from existing policies (scenario 5), significant reductions in nutrient loads can be achieved. For the Rhine basin, these measures are expected to reduce nitrogen and phosphorus levels considerably by 2030. Similarly, the Elbe will see substantial decreases in nitrogen and phosphorus, although the reductions for phosphorus will be less pronounced compared to nitrogen. Looking further ahead to 2050, the Rhine basin will continue to benefit from these measures, with further reductions in nutrient loads. The Elbe will also experience ongoing improvements, with notable decreases in phosphorus levels. However, climate change is anticipated to counterbalance the effects of measures on nitrogen loads in the Elbe by 2050.

In fact, climate change has a variable impact in space and time on both nutrients. Changes in discharge patterns are expected to be more pronounced in the Elbe compared to the Rhine basin. Under constant nutrient inputs (scenario 6), the changing hydrology will lead to a decrease in nitrogen fluxes and an increase in phosphorus fluxes by 2030. By 2050, however, nitrogen fluxes in the Elbe will rise slightly, while phosphorus fluxes will decrease.

The reductions reached in scenario 5 are close to, but do not reach the low end of the reduction range needed for the Safe Ecological Limits. Therefore, additional scenarios were developed including strengthening of existing policies, enhancement of nature-based solutions or more drastic measures like reduction of agricultural inputs and atmospheric deposition drastically reduced, e.g. by lower livestock densities and dietary changes. Only with these additional measures, reductions come within the range required for the Safe Ecological Limits. More detailed implications of these measures will be discussed in the next chapter.

Table 3. Percentage reduction of N loads compared to 2010-2020. Reduction percentage of N concentrations at the outlets is shown in brackets.

Scenario	Target of measures	Rhine 2030	Rhine 2050	Elbe 2030	Elbe 2050
1	Wastewater treatment	-7.1%	-5.4%	-24.3%	-3.9%
2	Agricultural input	-11.3%	-10.3%	-18.3%	-2.6%
3	Atmospheric deposition	-13.4%	-14.9%	-18.6%	-4.5%
4	Nature-based solutions for nutrient retention	-7.7%	-4.5%	-22.0%	-1.1%
5	All measures	-17.8% (-20)	-18.9% (-20)	-33.4% (-19)	-20.6% (-26)
6	No measures	-4.6%	-2.8%	-15.8%	+5.1%
7A	Strengthening policies	-23.3% (-24)	-27.3% (-28)	-40.8% (-30)	-30.7% (-37)
7B	Exploring synergies	-27.5% (-28)	-31.6% (-32)	-57.1% (-48)	-46.9% (-52)
7C	Drastic societal changes	-32.7% (-32)	-43.5% (-44)	-59.8% (-52)	-61.6% (-67)

Table 4. Percentage reduction of P loads compared to 2010-2020. Scenario 2 and 3 were not considered for reduction in P loads.

Scenario	Target of measures	Rhine 2030	Rhine 2050	Elbe 2030	Elbe 2050
1	Wastewater treatment	-22.7%	-23.4%	-8.4%	-37.8%
4	Nature-based solutions for nutrient retention	+10.0%	+9.0%	+15.5%	-20.1%
5	All measures	-23.7%	-24.4%	-9.3%	-38.7%
6	No measures	+11.0%	+9.6%	+16.4%	-19.3%
7A	Strengthening policies	-29.7%	-30.4%	-20.0%	-46.6%
7B	Exploring synergies	-30.4%	-31.0%	-21.9%	-48.1%
7C	Drastic societal changes	-30.4%	-31.0%	-21.9%	-48.1%

3.2.1. Reduction scenarios: the local Hunze case

The Hunze catchment provides a representative Dutch local case in which options to achieve the safe ecological limits protecting both the local and downstream aquatic ecology were studied in more detail and with input from the local water authority.

For exploring mitigation strategies towards reaching the existing WFD targets and the additional safe ecological limits, a water and nutrient transport model was developed using the Soil and Water Assessment Tool (SWAT; Neitsch et al., 2011). Within SWAT, water and nutrients are routed through hydrological response units (HRU's with unique combinations of soil type and land use) via sub-catchments towards the main surface water streams. The Hunze model consists of 33 subbasins and 1962 HRU's. This high level of spatial and land use detail aligned with that of the local measures and therefore supported the discussions with the local water authority.

The future scenarios to explore were defined together with the local water authority (Water Board Hunze and Aa's). Two ICCP climate change scenarios (RCP 4.5 (intermediate) and 8.5 (worst-case) in 2050) were implemented to explore the consequences of the changes in hydrology (more evaporation, more extremes) on nutrient transport. The other scenarios (Table 5) explore the effects of land use change, improved wastewater treatment, and nature-based solutions.

The effects of all scenarios on annual TP concentrations, and summer and winter TN concentrations 10 years after implementation are presented in Figure 2. The nutrient concentrations decrease in all scenarios except 4 (convert dairy to arable), which causes a significant increase in both TP (+20%), summer TN (+18%), and winter TN concentrations (+52%). The other catchment-scale land use transition scenario's (1,2,3,5) result in substantial reductions and in most cases in compliance with the targets. The effects of other individual measures (wastewater treatment improvement, agricultural measures, nature-based solutions) are smaller. The measures in these scenario's (6-13) however can be combined into a mitigation package that leads to reaching all targets. There are many potential combinations, and it is not always possible to add up the reduction effects of scenarios. Still, the results in Figure 2 give an indication of what combinations of measures would be sufficient, although combined scenarios have not yet been explored.

Table 5. List of model scenarios for the Hunze. The details about the scenarios are in Musolff et al. (2024).

Scenario	Explanation	SWAT model implementation
1.Convert agriculture to nature	All agricultural land used is converted to nature	Agricultural land use types changed into natural grassland, fertilizer input and drainage removed, improved soil quality, reduced erosion
2.Convert agriculture to mammut grass cultivation	Mammut grass cultivation for bio-based building materials, co-benefits for soil quality, water quality, C sequestration.	Agricultural land use types changed into Mammut grass, improved soil quality, reduced fertilizer input, reduced erosion
3.Convert arable into dairy	Arable farming is replaced by dairy farming (grass-maize rotation)	Change arable land use types into grass and maize (PAST and CORN, Bouwplan A), improved soil quality, reduced fertilizer input, reduced erosion
4.Convert dairy into arable	Dairy farming (grass-maize rotation) is replaced by arable farming	Change grass and maize land use types into most common row crops (potato and winter wheat, Bouwplan B), reduced soil quality, increased fertilizer input, increased erosion
5.Convert to beans	Land use change related to the protein transition; change arable crops to beans like field bean (vicia faba)	Change arable agricultural land use types into beans, improved soil quality, reduced fertilizer input, reduced erosion
6.WWTP improved	Improved Wastewater treatment for P, effluent concentrations reduce from max. 0.5 mg/l to max 0.27 mg/l	Top off TP concentrations in effluent above 0.27 mg/l. No effect on TN.
7.WWTP buffer	Enhanced purification, e.g. by increased buffering of extreme events	Reduction N/P load of 20% in summer and 10% in winter
8. Optimize crop nutrient uptake efficiency	Combination of measures to improve nutrient uptake (soil quality, fertilization method (timing, dosing, type).	Increase crop uptake in all arable area with 10%
9. Optimize infiltration/groundwater P and N in arable areas	Reduce overland flow by optimized infiltration (improved soil structure, infiltration trenches, dams between crop rows)	Reducing CN2 (75 to 55) in .mgt and USLE_C (0.20 to 0.10) in crop.dat for enhanced infiltration, decreases runoff, reduced soil erosion and phosphorus loss
10. Optimize in-stream retention	Increased in-stream retention in main streams, e.g. by longer residence times by re-meandering, more N/P capture in vegetation/ sediment, more denitrification (N).	Increase the in-stream N and P retention with 10%
11. Optimize riparian retention 20m	Riparian buffer zones around main streams, more retention of water, nutrients, sediments.	Riparian 'strip buffer' activated in SWAT for larger surface water system, reduced overland flow, no fertilizer input around streams.
12. Optimize riparian retention 100m	Riparian buffer zones around main streams, more retention of water, nutrients, sediments.	Riparian 'strip buffer' activated in SWAT for larger surface water system, reduced overland flow, no fertilizer input around streams
13. Extend purification wetland	In 2019, a 230 ha marsh area (Tusschenwater) was implemented. This will be extended with an extra 90 ha. Part of Hunze storm water runoff can flow over into this buffer.	Land use change from agriculture (mainly grassland) to marsh. Reduction of storm water load peaks in Hunze stream

