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Consequences for the Netherlands

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Summary

OSPAR is carrying out an update of its assessment of the eutrophication status as part of the Quality Status Report 2023 on the environmental status of the North East Atlantic. In the preparation of this eutrophication assessment, which will be the 4th application of the Comprehensive Procedure (COMP4), several changes in the assessment methods were made. Those changes were made after the previous assessment in 2017 (COMP3) as it was concluded that an improvement of the coherence of the assessment was needed. New assessment areas, based on ecological criteria, were defined and new assessment thresholds were developed, that represent the boundary between classification as eutrophication problem area or non-problem area. The assessment thresholds were derived from a model exercise by OSPAR's Intersessional Correspondence Group on Ecosystem Modelling (ICG-EMO), using models describing historic, pre-eutrophic, conditions as the basis for the definition of thresholds for nutrients and chlorophyll in each assessment area. Rijkswaterstaat WVL asked Deltares to give insight in potential consequences of the new COMP4 thresholds for the Netherlands.

1. What reductions in the riverine loads of TN and TP are necessary to meet the COMP4 thresholds in the assessment areas in the Dutch part of the North Sea?
2. What are the nutrient thresholds for the rivers to ensure that the maximum allowable load defined under 1) is not exceeded?
We carried out a statistical analysis of the relation between annual riverine nitrogen loads and (growing season mean) concentrations of chlorophyll at sea using data from the Dutch MWTL routine monitoring program over the last 35 years, under the assumption that riverine nitrogen loads are the main determining factor of chlorophyll concentrations. At three coastal monitoring stations of the Noordwijk and Terschelling transect, downstream from the major outflows of the rivers Meuse and Rhine, chlorophyll concentrations show a positive linear relation with nitrogen loads: the higher the loads, the higher the chlorophyll concentrations. Based on this relation, it was calculated at what level of riverine nitrogen loads the chlorophyll concentrations would not exceed the COMP4 assessment thresholds. At various other monitoring locations, no significant relation was found as either other factors than riverine load are more dominant or the riverine influence offshore is minimal.

Based on the relation at the Noordwijk and Terschelling monitoring stations, the estimated average reduction in nitrogen loads in Rhine/Meuse to meet OSPAR COMP4 thresholds was calculated at approximately 20% (range 0-46%) compared to the average loads for the years 2010-2017.
However, given the considerable uncertainty and the limited number of representative monitoring stations, the estimated average reduction should be considered as a preliminary estimate only.

For a conservative estimate, we used a reduction of 25% in nitrogen loads to derive nutrient thresholds for the rivers Meuse and Rhine. This threshold is based on an average load of 133 kton/year for Haringvliet and Nieuwe Waterweg together (25% less than the average load of 177 kton/year for 2009-2017) with an average discharge of 1850 m^3/s.
The estimated threshold for annual average total nitrogen (TN) concentrations in the rivers is 2.3 mg/l, which is 25% lower than the present threshold of 2.8 mg/l agreed in the international River Basin Management Plan for the Rhine. It should be realized that with a fixed threshold for TN concentrations in the rivers, actual riverine TN loads may still show considerable differences between years due to differences in the volume of water discharges.

A model simulation was carried out to quantify the effect of a 25% nitrogen load reduction in Rhine and Meuse, on concentrations of nutrients and chlorophyll in the Dutch part of the North Sea. The load reduction leads to a proportional change in nitrogen concentrations in the coastal stretch of the North Sea that has a major freshwater influence (>5% freshwater). Further offshore, effects on nitrogen concentrations are negligible as the influence of freshwater discharges is small. As there is no reduction of total phosphorus (TP) loads in this model scenario, phosphate concentrations at sea do not change.

The effect of nitrogen load reductions on chlorophyll concentrations is much more limited, with a 3-7 % reduction in coastal waters and no reduction offshore. The fact that the response of chlorophyll is smaller than the reduction in nitrogen concentrations is the consequence of other factors influencing phytoplankton growth. The model results show a limited effect of nitrogen reduction on chlorophyll, which does not agree with the statistical extrapolations based on data of nitrogen loads and chlorophyll concentrations. This discrepancy is due to the additional role of light and phosphorus limitation. In coastal waters, both phosphorus and nitrogen availability have an impact on phytoplankton growth, but there is still some uncertainty about the relative contribution of both nutrients. The consequence of those different outcomes is that there still is uncertainty about the magnitude of the effect of nitrogen load reductions.

3. Define the relative contribution of sources of N and P (both emissions in the Netherlands and contribution from transboundary transport) to the riverine loads of N and P to the sea and compare the required reduction in emissions with the results of the Ex Ante evaluation of the Water Framework Directive (WFD) river basin management plans.

We used the WFD Explorer, a tool that is commonly used in the Netherlands to quantify effects of measures on emissions and water quality for the Water Framework Directive (WFD). Using the data from the Ex Ante evaluation of the 3rd river basin management plans for the WFD, the contribution of various sources to riverine nutrient loads of nitrogen and phosphorus to the North Sea was calculated. This includes several diffuse and point sources within the Netherlands and transboundary transport of nutrients (from Germany and other upstream countries through the Rhine, from Belgium and France through the Meuse). For a description of the present situation, data for 2019 were used. The situation in 2027 was described considering the effects on emissions of the programs of measures that are currently foreseen. This source apportionment shows that the major part of riverine P loads (44%) and N loads (69%) to the sea comes from transboundary transport through the Rhine. In addition, agriculture in the Netherlands (including approximately 20% leaching from nature/urban areas) forms a significant contribution (P: 27%; N:10%) as well as transboundary transport through the Meuse (P: 15%; N:9%), followed by wastewater treatment plants in the Netherlands.