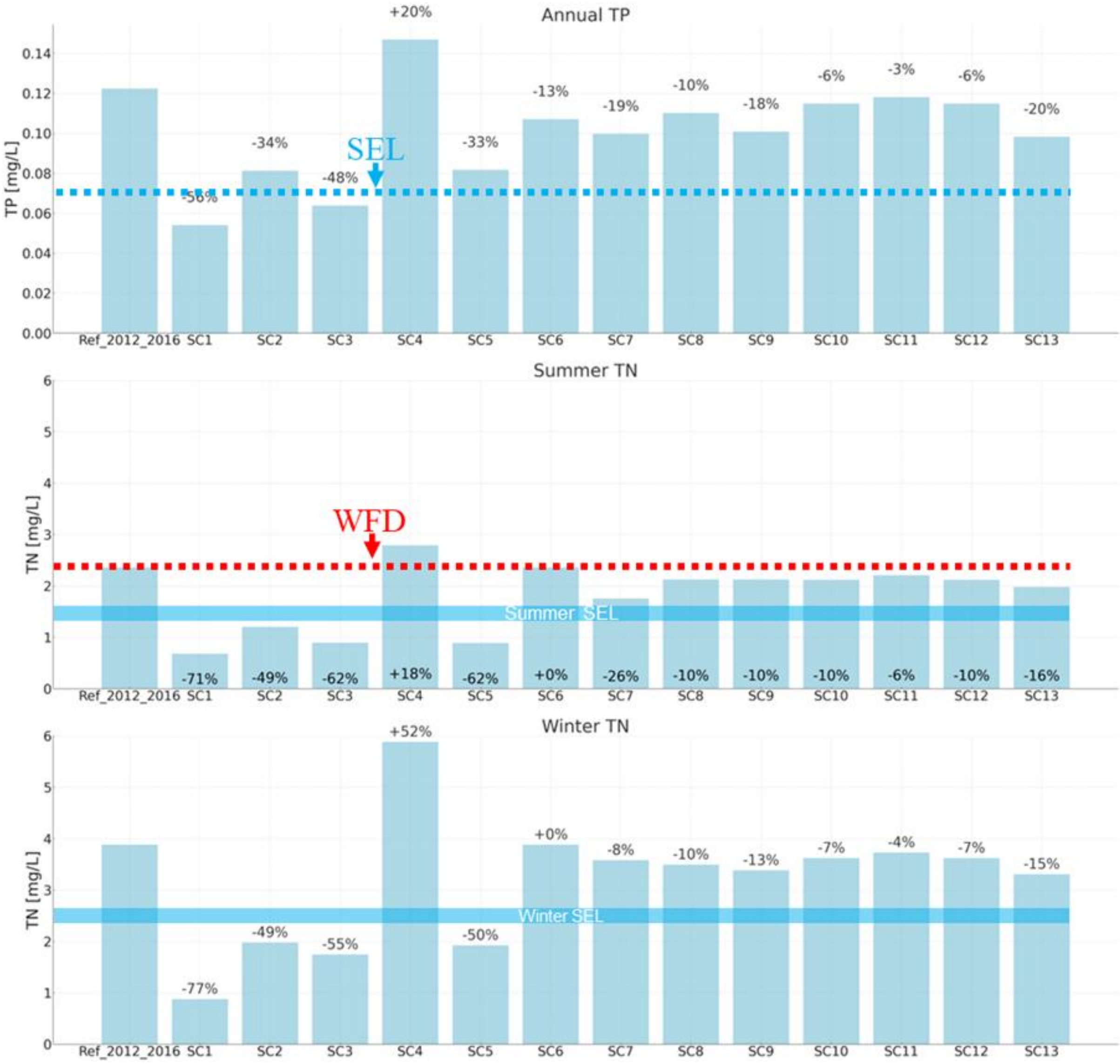


Figure 2. TN and TP concentration results for all scenarios, SEL is the Safe Ecological Limit target, which differs for nitrogen between summer and winter. WFD refers to the Water Framework Directive target. Note that the upper (TP) graph gives annual average concentrations; while the middle and lower plots give summer and winter average TN concentrations, respectively. Detailed results are reported in Musolff et al. (2024).

4. IMPLICATIONS OF THE DIFFERENT REDUCTION SCENARIOS FOR REACHING SAFE ECOLOGICAL LIMITS

In this section the implications of the different reduction scenarios for reaching safe ecological limits are discussed per case study.

4.1 Wadden Sea

4.1.1 Wadden Sea observation

The Wadden Sea is strongly impacted by riverine nutrient loads, influencing many aspects of the Wadden Sea ecosystem, like phytoplankton blooms, seagrass decline, blooms of green macroalgae, phytoplankton species composition or macrobenthos biomass. But only a few components of the Wadden Sea ecosystem show significant correlations with riverine nutrient inputs (van Beusekom et al., 2001) that are strong enough to use for management purposes. On this basis, autumn release of NH_4 and NO_2 and Summer Chlorophyll levels were selected as eutrophication indicators. These indicators highlight, among other aspects, regional differences in the Wadden Sea with a less eutrophic northern part where seagrass recovered (Reise & Kohlus, 2008) and a more eutrophic southern part where seagrass did not recover yet (van Beusekom et al., 2001, 2019; van Katwijk et al., 2024). The main driver of these regional differences is a difference in import of organic matter from the adjacent North Sea into the Wadden Sea (van Beusekom et al., 2019).

On basis of van Katwijk et al., 2024, our first safe ecological limit for the Wadden Sea was defined as ‘seagrass recovery in the entire Wadden Sea'.

Seagrass has recovered in the less eutrophic northern Wadden Sea. Based on the eutrophication conditions during recovery, van Katwijk et al., (2024) estimated that compared to 2010 – 2017 a reduction of riverine TN loads of 34% is needed for recovery in the Dutch Wadden Sea and of 43% for the Lower Saxonian Wadden Sea. Given that the Rhine is the major source of TN, the planned measures (Scenario 5, ~18%) would not be sufficient to reach this goal and more drastic measures are needed. For the Dutch Wadden Sea, Scenario 7B (up to 32%) may be sufficient but for the Lower Saxonian Wadden Sea to reach a reduction of 43% on the long term additional drastic changes (Scenario 7C) are needed. Possibly, a stronger reduction of Ems N loads beyond the envisioned 43% based on N/Si ratios may alleviate the pressure on the Lower Saxonian Wadden Sea (see below).

A second Safe Ecological Limit for the Wadden Sea was defined as 'a return to the pre-eutrophic conditions where spring phytoplankton blooms are limited by N and not Si’. For this, winterly N/Si ratios of about 1 are needed (van Beusekom et al., 2024). In the scenarios, climate related changes in discharge were considered. Therefore, we will focus on concentrations changes instead of loads. These are given in Table 3 (values in brackets). For the Elbe a reduction in N of about 30% was estimated. With all planned, this may be reached in 2050, with scenarios 7, already in 2030.

In order to reach winterly N/Si ratios of 1 in the Rhine, stronger measures are needed as compared to the Elbe. This is partially due to the somewhat lower Si concentration in the Rhine due to the diluting effect of melting glaciers. To reach the needed reduction of 50% for the Rhine to reach an N/Si ratio of 1, additional measures as outlined in Scenario 7C will be necessary. Compared to the Rhine, other rivers impacting the Wadden Sea like the Ems or Weser have much higher N concentrations necessitating also much higher reduction needs to reach winterly N/Si ratios of 1. For the Ems, reductions of ~55% are needed, for the Weser ~40% suggesting the need for drastic reduction measures in the respective river basins as outlined in scenario 7 (see D4.2: van Beusekom et al., 2024).

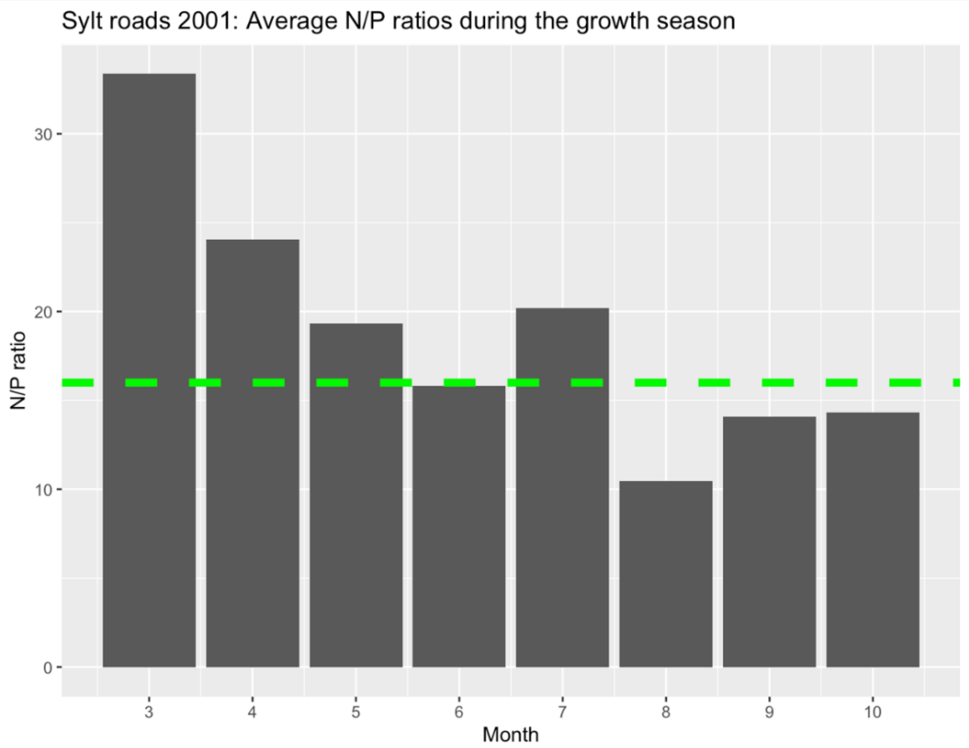


Figure 3. Seasonal dynamics of N/P ratios, as shown by monthly averages of N/P ratios in fresh organic matter present in the northern Wadden Sea (2001) during the growing season, based on the long term monitoring data (Sylt roads) from the Wadden Sea Station in List/Sylt (van Beusekom, Boersma, unpublished results). In 2001, an early spring bloom was limited by Si availability. At the same time, PO4 reached low values and high NO3 concentrations lead to high N/P ratios in freshly formed organic matter.