With the expected measures, the largest reductions in the emissions are expected for agriculture in the Netherlands and transboundary transport through smaller rivers. For Dutch sources a reduction in emissions of 6% for P and 12% for N is expected. Transboundary transport is expected to show hardly any change, based on information received from neighbouring countries (3% for N and 2% for P). The overall expected reduction in riverine nitrogen loads to the sea is small (4%) compared to the estimated necessary reduction of 18-20%.

4. Describe the differences between the catchment models E-Hype and Moneris and provide an advice on the preferred historic reference scenario.

In the model approach by OSPAR ICG-EMO, two pre-eutrophic scenarios were used to derive nutrient and chlorophyll concentrations at sea under historic, pre-eutrophic, conditions. Both scenarios describe the situation before intensification of agriculture and the widespread use of fertilizer and with historic population densities. For those scenarios, two catchment models were used describing emissions and transport of nutrients in the river catchment. The pan-European catchment model E-hype had higher total phosphorus concentrations in the rivers than the catchment model Moneris which focuses on German rivers (including the Rhine). The catchment models only differed in the estimates of riverine phosphorus loads to the sea. A comparison of the assumptions underlying both models was made. However, with the information available it was not possible to draw firm scientific conclusions on possible biases in the models. A comparison with information on natural background concentrations of phosphate indicates that the Moneris model gives total-P concentrations in the Rhine which are lower than natural background concentrations reported in the scientific literature and may therefore be considered less likely.

5. Describe the relation between riverine nutrient loads and the occurrence of oxygen depletion in the North Sea.
Oxygen depletion is a determining indicator in the assessment of eutrophication. The threshold value of 6 mg/l aims to prevent significant adverse effects on benthic organisms. In some parts of the central North Sea, low oxygen concentrations can occur in the deeper water layers near the seafloor in late summer, potentially leading to mortality of benthic fauna. This oxygen depletion is caused by physical factors, such as thermal stratification that impedes the transport of oxygen from the surface layers to the deeper water layer below the pycnocline. In combination with high water temperatures in summer and a relatively small volume of water below the pycnocline in the shallow part of the North Sea, oxygen consumption caused by bacterial degradation of organic matter results in a decrease in oxygen concentrations. This phenomenon regularly occurs in areas like the Oyster Grounds. The southern North Sea is well mixed, which prevents oxygen depletion. The northern North Sea is too deep (large volume) to develop oxygen depletion. At the Oyster Grounds, organic matter supply (in combination with the physical factors) determines oxygen consumption. The model results from the ICG-EMO study show that in the pre-eutrophic scenario (with lower nutrient loads) oxygen concentrations at the Oyster Grounds in summer are higher and the duration of oxygen depletion is shorter, compared to the present state. This indicates that reduction in riverine nutrient loads (including Rhine/Meuse) can reduce the risk of oxygen depletion. A recent study on the effects of climate change shows that the area of the Oyster Grounds is likely to have longer periods of stratification and stronger oxygen depletion in the future. This indicates that, in addition to effects on nutrients and chlorophyll, reduction scenarios should also consider the risk of oxygen depletion near the seafloor in parts of the North Sea.

Contents

1 Introduction

1.1 Background

OSPAR is preparing a new eutrophication assessment of the NE Atlantic, as a follow up to the previous three assessments (OSPAR 2003; 2008; 2017). The previous approach for the eutrophication assessment (the Comprehensive Procedure COMP) has been revised into a new updated procedure (COMP4; OSPAR 2022b). As a part of this revision, OSPAR has developed harmonized and coherent targets for the assessment of eutrophication. To support this development of coherent targets, OSPAR's Intersessional Correspondence Group on Ecosystem Modelling (ICG EMO) carried out an ensemble modelling approach in 2020-2021 with the aim to propose thresholds for nutrients and chlorophyll-*a* based on a common and harmonized approach (Lenhart *et al.* 2022). The thresholds were derived from a model simulation describing historic, pre-eutrophic, reference conditions for the year 1900. In those reference conditions, riverine nitrogen and phosphorus loads to the sea were much lower than in the present situation. For the quantification of the riverine nutrient loads under those reference conditions, two scenarios have been used. One (Historic Scenario 1, HS1) was based on the application of the pan-European catchment model E-hype. The second scenario (HS2) was partly based on the German catchment model Moneris and describes reference conditions that, compared with HS1, has lower riverine P loads for Denmark, Germany and the Netherlands. Both scenarios were used in the modelling approach as there was no prior agreement on which of the two catchment models was most accurate.

The Ministry of Infrastructure and Water Management asked Deltares to provide more insight in the consequences of the new COMP4 thresholds for dissolved inorganic nitrogen (DIN) and phosphorus (DIP) and chlorophyll applicable to the Dutch part of the North Sea. The new COMP4 thresholds can potentially lead to an assessment of eutrophication in the Dutch part of the North Sea that deviates from previous assessment outcomes. This may also have implications for the required measures to reduce anthropogenic nutrient loads to the North Sea through the rivers (Scheldt, Meuse, Rhine, Ems) and consequently, for nutrient emissions to inland water systems.

1.2 Scope of this report

Deltares was asked to carry out an analysis of the consequences of the new COMP4 thresholds and answer the following questions:

1. What reductions in the riverine loads of TN and TP are necessary to meet the COMP4 thresholds in the assessment areas in the Dutch part of the North Sea?
2. What are the nutrient thresholds for the rivers to ensure that the maximum allowable load defined under 1) is not exceeded?
3. Define the relative contribution of sources of N and P (both emissions in the Netherlands and contribution from transboundary transport) to the riverine loads of N and P to the sea and compare the required reduction in emissions with the results of the *ex ante* evaluation of the WFD river basin management plans.
4. Describe the differences between the catchment models E-Hype and Moneris and provide an advice on the preferred pre-eutrophic reference scenario.
5. Describe the relation between riverine nutrient loads and the occurrence of oxygen depletion in the North Sea.