For the Wadden Sea, no specific P goals were selected as the Wadden Sea is ultimately N limited. However, N/P ratios may still play an important role in its ecosystem functioning: Preliminary results from the northern Wadden Sea (time series of the Wadden Sea Station Sylt) suggest that during spring blooms the N/P ratio in fresh organic matter reached values >30. After the spring bloom the values decreased to an average value of below 16 (van Beusekom, Boersma, unpublished results, see Figure 3). The high spring values suggest a reduction in food quality, because increased N/P ratios (Sterner and Elser, 2002) may have negative consequences for the pelagic food web in terms of growth, survival and reproduction of the herbivores including negative effects on top predators like fish larvae (e.g. Malzahn et al., 2007). Consumers cope with dietary imbalances by altering their grazing behaviour and physiological conditions to maintain nutritional/stoichiometric homeostasis, often at additional energetic costs (Sterner and Hessen, 1994). Philippart et al. (2007) noted a possible relation between riverine P-loads and higher trophic level biomass in the Wadden Sea.

Since the maximum eutrophication during the 1980s and 1990s, riverine nutrient loads to the Wadden Sea have decreased by about 50% for N and about 75% for P (e.g. van Beusekom et al., 2019), which has led to an increased N/P ratio in coastal waters. The model results for the different scenarios show that in most cases, N-reductions are larger than the P reductions, which would partially counteract the current increase in N/P ratio. However, a few exceptions exists, and especially wastewater treatment would probably lead to a higher reduction of P than of N. This would have negative effects on the N/P ratio. In general, care should be taken that any measure that only focuses on one nutrient should be accompanied by measures to prevent increased N/P ratios.

4.1.2 Wadden Sea simulation

The DCSM model was used to simulate water quality and eutrophication processes (see Appendix for model details). Three simulations were conducted covering the period 2015–2017, excluding the spinup years 2012–2014. The reference run represents current conditions, scenario 5 reflects the combined effects of scenarios 1–4 (Table 2) and scenario 7c represents the most drastic societal changes (Table 2). Further details on the scenario configurations are provided in Section 3.2.

Figure 4 shows the model results for the maximum nitrogen and phosphorous reduction (scenario 7c) as compared to the baseline reference conditions. More specifically, it shows the spatial distribution of dissolved inorganic nitrogen (DIN; Figure 4a), ortho-phosphate (PO_4; Figure 4b), and summer chlorophyll-a concentrations (Figure 4c) in and around the Wadden Sea. Both DIN and PO_4 concentrations exhibit a pronounced spatial gradient, decreasing from higher levels near the coast to lower levels in the open sea, driven by substantial reductions in nitrogen and phosphorus inputs from inland river sources. These nutrient reductions also result in a significant decrease in summer chlorophyll-a concentrations, with the most notable reductions observed at the Elbe River mouth, reflecting the sensitivity of phytoplankton biomass to altered nutrient dynamics. At the German Norderelbe station (Figure 5d), in comparison to the reference run and scenario 5, the more drastic scenario 7c achieves a significant decrease in summer Chl-a concentration to 8.2 µg/L. Hence, these deterministic model results align with the statistical derivation of the safe ecological limits. In Katwijk et al. (2024) the chlorophyll-a range for potential seagrass recovery was derived from the correlation between TN river loads and summer chlorophyll. This correlation was demonstrated for measured (van Katwijk et al., 2024) and modelled scenarios in Figure 6, and illustrates the potential for seagrass recovery in many of the tidal basins. The eutrophication (chlorophyll-a) situation around North Frysia was already in suitable conditions for seagrass to recover, which has occurred since early 2000s (van Katwijk et al., 2024 and references herein). For the western Dutch Wadden Sea conditions were in range of suitable for seagrass to recover, emphasized by stronger reductions in summer chlorophyll-a for scenarios 5 and 7c. For the western German Wadden Sea, nears Ems-Jade, the average summer chlorophyll-a is also in the suitable range for seagrass to recover. For all three, but especially the southern Wadden Sea locations (western Dutch and German Wadden Sea), there is a clear difference between measured and modelled chlorophyll-a for the years 2015-2017 with modelled Chl-a generally higher in modelled outcomes (1.2-2.4 times higher). The difference in summer chlorophyll-a between the modelled reference scenario and the measurements (van Katwijk et al. (2024)) are likely related to differences in temporal resolution. Where for measurement the summer averages are based on a few values in time, the model calculates chlorophyll-a with a 10-min interval therefore resulting in much larger variation over time (see example for model-measurements comparisons for station Vliestroom and Marsdiep in Figure B.4 and Figure B.5 in Appendix B).

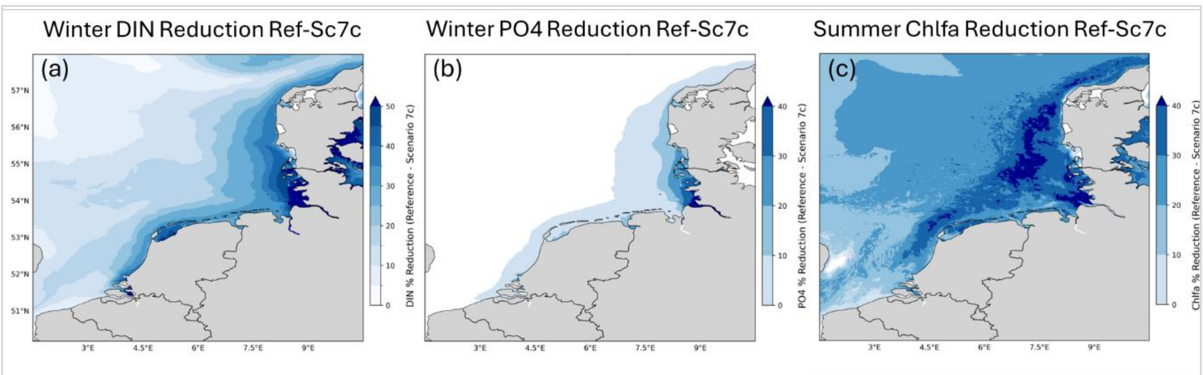


Figure 4. Winter DIN (a) and PO4 (b) and summer Chl-a (c) reduction percentages for the reference run and scenario 7c.

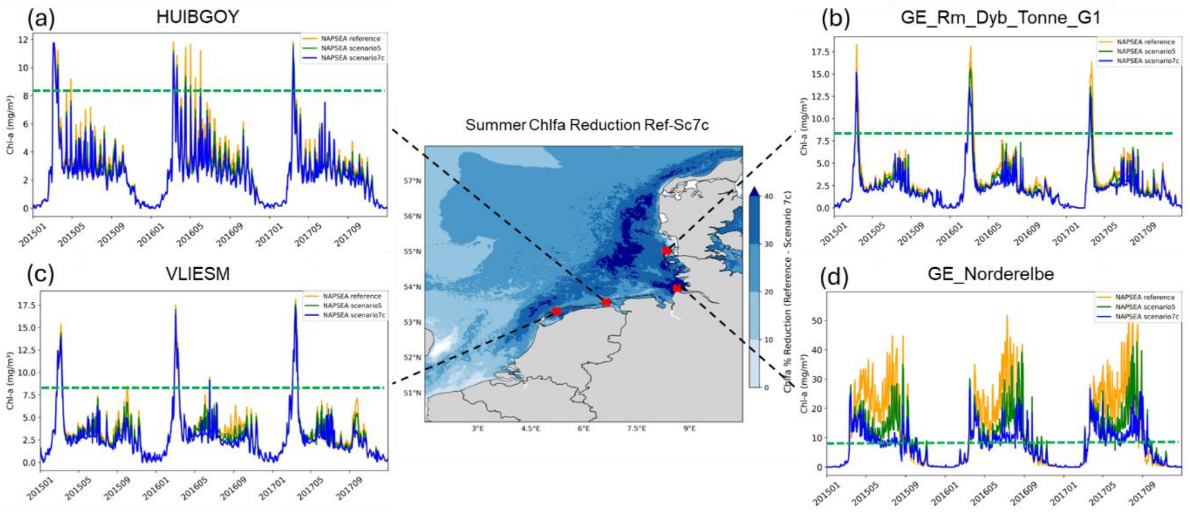


Figure 5. Temporal dynamics of Chl-a at various stations in the Wadden Sea: baseline conditions (reference) and responses to nitrogen and phosphorus reduction under scenario 5 and scenario 7c.

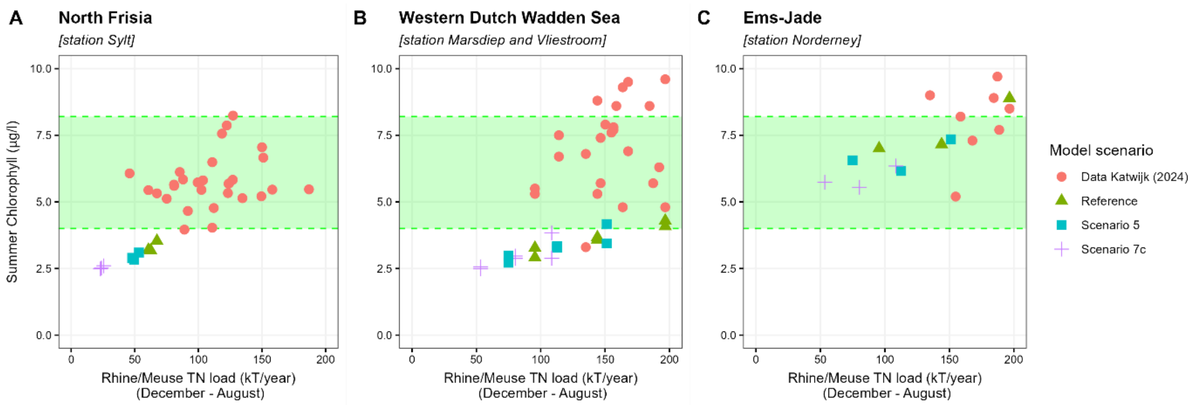


Figure 6. Relation between modelled summer chlorophyll levels and measured TN loads by the rivers Elbe/Weser (A) from January-August and (B) Rhine/Meuse from December–August, for the stations (A) Sylt in the North Frisian region, (B) Marsdiep and Vliestroom in the western Dutch region, and (C) at Norderney in the Ems-Jade region. Three different scenarios are modelled, the reference (circle), scenario 5 (triangle) and scenario 7c (square), and the figure includes also the raw data from Figure 6 in van Katwijk et al., 2024. The critical summer chlorophyll concentration (green range) for seagrass to recover is also derived from Figure 6 in Katwijk et al., 2024. Figure B demonstrates both markers for station Marsdiep and station Vliestroom, hence the duplicated markers. Note: for clear demonstration the y-axis and x-axis are reduced, figure with full axis is in Appendix B in figures Figure B.1Figure B.2Figure B.3.

Figure 7a illustrates the current (2015-2017) eutrophication state of the Wadden Sea, indicating a high potential for seagrass recovery in the western Dutch tidal basins, Chl-a concentrations approach the threshold (<8.2 µg/L) supportive of seagrass restoration. Conversely, most eastern Dutch tidal basins and portions of the German Wadden Sea exhibit Chl-a levels above this threshold, classifying them as non-recovered. Under the nutrient reduction scenario 5, the majority of Dutch Wadden Sea tidal basins are projected to achieve Chl-a concentrations below 8.2 µg/L, with the exception of the Ems mouth basin. In the more drastic scenario 7c, most German tidal basins are also expected to reach this threshold, suggesting a high potential for seagrass recovery across the majority of Wadden Sea tidal basins. These results emphasize the spatial variability in eutrophication status and highlight the necessity for targeted nutrient reduction measures, particularly in the eastern Dutch and German regions, to facilitate seagrass recovery.

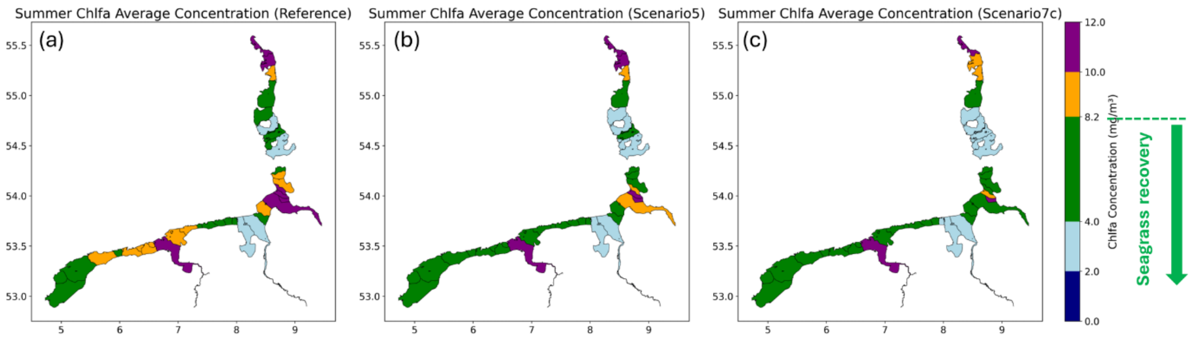


Figure 7. Simulated marine eutrophication responses (summers of 2015–2017) across three scenarios: baseline reference conditions (a), combined reduced riverine nutrient input under scenario 5 (b), and extreme riverine nutrient reduction under scenario 7c (c). The green dotted line denotes a Chl-a threshold (<8.2), indicating a high potential for seagrass recovery.

Do note that the validation figures in Appendix B demonstrate the underestimation of the modelled summer Chl-a compared to measurements. This implies that the modelled Chl-a values for scenarios 5 and 7c which are below threshold should be taken with a degree of uncertainty. And since these summer average values might have been slightly higher, reaching the threshold is thereby also less certain. However, besides the statistical trustworthiness of the model, the direction and trend of decreasing summer Chl-a with modelled scenarios is clear.

4.2 Elbe estuary

One of the major environmental problems in the upper Elbe estuary is the summer O_2 deficit, caused by the intensive remineralization of massive phytoplankton blooms under O_2 consumption in the light-limited dredged estuarine part. Currently, oxygen levels in the Elbe estuary drop to low levels of approximately 5 mg O_2/l (about 156 µmol O_2/l) in summer (Figure 8), which is well below the Safe Ecological Limit of 219 µmol O_2/l or 7 mg O_2/l as defined by the framework of the WFD and demanded by the OGewV. Low oxygen conditions can have negative consequences for vital conditions of aquatic organisms (e.g. Ekau et al, 2010). In particular, concentrations of 5 mg O_2/l and lower have been shown to affect population structures and reduce abundances of fish species in the Elbe estuary by impairing their mortality, growth, and reproduction (e.g. Möller and Scholz, 1991; Sepulveda, 1994; Theilen et al. 2025). Similarly, studies from the neighbouring Scheldt estuary suggest that planktonic organisms were hindered in their spatial distribution and occurrence at the threshold of approximately 4 mg O_2/l, which may have acted as a lethal barrier (Mialet et al., 2010). In recent decades, successful restoration efforts and pollution control measures in the Scheldt estuary, which have resulted in increased oxygen levels above 7 mg/l, have been associated with a corresponding rise in zooplankton abundance and diversity (see Mialet et al. 2011; Chambord et al., 2016). Studies like these emphasise the need to achieve the Safe Ecological Limit of 7 mg O_2/l in the Elbe estuary and consequently the reduction of excessive nutrient loads and resulting phytoplankton blooms. At present, oxygen conditions in the Elbe estuary are in a critical range for aquatic organisms, which can even fall below 5 mg O_2/l during dry and warm climatic conditions (see Discussion: Impact of Climate Change on Reduction Scenarios).

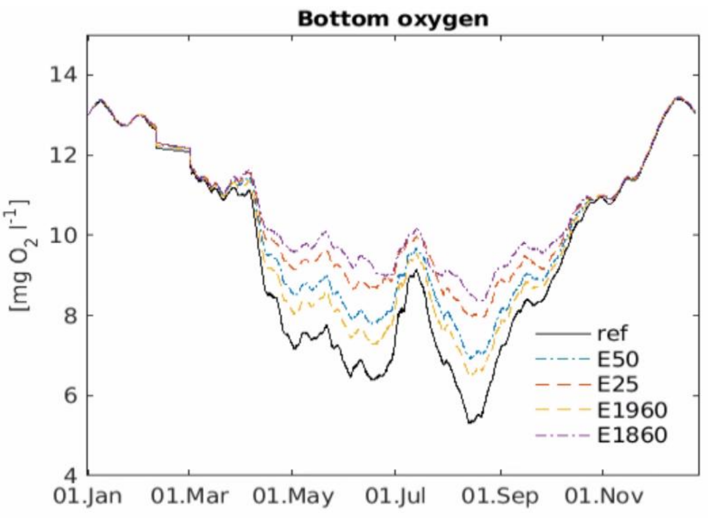


Figure 8. Bottom oxygen concentration in port of Hamburg (Elbe estuary) in model simulation of 2020 where "ref" refers to the reference simulation, and "E-50", "E-25", "E-1960" and "E-1860" refer to reduction to 50%, 25% in relation to reference N load and historical scenarios, respectively, illustrating the effect of reduced nitrogen inputs into the Elbe estuary.