1.3 Outline of the report

In Chapter 2 a statistical analysis was used to estimate the reduction in riverine nitrogen load that is required to achieve the OSPAR COMP4 thresholds. This maximum allowable load is translated into a threshold for total nitrogen concentrations in the rivers. In addition, a model application was used to evaluate the effects of the maximum allowable load on nutrient and chlorophyll concentrations in the Dutch part of the North Sea (questions 1-2).

The WFD Explorer was used to quantify the contribution of emission sources in the Netherlands and the contribution of transboundary transport via the rivers Meuse and Rhine. This analysis, presented in Chapter 3, gives insight in the relative importance of sources for the riverine nutrient loads to the North Sea (question 3). In addition, the effect of planned measures to reduce nutrient emissions is compared to the required nutrient load reduction from Chapter 2.

The differences in the two catchment models used in the pre-eutrophic scenarios of ICG EMO are discussed in Chapter 4 (question 4).

The effects of riverine nutrient loads on the occurrence of reduced oxygen concentrations in parts of the North Sea are analyzed in Chapter 5 through a combination of literature review and analysis of the Deltares model results from the ICG EMO project (question 5).

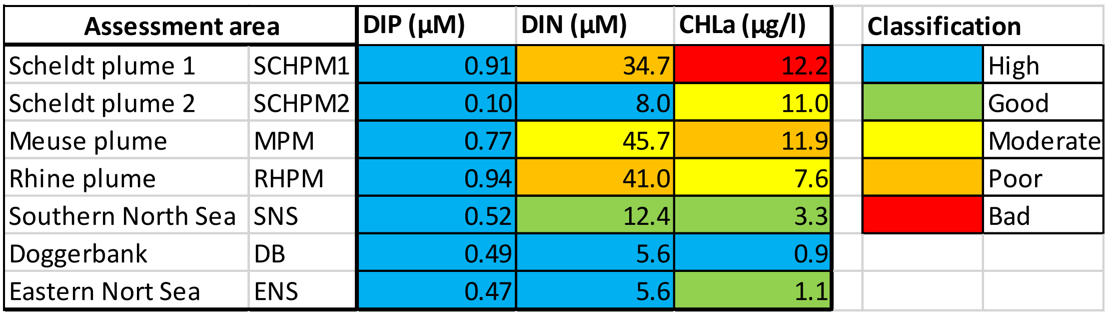
2 Analysis of the required riverine nutrient load reduction

2.1 Assessment result with COMP4 thresholds

In June 2022 an agreement was reached on the new COMP4 thresholds for nutrients (N, P) and chlorophyll (OSPAR 2022a). The Netherlands decided to use the results of the scenario HS1. This decision was based on the fact that HS2, using the MONERIS ‘1880’ reference, gives TP concentrations in the range of 0.03-0.04 mg/l for the main outlets of Rhine and Meuse, which is in the range of natural background concentrations and lower than pre-eutrophic conditions. For the Rhine, several Dutch studies gave estimates of natural background concentrations of ca. 0.06 mg/l TP and 0.6 mg/l TN (Laane 1992, Van Raaphorst et al. 2000). The results of the assessment by OSPAR for nutrients and chlorophyll in the Dutch assessment areas is shown in Table 2.1. Figure 2.1 shows the assessment results of the COMP4 application for the southern North Sea.

Concentrations of dissolved inorganic phosphorus (DIP) are below the threshold in all assessment areas. Concentrations of dissolved inorganic nitrogen (DIN) and chlorophyll exceed the COMP4 thresholds in the river plumes (except DIN in SCHPM2), which are the assessment areas with the highest freshwater influence. Therefore, this report and in particular the estimate of the threshold for riverine load and riverine concentration focuses on nitrogen only.

Table 2.1 Concentrations of winter means of DIP and DIN and growing season means of chlorophyll (average per assessment area) and classification from the application of the COMPEAT assessment tool (OSPAR 2022b)



Assessment area		DIP (µM)	DIN (µM)	CHLa (µg/l)
Scheldt plume 1	SCHPM1	0.91	34.7	12.2
Scheldt plume 2	SCHPM2	0.10	8.0	11.0
Meuse plume	MPM	0.77	45.7	11.9
Rhine plume	RHPM	0.94	41.0	7.6
Southern North Sea	SNS	0.52	12.4	3.3
Doggerbank	DB	0.49	5.6	0.9
Eastern Nort Sea	ENS	0.47	5.6	1.1