Based on NAPSEA model results with reference year 2020 (expanding on D4.2 referring to 2012), a reduction need of the organic loads (phytoplankton blooms of 45%) was estimated to stay within safe limits of 7 mg O_2/l. A first step towards Safe Limits for O_2 is reached when N and P loads are reduced by about 45% and implies a strengthening of policies as included in Scenario 7B. This reduction would also enable N/Si ratios of 1 enabling N limited spring diatom blooms in the northern Wadden Sea to stay within an N/Si ratio of 1 would be reached. However, synergies between N and P reductions should be investigated. As mentioned above, since the 1980s policies have led to a stronger decrease in P compared to N. In the Elbe River, the recent droughts caused massive algae blooms (e.g. Rewrie et al., 2023, Schulz et al., 2024). This has resulted in extremely low dissolved PO_4 concentrations during summer, leading to an increase in N/P ratios in organic matter from around 16 in the 2000s (a normal value e.g. Elser et al. 2000) to values between 20 and 30 in the 2010s (Figure 9). This may have consequences for the aquatic food web (e.g. Malzahn et al., 2007, Sterner and Elser, 2002). For the Elbe estuary, Biederbick et al. (2025) demonstrated that a decline in the quality of algal food sources induces changes in zooplankton feeding behaviour by switching from herbivorous to primarily carnivorous diets. Such dietary shifts can affect the transfer of matter and energy within the food web, with potential consequences for the ecosystem productivity (e.g. Lerner et al. 2022).

Therefore, measures to reduce riverine phytoplankton blooms should include both N and P reductions. Also, the effects of reduced N concentrations on the development of riverine algae blooms including a potential N limitation should be investigated.

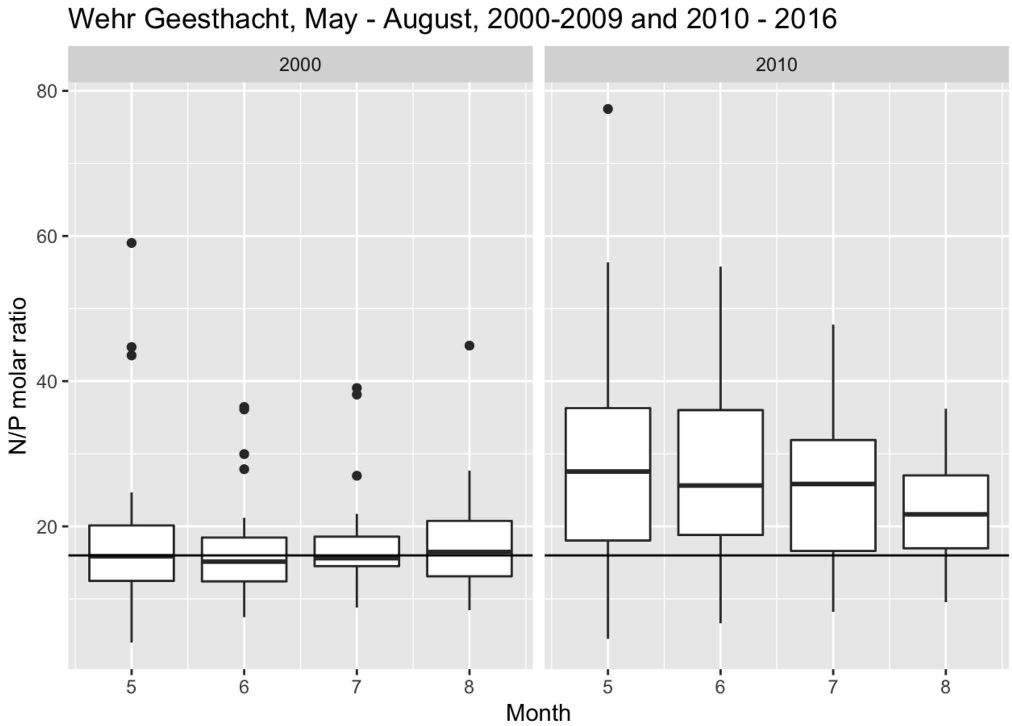


Figure 9. The ratio of N and P in organic matter in the Elbe near Geesthacht during the 2000s and 2010s. The line marks the N/P ratio of 16. Data: FGG Elbe.

In summary, the scenarios based on planned measures will be a step forward to alleviate the O_2 problems in the Elbe estuary. They will also be a great step towards reaching Safe Ecological Limits for the Northern Wadden Sea. However, in the last years a reduction in flow, and therefore lower organic load, is observed leading to O_2 problems in the shallow upper Elbe estuary ("new normal"). Besides keeping track of effects of lower discharge, it is also important to manage both N and P. Especially, N/P input ratios should lead to lower N/P ratios in the phytoplankton (N inputs should be stronger reduced than P). Furthermore, the possible consequences of N limitation on the size of riverine phytoplankton blooms should be investigated.

4.3 Rhine Basin

The reduction of nutrient loads from the Rhine basin towards the estuary and Wadden Sea taking climate change and the current planned measures into account (scenario 5) is comparable for P (-24%, 2050) and N (-19%, 2050). This efficiency for the catchment outlet is not fully reflected in reductions of mean annual nutrient concentrations in the stream network of the river Rhine. More specifically, the share of modelled subcatchments that are above the defined threshold concentration for NO_3-N (1.9 mgN/L) would only be reduced from 89% to 79 (2050). For P, the share of the total Rhine river network that is above the threshold concentration (0.055 mg/L SRP) would improve from 27% to 15%, meaning that the measures planned for scenario 5 are more efficient for P than for N-concentration in the stream network. For the enhanced scenarios 7A-7C we note that even under the most ambitious scenario 7C, still more than half (54%, 2050) of the modelled subcatchment area would not meet the 1.9 mg N/L concentration threshold. In contrast, the fraction of the stream network of the Rhine basin that does not meet the SRP concentration threshold of 0.055 mg/L is further reduced to 13% (2050) in scenarios 7A, 7B and 7C.

4.4 Hunze

The Hunze model explorations provides a more detailed and local case in which options to achieve the safe ecological limits were studied. The Hunze catchment directly drains into the N2000-reserve

Zuidlaardermeer and ultimately the Hunze discharge contributes to the Wadden Sea. Therefore, both the existing local WFD targets and the additional safe ecological limits for Zuidlaardermeer and the Wadden Sea were considered.

Since the 1990s, the nutrient concentrations in the Hunze have decreased and are now stabilizing around the WFD targets for summer average TN and TP concentrations. Additional more stringent safe ecological limits (particularly for the winter concentrations and loads) have been proposed to restore the ecology of the receiving downstream water resources, like Zuidlaardermeer and the Wadden Sea. Especially the winter nutrient concentrations and loads still need substantial reductions to reach these additional targets.

The scenario explorations in a SWAT model of the Hunze catchment (Table 5 and Figure 2) show that the existing local WFD targets and the additional safe ecological limits are achievable through several complementary measures. The planned wetland extension and upgrades to the wastewater treatment plant, would already bring the targets in sight. The remaining reduction step can be realized through a combination of land use change, further WWTP load reduction, agricultural management measures and/or nature-based solutions.

While reducing cattle densities is probably needed to reduce the atmospheric nitrogen loading, our results show that a land use conversion from dairy to arable farming is a risk for water quality and aquatic ecology. Keeping or extending (preferably permanent) grasslands while lowering the cattle densities is profitable for both nitrogen emissions to water and atmosphere.

Under climate change, our results indicate an increase in nutrient concentrations especially in winter. Meanwhile, higher temperatures generally make water systems more vulnerable for eutrophication. Extra reductions may be needed to meet the safe ecological limits also in unfavorable extreme weather conditions. We expect that buffering hydrological extremes through water conservation practices also helps to protect downstream ecosystems from higher nutrient load pulses.

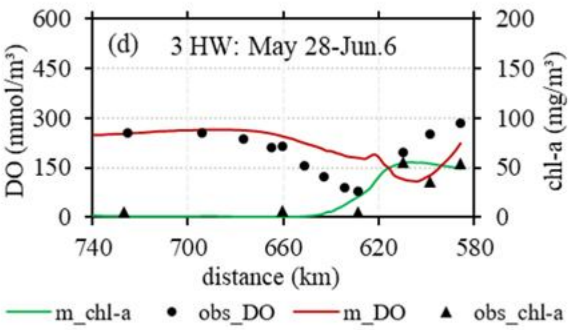
5. DISCUSSION

5.1 Impact of climate change on the effectiveness of reduction scenarios

Climate change can interact with nutrient retention measures in various ways. For instance, in dry years more N is retained in the Elbe catchment as compared to wetter years (Schulz et al., 2024). The applied modelling approach focusses on the effect of changes in the discharge that reflect changes in precipitation and evapotranspiration in the catchments. The effect of changing discharge is contrasting for N and P. This is due to the enhanced mobilization and export of diffuse N from soils in wetter years (in 2050) compared to a reduced mobilization of N in dryer years (around 2030). In contrast a higher discharge leads to less effective P retention in the network while lower discharge allows for more P removal by algal growth and subsequent sedimentation.

We note that the climate scenario that was used is one realization of the projected climate change effects. Therefore, other realizations of may have different effects on the effectiveness of measures in terms of timing (i.e., wetter of dryer conditions in 2030 and 2050) and in terms of dimensions. However, the direction of influence (higher N and P loads as wetter years mobilize more N and retain less P) will be similar. To separate effects of climate change and nutrient reduction measures we recommend assessing both, changes compared to the reference years as well as changes compared to a scenario that quantifies the climate change effect only (here: scenario 6).

Also note that climate change does not only change the hydrology, but also changes the biogeochemical aspects of nutrient transport. These complex biogeochemical impacts of climate change are not fully understood and were not considered in the modelled climate scenario. Reconstructing the ecosystem response to climate extremes (like the 2018 drought) is valuable for understanding climate change effects. A recent modelling study of coupled physical-biogeochemical dynamics in the Elbe estuary during the extreme year of 2018 demonstrated a changed axial pattern of the oxygen minimum. In this particular year, early summer heatwaves led to the breakdown of phytoplankton blooms in both the German Bight (Kaiser et al., 2023) and the Elbe estuary (Figure 10). This is evidenced by the relatively low chlorophyll-a concentrations observed at the tidal weir at Figure 10. In this situation, decreased oxygen concentrations occurred already upstream from the port instead of downstream as in "normal years" (see e.g. Pein et al., 2021; Schöl et al. 2014). Extreme weather events, such as those experienced in 2018, could be indicative of the impending effects of climate change as the new normal. Decisive for the course of the events seems to be the breakdown of phytoplankton bloom and depletion of oxygen levels in the Elbe river. This led to the import of waters containing decaying organic matter, high levels of chlorophyll and low levels of oxygen at the Geesthacht weir. Should this scenario become a long-term situation, it will be necessary to revise the nutrient reduction targets in order to avoid intense phytoplankton blooms in the Elbe river, which is susceptible to collapse and hypoxic states in the Elbe estuary. In addition, the extent to which these potential climatic changes in oxygen levels and food quality could have a cascading effect on the aquatic food web in the Elbe estuary needs to be further investigated.



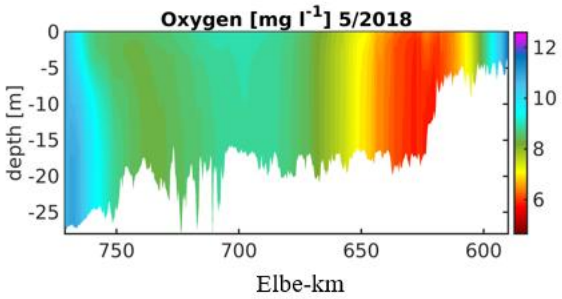


Figure 10. (left) Observations of dissolved oxygen and chlorophyll-a along the Elbe estuary compared to simulations of oxygen and chlorophyll-a (solid lines) during an early summer heat wave event. (right) along-channel profile of simulated dissolved oxygen during May 2018.

5.2 Towards a holistic view on nutrient ratios: An option to link N and P reduction scenarios?

The reduction scenarios show that planned measures are an important step forward in reaching the SEL, but that further reductions are needed to reach the necessary reduction goals. Future plans to reduce N and P loads into the environment should also focus on the effects on the N/P ratios. These ratios have strongly increased since the implementation of nutrient reduction measure. Past nutrient reduction measures led to a stronger reduction of P loads in comparison to N loads which resulted in increase of N/P molar ratios from around 25 (Rhine/Meuse) and 40 (Elbe/Weser) around 1980 to 60-70 (Rhine/Meuse) and 50-60 (Elbe/Weser) during the 2010s (van Beusekom et al., 2019). The recent estimates for the Elbe underestimate the riverine N/P ratios: loads are based on measurements in the upper estuary (Hamburg) and suspended matter from the North Sea leads to an overestimation of the P loads. In the upper river (near the weir separating the river from the estuary) N/P ratios of up to 80 were recently observed (van Beusekom, unpublished).

The importance of N/P ratios for both marine and freshwater ecosystems is recognized since a long time (e.g. Sterner and Elser, 2002; van der Waal et al., 2017) but the importance of nutrient ratios is not reflected in the policies to govern nutrients as either N or P are tackled by laws and regulations (Enserink et al., 2023).

Whereas phytoplankton composition reflects the N/P ratios in the surrounding water (e.g. Rhee, 1979; Redfield, 1958), higher trophic levels are characterized by so-called homeostasis: a needed fixed N/P ratio that is species-specific (Sterner and Elser, 2002). As shown in Chapter 4, Wadden Sea phytoplankton reflects the high N/P ratios during winter followed by a N limitation and N/P ratios around 15 during summer. In the North Sea outside the Wadden Sea, a gradient from P limitation in coastal waters to N limitation in the central North Sea prevails (Burson et al., 2016). In a recent study, Brandenburger et al. (2025) showed that between 2000 and 2018 increased N/P ratios in concert with warming contributed to an increase in Harmful Algae Blooms in the coastal North Sea despite decreasing eutrophication and decreasing phytoplankton biomass. This certainly will have effects on higher trophic levels in the North Sea. Support from this comes from experiments with North Sea plankton by Malzahn et al., (2007): they showed that a phosphorus-limited food chain resulted in larval fish with a significantly poorer condition than their counterparts reared under nitrogen-limited or nutrient-sufficient conditions. Similar observations are made in freshwater system. Meunier et al. (2016) showed that N enrichment leads to increased P limitation in Swedish boreal lakes with ultimately a negative effect on the higher trophic levels.

To reach SEL both in marine and freshwater ecosystems in the Wadden Sea and its catchments, nutrient loads must be reduced. Depending on which measures are taken, this will affect the N/P ratios. Care must be taken that N/P ratios do not further increase to prevent more drastic negative effects on the aquatic food web. As a first step, nutrient reduction policies are necessary that address both N and P and that should be directed to lower nutrient loads in general and to lower the presently too high N/P ratios.

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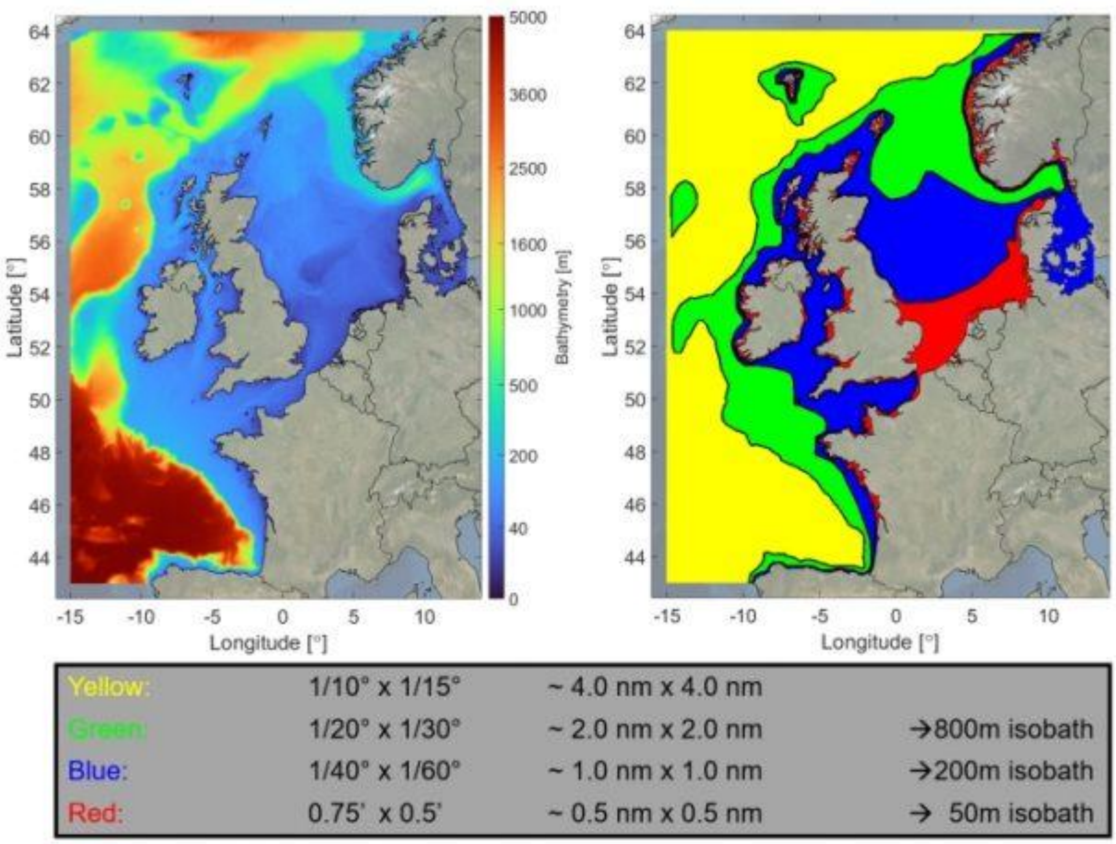
Appendix A