Classification	
🟦	High
🟩	Good
🟨	Moderate
🟧	Poor
🟥	Bad

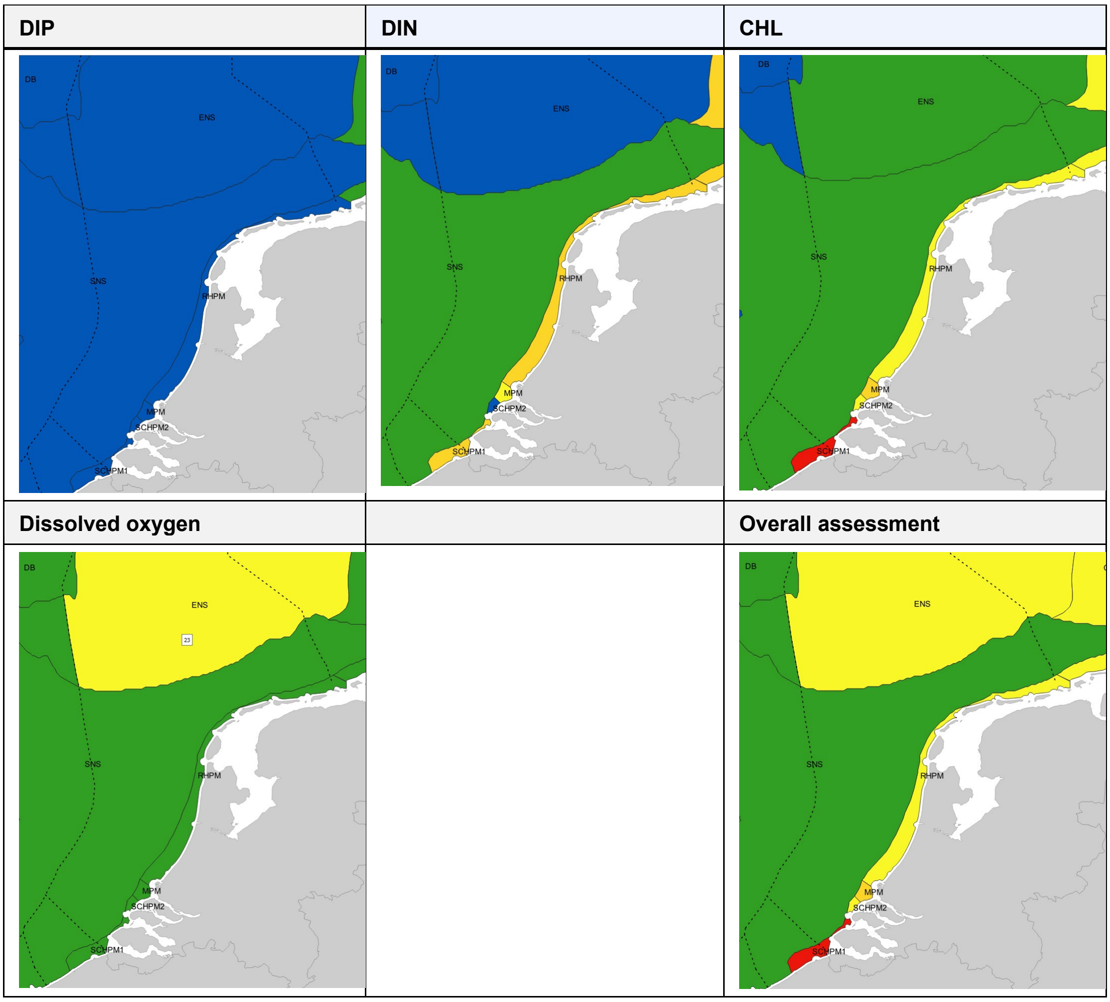


Figure 2.1 Map with the results of the assessment for DIP, DIN, chlorophyll, oxygen and the final COMP4 assessment. Color coding and assessment area codes as in Table 2.1. The broken line indicates the EEZ borders.

2.2 Estimate of maximum allowable riverine nutrient loads

The concentrations of nutrients in the coastal waters (>5% freshwater) of the North Sea are, to a large extent, determined by the riverine loads of nutrients to the North Sea. Similarly, there is a relation between riverine nutrient loads and chlorophyll concentrations in coastal waters as nutrient loads determine phytoplankton growth, together with other factors such as, for example, light conditions. Note that winter means of DIN and DIP are used in assessments as the effect of biological processes is negligible and the concentrations are a suitable proxy for the level of nutrient enrichment. To quantify riverine nutrient loads it is necessary to look at total N and P.

Since 1990, riverine nutrient loads of P and N decreased and this is reflected in decreasing concentrations of nutrients and chlorophyll in Dutch coastal waters. This decreasing trend in nutrient loads provided the opportunity to determine the quantitative relation between riverine nitrogen loads and chlorophyll concentrations at several monitoring stations in the Dutch North Sea. An example for MWTL station Noordwijk20 is shown in Figure 2.2.

Those ‘dose-response’ relations were used to estimate the maximum allowable load, i.e. the riverine nitrogen load at which chlorophyll concentrations can be expected to be at the level of the COMP4 threshold. Figure 2.3 gives an example of the approach. The focus in this approach is on total nitrogen (TN) loads as total phosphorus (TP) loads have already decreased by more than 60% since 1990 while the reduction in TN loads is smaller. Also, correlations between chlorophyll concentrations and nutrient loads were stronger for TN loads than for TP loads for stations near the Rhine outflow (Noordwijk2, 10, 20). Hence, this supports the assumption that chlorophyll is predominantly limited by nitrogen.

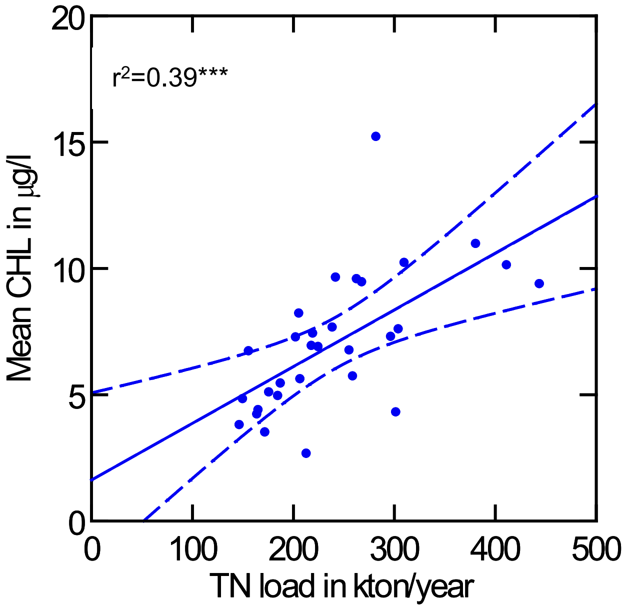


Figure 2.2 Summer mean chlorophyll-a concentrations at station Noordwijk20 as a function of riverine TN loads, for the years 1988-2017, with linear regression line ±95% confidence interval (broken lines).

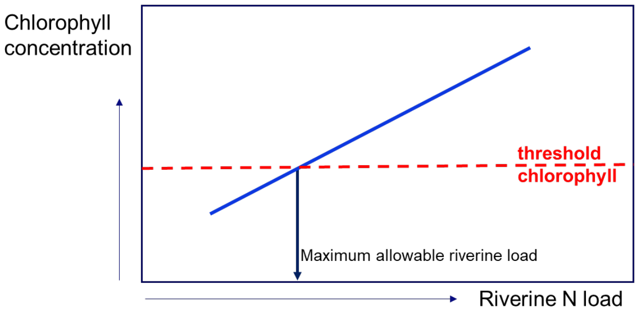


Figure 2.3 Example of the approach to estimate the maximum allowable riverine nutrient load. The blue line represents the linear relation between chlorophyll concentrations at a monitoring station and the riverine nitrogen loads. The riverine N load where the blue line crosses the threshold for chlorophyll, is the maximum allowable load. For simplicity, confidence intervals are not included. Including the confidence intervals could give an estimate of the uncertainty in the calculated maximum allowable load.

For the analysis we used the sum of the annual riverine TN loads of Haringvliet and Nieuwe Waterweg, as these two discharge points represent the major fraction (>80%) of the total riverine nitrogen loads that are discharged from the Netherlands to the Dutch part of the North Sea. The other 20% comes from the river Scheldt, North Sea Canal, Lake IJssel, the river Ems and several smaller discharge points like sluices and pumping stations. Additionally, there are contributions from other rivers, like Seine, Somme, Thames and Humber that contribute to nutrients in parts of the Dutch North Sea, but these contributions are smaller as well. The analysis was done with data for the years 1990-2017, as this represents a period with good availability of MWTL monitoring data and data for riverine discharges. In addition, during this period a significant decrease in TN loads occurred which makes it possible to establish a relation between riverine TN loads and chlorophyll (CHL) concentrations at sea.

Initially, we analyzed the relation between CHL concentrations and TN loads for all Dutch MWTL monitoring stations in the North Sea and Wadden Sea (for location of the stations, see Figure 2.4). As was to be expected, offshore stations with <5% freshwater influence did not show a significant correlation between chlorophyll concentrations and riverine nitrogen loads. Wadden Sea stations showed very different and contrasting correlations between chlorophyll concentrations and riverine nitrogen loads (positive, negative, or no relation). The cause or causes for these differences in responses were not investigated. Probably other factors like light climate and grazing by benthos strongly influence chlorophyll concentrations at those sites. Several other MWTL stations did not show significant correlations either. For example, MWTL stations Goeree 2 and Goeree 6 show high interannual variability in mean chlorophyll concentrations that are not correlated to interannual differences in TN loads. Due to the proximity of the river discharge point, there is a surplus of nitrogen at those sites and light is the predominant limiting factor.

In the end, we selected a few stations that showed a significant correlation between riverine nitrogen loads and chlorophyll concentrations and were located in the plume of the river Rhine: Noordwijk 10 and Noordwijk 20 and Terschelling 10. Noordwijk 2 was also included, although the correlation between CHL concentrations and TN loads was rather weak (Table 2.2). In addition to those monitoring stations, we applied the regression method using chlorophyll concentrations for the entire COMP4 assessment area “Rhine plume”) (Figure 2.4). In the latter case, chlorophyll concentrations are the growing season mean for the entire assessment area, derived from the combination of *in* situ and satellite data as used in the COMP4 assessment.

The regression results are shown in Table 2.2 and Figure 2.5. Based on those results, we estimated the maximum allowable load of TN. For this estimate we used the thresholds for growing season mean chlorophyll as shown in Table 2.3. For station Noordwijk 2 we also used the WFD Good/Moderate boundary for coastal water body “Hollandse kust” (van der Molen *et al.* 2018), where we applied the commonly used assumption that the 90-percentile for growing season chlorophyll is twice the growing season mean. For all stations, we made estimates of the maximum allowable load (Table 2.4) using the WFD boundary, the chlorophyll thresholds from COMP3 (OSPAR 2017) and the thresholds agreed for COMP4 (OSPAR 2022a).
For station Noordwijk 2, the difference in thresholds (WFD, COMP3, 4) leads to very different estimates of the maximum allowable load. Also, the estimates based on the COMP4 thresholds differ substantially from the estimates for the other stations and for the Rhine plume. As the regression for Noordwijk 2 was very weak (r^2=0.15, Table 2.2) indicating large uncertainty in the regression estimate, we excluded those results in the final estimate in Table 2.4.