DCSM model description

The 3-D Dutch Continental Shelf Model – Flexible Mesh (3D DCSM-FM[1]) is Deltares' state-of-the-art framework for shelf-scale hydrodynamics and water-quality simulation, covering the entire Northwest European Shelf from the Irish Sea to the Baltic and from northern Spain to Scandinavia. Its unstructured, resolution-adaptive grid concentrates kilometre-scale cells in shallow, morphologically intricate coastal waters while relaxing offshore, allowing precise yet computationally efficient integration of tide- and surge-resolving currents, salinity and temperature with an online nutrient–oxygen–phytoplankton chemistry engine. Extensive calibration and validation against in-situ and remote-sensing data have reduced Dutch-coast water-level errors by up to 75 % relative to earlier 3-D models and markedly improved representations of bathymetry-driven tidal propagation and seasonal temperature stratification, thereby enhancing its suitability for ecological and water-quality applications. The model's modular architecture accommodates suspended-sediment and dissolved-tracer transport, enabling studies that span climate-driven sea-level and stratification trends, offshore-wind farm impacts on flow and ecosystems, continent-scale nutrient dispersion standardisation, real-time surge forecasting, and even high-resolution current advice for ocean-racing routes. Coupled to D-Water Quality, 3D DCSM-FM thus forms the shelf-scale cornerstone for nested coastal, estuarine and harbour-scale forecasts and for integrated assessments of eutrophication, sediment dynamics and habitat change across the North Sea domain.



Model bathymetry and grid resolution of DCSM

[1] D-Flow FM User Manual

https://www.deltares.nl/en/expertise/projects/3d-dutch-continental-shelf-model-flexible-mesh

Appendix B

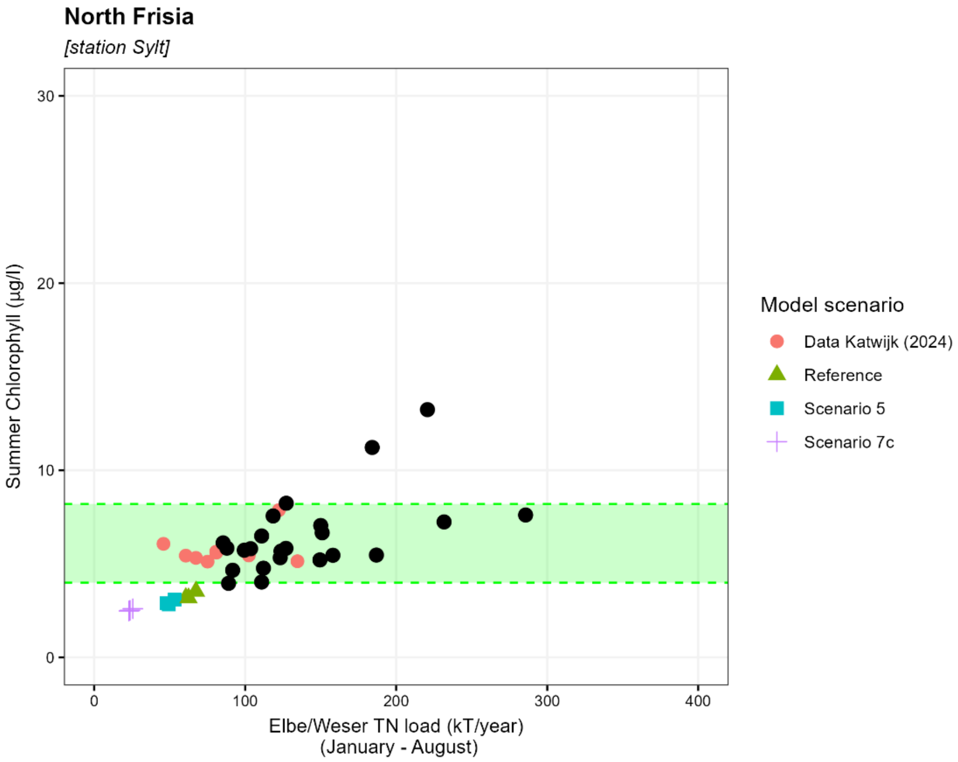


Figure B.1. Relation between modelled summer chlorophyll levels at station Sylt and measured TN loads by the Elbe/Weser rivers from January-August. Three different scenarios are modelled, the reference (green triangle), scenario 5 (blue square) and scenario 7c (purple cross), and the figure includes also the raw data from Figure 6 in van Katwijk et al., 2024 (red circle = 2007-2017; black circle before 2007). The critical summer chlorophyll concentration (green range) for seagrass to recover is also derived from Figure 6 in van Katwijk et al., 2024.

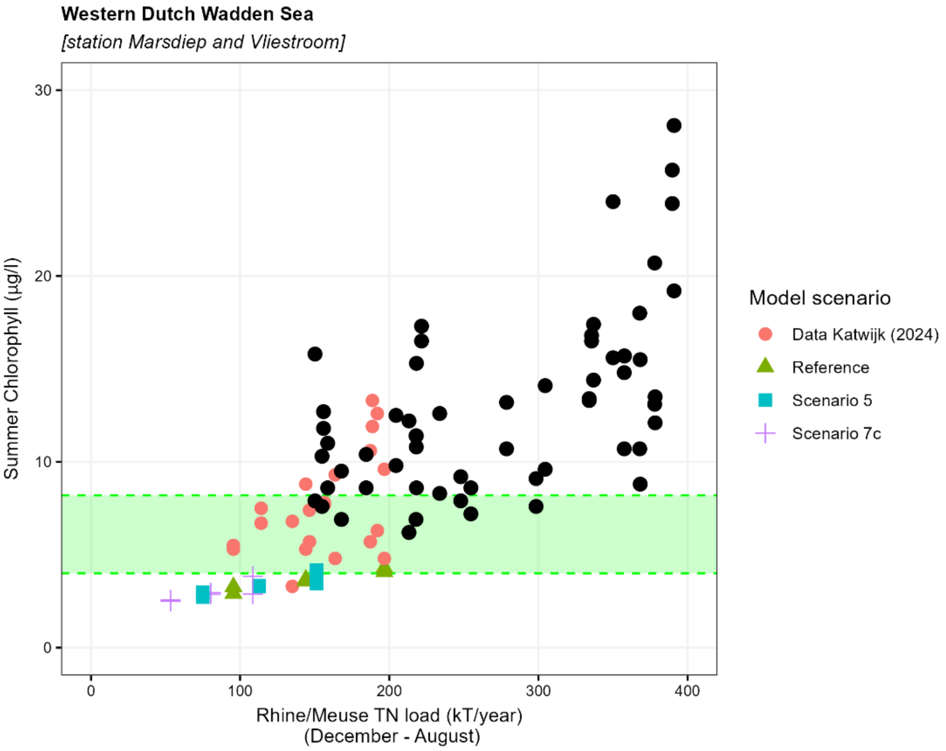


Figure B.2. Relation between modelled summer chlorophyll levels at stations Marsdiep and Vliestroom and measured TN loads by the Rhine/Meuse rivers from December–August. Three different scenarios are modelled, the reference scenario (green triangle), scenario 5 (blue square) and scenario 7c (purple cross), and the figure includes also the raw data from Figure 6 in van Katwijk et al., 2024 (red circle = 2007-2017; black circle before 2007). The critical summer chlorophyll concentration (green range) for seagrass to recover is also derived from Figure 6 in van Katwijk et al., 2024. Duplicate markers for each scenario and year represent the two stations included in this figure, station Marsdiep and station Vliestroom.