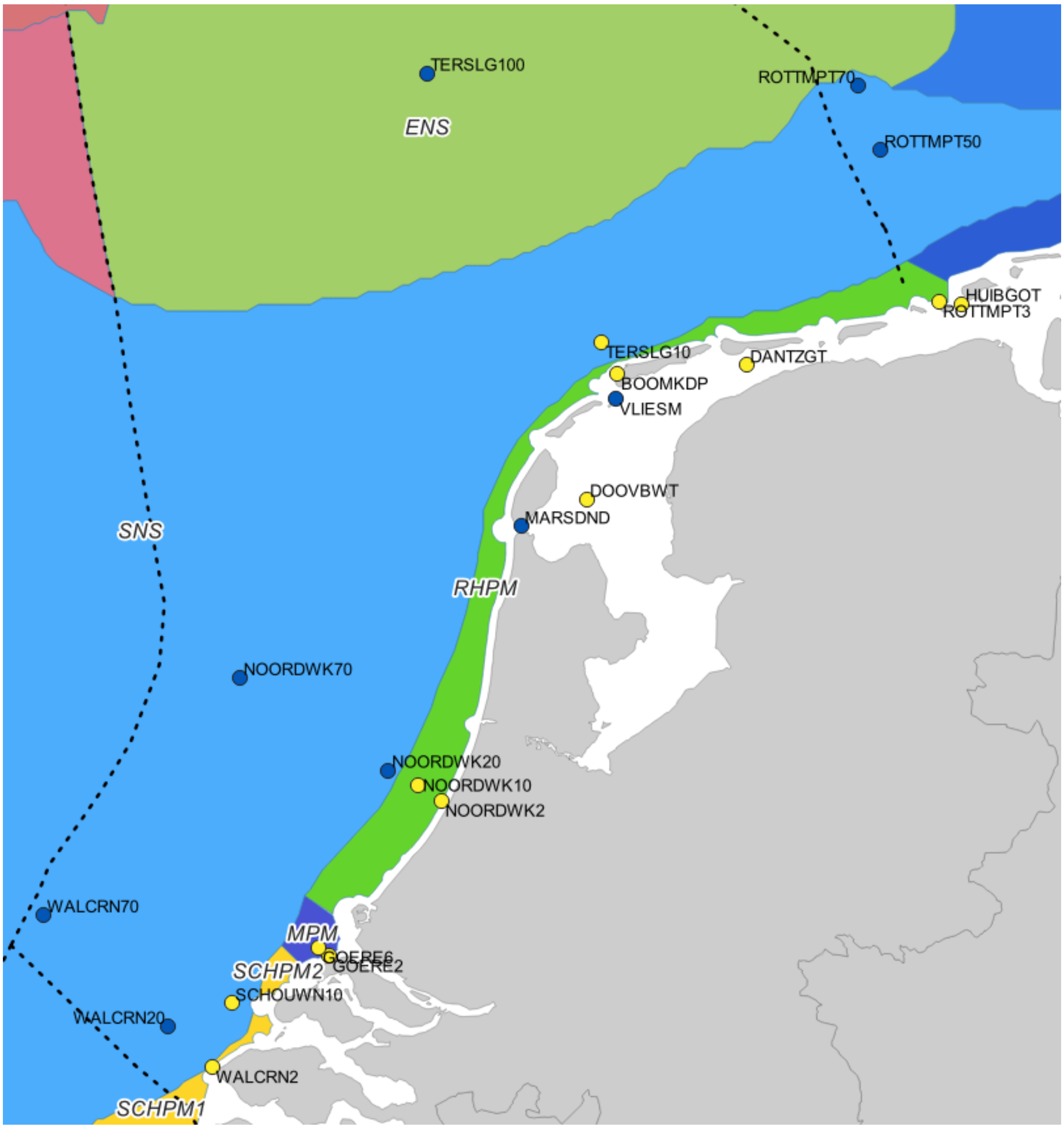


Figure 2.4. Map of COMP4 assessment areas and MWTL monitoring stations. Yellow stations are also used for assessments for the Water Framework Directive (WFD). Blue stations are used for OSPAR assessments. The assessment areas are, from south to north: Scheldt plume (SCHPM1, SCHPM2, orange), southern North Sea (SNS, light blue), Meuse plume (MPM, dark blue), Rhine plume (RHPM, green), Eastern North Sea (ENS, dark green). The WFD water bodies (small white strip along the coast) are excluded from the COMP4 assessment areas. Broken lines indicate the borders of the EEZ.

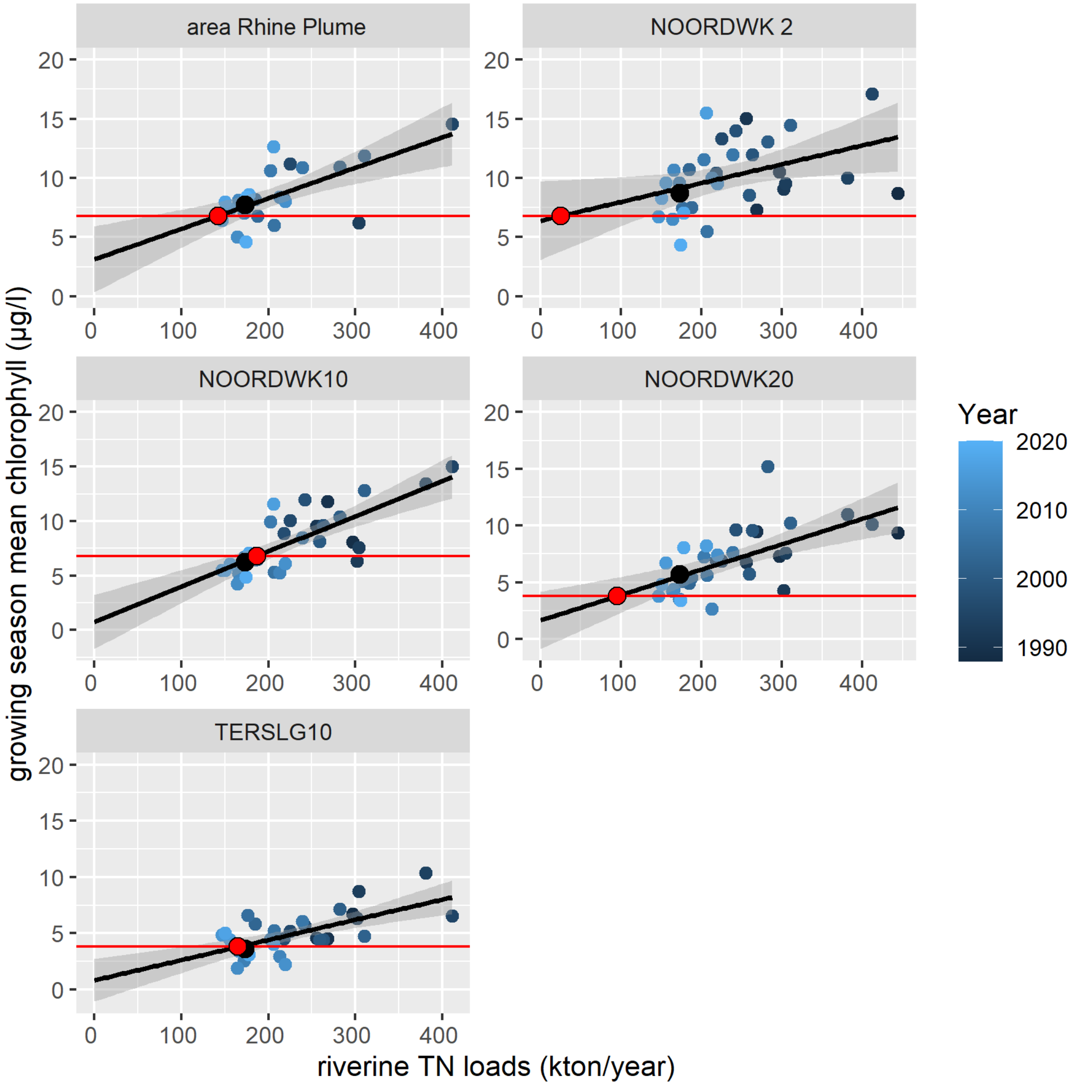


Figure 2.5. Results of the linear regression of growing season mean chlorophyll (µg/l) against riverine TN loads (kton/year). The dark grey area indicates the 95% confidence interval. Data for the years 1988-2017 were used. For illustrative purposes, the large black circle represents the average for the years 2010-2017. The red circle shows the point where the regression line crosses the threshold level for chlorophyll, which is indicated by the red line. Note that the threshold levels differ between MWTL stations Noordwijk 2, 10 (COMP4 assessment area Rhine plume) and stations Noordwijk20 and Terschelling10 (COMP4 assessment area Southern North Sea). For some stations data there were years with missing data.

Table 2.2 Summary of the results of the regression of mean chlorophyll concentration (µg/l) against annual riverine TN loads (kton/year), for the years 1990-2017.

		WFD water body / OSPAR assessment area	Regression results		
			Linear relation CHL - TN_{load}	**r^2**	**p-value**
MTWL station	Noordwijk 2	WFD: Holland coast OSPAR: Rhine plume	$CHL=6.39+0.0159*TN_{load}$	0.15	<0.050
	Noordwijk10	OSPAR: Rhine plume	$CHL=0.75+0.0323*TN_{load}$	0.56	<0.001
	Noordwijk20	OSPAR: Southern North Sea	$CHL=1.65+0.0224*TN_{load}$	0.38	<0.001
	Terschelling10	OSPAR: Southern North Sea	$CHL=0.84+0.0179*TN_{load}$	0.42	<0.001
COMP4 assessment area	Rhine plume	OSPAR: Rhine plume	$CHL=3.14+0.0257*TN_{load}$	0.42	<0.001

Table 2.3 Thresholds for growing season mean chlorophyll concentration (µg/l) in WFD, COMP3 and COMP4. Only station Noordwijk2 is used for WFD assessment (water body Holland coast).

		Threshold for growing season mean CHL		
		WFD	**COMP3**	**COMP4**
MTWL station	Noordwijk 2	8.44	7.5	6.8
	Noordwijk10	*n.a.*	7.5	6.8
	Noordwijk20	*n.a.*	7.5	3.8
	Terschelling10	*n.a.*	7.5	3.8
COMP4 assessment area	Rhine plume	*n.a.*	7.5	6.8

Table 2.4 Maximum allowable load and required reduction compared to the average load for 2009-2017. Only station Noordwijk2 is used for WFD assessment (water body Holland coast).The shaded row gives the average of stations Noordwijk10, Noordwijk20, Terschelling10. Noordwijk2 was not included as explained in the text.

		TN load (kton/yr)	**Maximum allowable load (kton/year)**			**Reduction compared to 2009-2017**		
		2009-2017	WFD	COMP3	COMP4	WFD	COMP3	COMP4
MWTL station	Noordwijk 2*	177	129	70	26	-27%	-61%	-85%
	Noordwijk10	177	*n.a.*	209	187	*n.a.*	0%	0%
	Noordwijk20	177	*n.a.*	261	96	*n.a.*	0%	-46%
	Terschelling10	177	*n.a.*	372	165	*n.a.*	0%	-7%
	Average (NW10, 20, TS10)	*177*	*n.a.*	*281*	*149*	*n.a.*	*0*	*-18%*
COMP4 assessment area	Rhine plume	177	*n.a.*	169	142	*n.a.*	0%	-20%

The results in Table 2.4 show that the application of linear regression estimates of the relation between mean chlorophyll concentrations and riverine TN loads, in combination with the thresholds for chlorophyll, results in a relatively large range of the maximum allowable load when the estimates for the various stations are compared. In addition, there are sometimes relatively large uncertainty ranges around the linear regression lines. This uncertainty needs to be considered when interpreting the results.

For station Noordwijk10 no further reduction is required based on the regression, while for station Noordwijk20 a reduction of 48% is estimated. There are several reasons why the difference between stations is large:

- The COMP4 thresholds are defined for an entire assessment area, like Rhine plume or Southern North Sea. In the assessment in COMPEAT, the average of all monitoring sites is used. For a specific monitoring site within an assessment area, conditions will differ from the 'average' condition of an entire assessment area, particularly if there are strong spatial gradients in concentrations as is the case for the coastal waters in both assessment areas, where stations closer to the coast have a higher freshwater influence, higher nutrient concentrations and generally higher chlorophyll concentrations. Consequently, the threshold applicable to the average conditions of an assessment area will also be less optimal for a specific monitoring site.
- The regressions for the MWTL stations and for the entire Rhine plume show a plausible gradient (closer to the coast, stations have higher chlorophyll concentrations and a stronger response to TN loads) but there is uncertainty in the regression estimates as illustrated by the confidence intervals.
- Some of the scatter in the plots of chlorophyll against TN loads can be explained by the fact that TN loads are not the only factor determining chlorophyll concentrations. In addition to nitrogen, other factors influence phytoplankton growth such as limitation by light (irradiance, turbidity) or other nutrients (P, Si), grazing, vertical mixing and hydrodynamic transport.