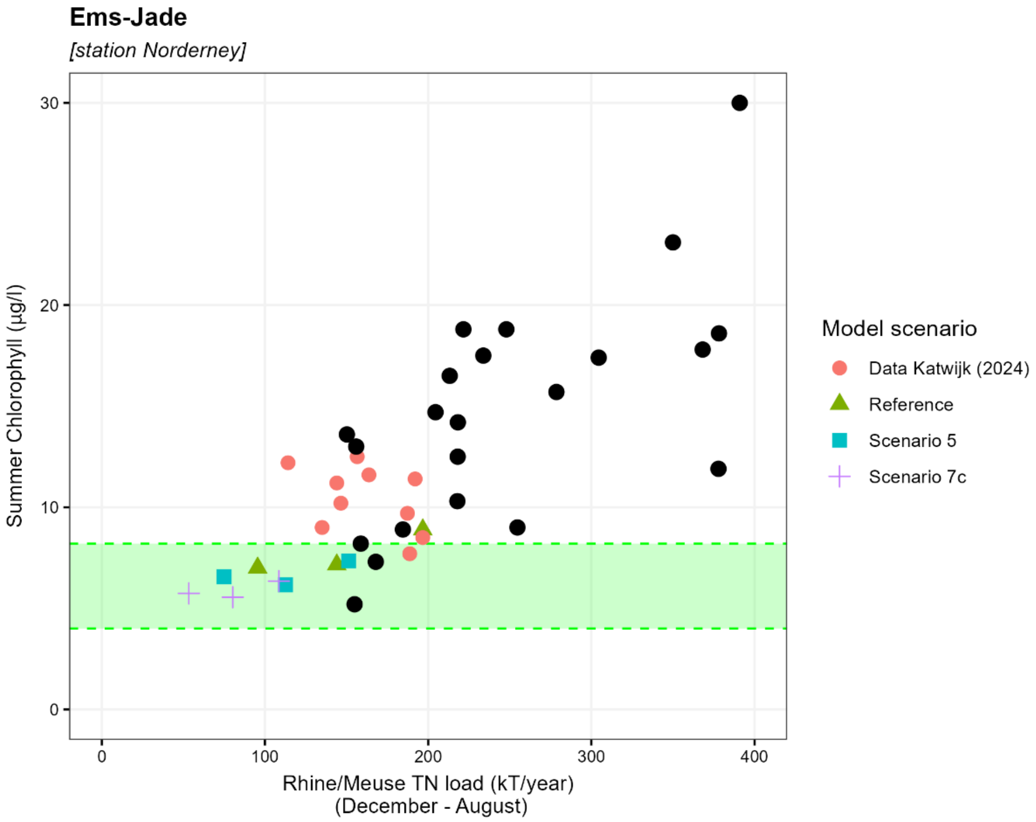


Figure B.3. Relation between modelled summer chlorophyll levels at station Norderney and measured TN loads by the Rhine/Meuse rivers from December–August. Three different scenarios are modelled, the reference scenario (green triangle), scenario 5 (blue square) and scenario 7c (purple cross), and the figure includes also the raw data from Figure 6 in van Katwijk et al., 2024 (red circle = 2007-2017; black circle before 2007). The critical summer chlorophyll concentration (green range) for seagrass to recover is also derived from Figure 6 in van Katwijk et al., 2024.

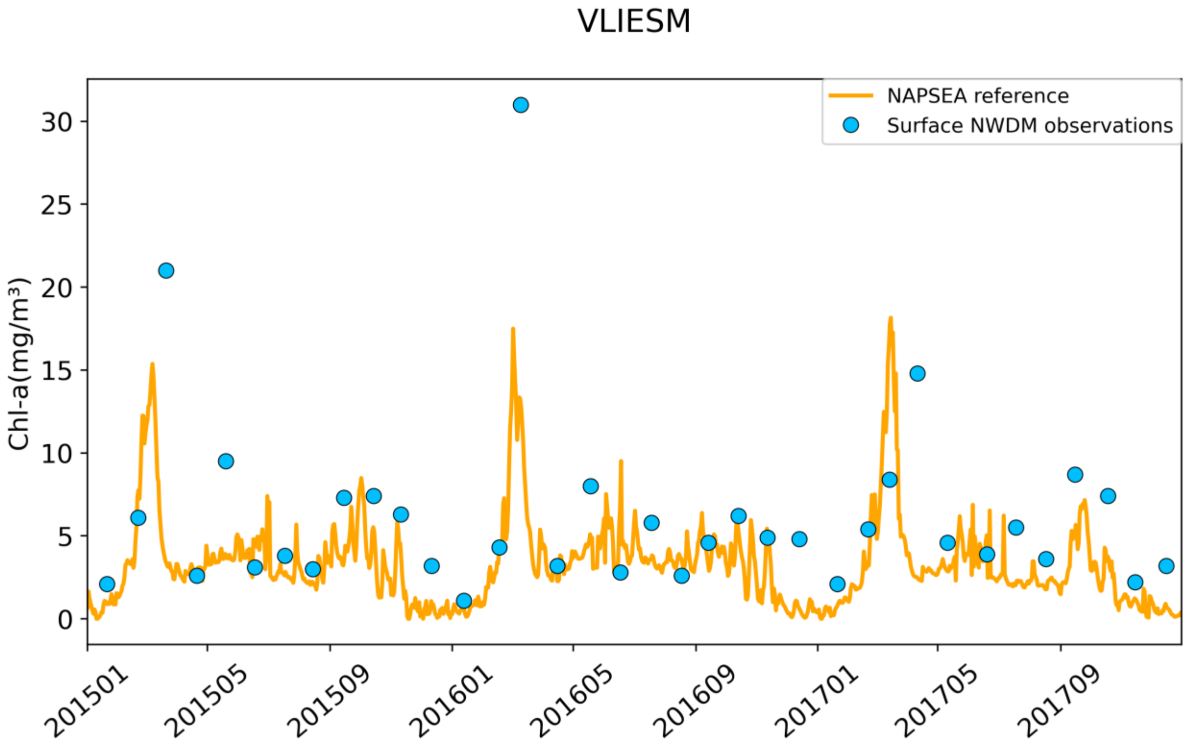


Figure B.4. Validation plot for modelled chlorophyll-a (yellow line) compared to measurements (blue circles) for station Vliestroom (VLIESM), western Dutch Wadden Sea.

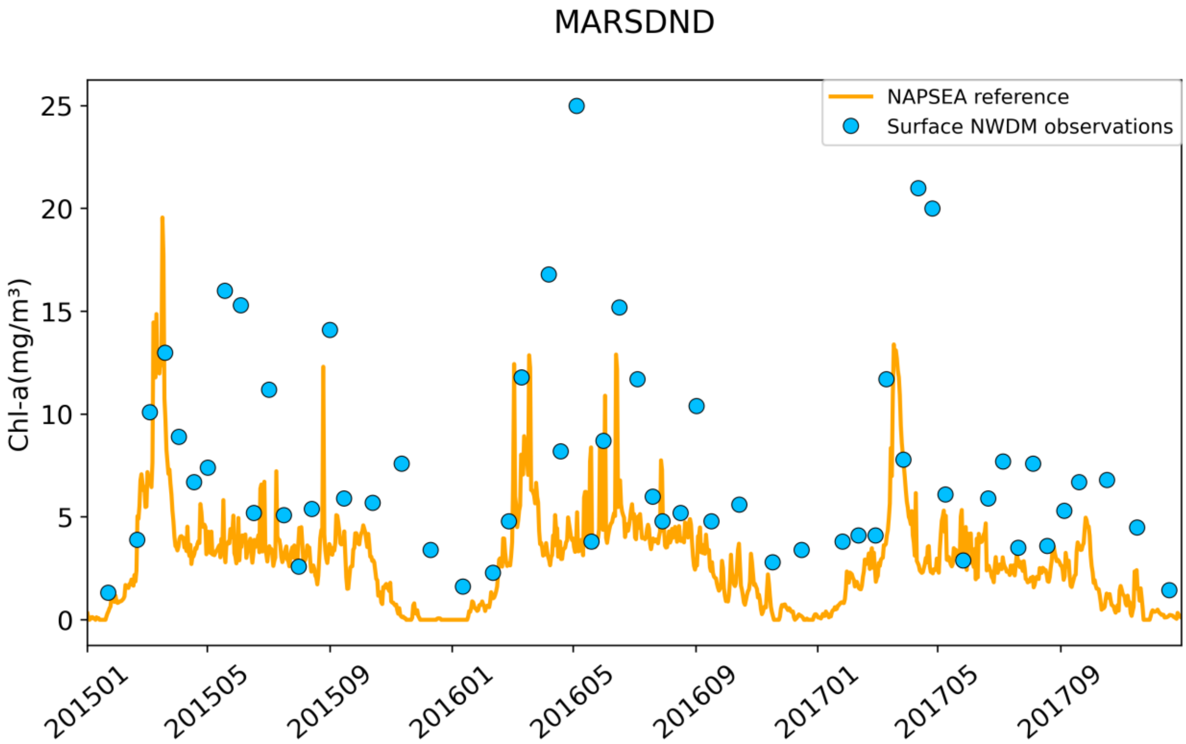


Figure B.5. Validation plot for modelled chlorophyll-a (yellow line) compared to measurements (blue circles) for station Marsdiep (MARSDND), western Dutch Wadden Sea.