The estimated maximum allowable load (shaded row in Table 2.4, results for Noordwijk 2 excluded) with the COMP4 thresholds varies between 96-187 kton/year, which implies a necessary reduction in loads of 0-46% (compared to the average load for 2009-2017 of 177 kton/year). The average for MWTL stations Noordwijk10, Noordwijk20 and Terschelling10 is a reduction of 18%. The result for the Rhine plume area is a reduction of 20%. Given the uncertainty due to the relatively large range in the estimated maximum allowable load, we have chosen a reduction in riverine TN loads of 25% as the maximum required reduction to meet the chlorophyll thresholds for COMP4. This reduction of 25% is used in the next paragraphs §2.3, §2.4 and in Chapter 3.

2.3 Estimate of the nitrogen threshold in Dutch rivers

The estimated maximum required reduction in riverine TN loads of 25% that was derived in the previous chapter, applies to the average TN loads of 2009-2017. The TN loads differ substantially between years, mainly due to variation in the total discharge (Figure 2.6) in particular for Haringvliet where discharges are small during periods with relatively low river flow. However, the variation in TN concentrations between years is relatively small (Figure 2.7).

TN concentrations in the Meuse at the Belgian/Dutch border (Eijsden) are much higher than the concentrations in the Rhine at the German/Dutch border (Lobith) and in downstream distributaries of the Rhine/Meuse delta (stations Nieuwe Maas, Oude Maas, Hollands Diep, Haringvliet).

The Rhine Commission has decided on a threshold for annual average TN concentrations of 2.8 mg/l. The Netherlands use a threshold for summer mean TN concentrations of 2.5 mg/l.

The figures show the currently available monitoring data from the monitoring program MWTL[1]. Recently, it has been found that Dutch data for TN at Lobith give higher concentrations (>0.2 mg/l), since 2016, than German analyses. This is due to differences in analytical methods. Data presented here have not been corrected for this.

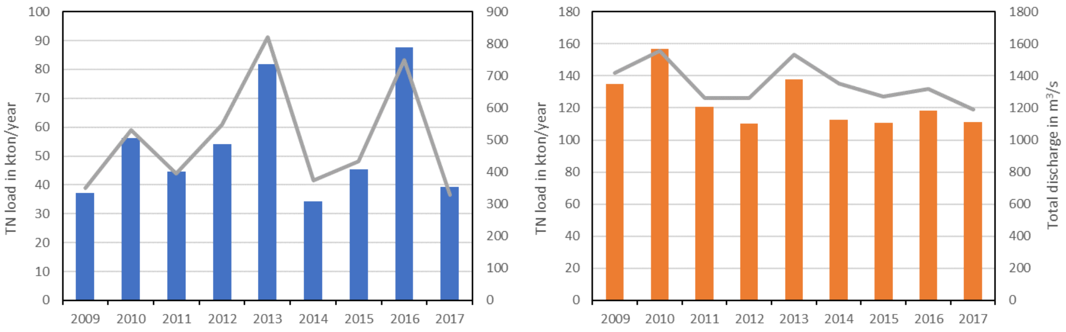


Figure 2.6 Annual TN loads from Haringvliet (bars, left) and Nieuwe Waterweg (bars, right) with annual average water discharge (grey line). Data source: https://waterinfo.rws.nl/.

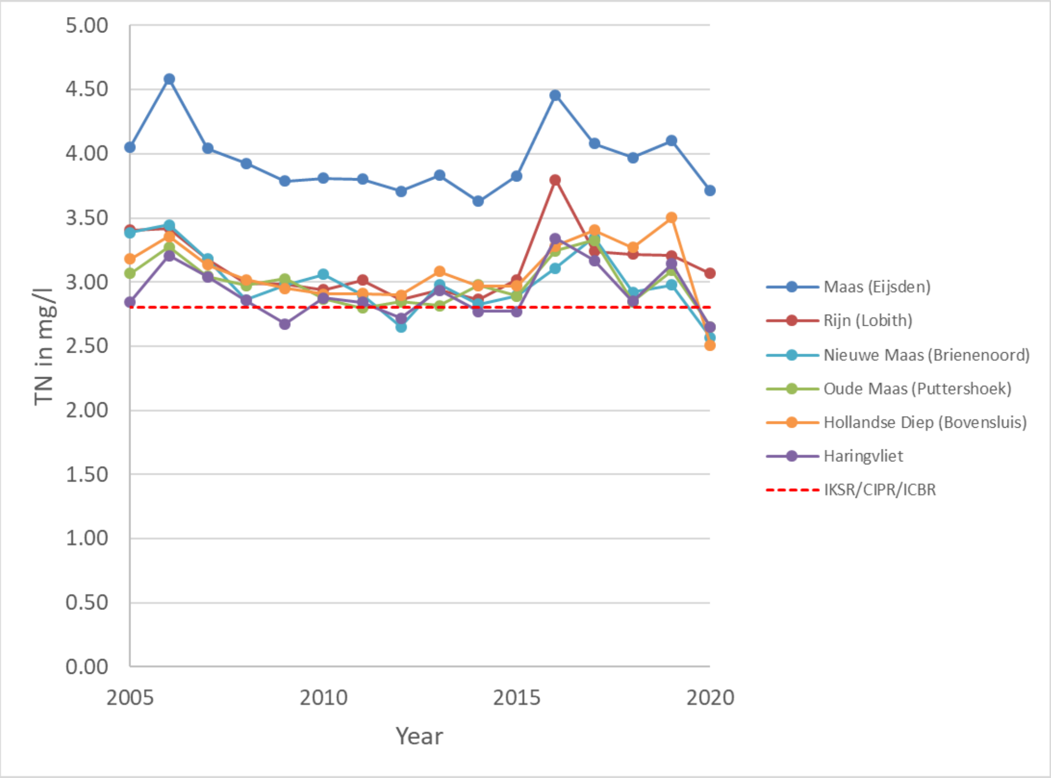


Figure 2.7a Annual average TN concentrations in Rhine and Meuse distributaries, with the ICPR threshold of 2.8 mg/l. Data source: https://waterinfo.rws.nl/.

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[1] https://waterinfo.rws.nl/

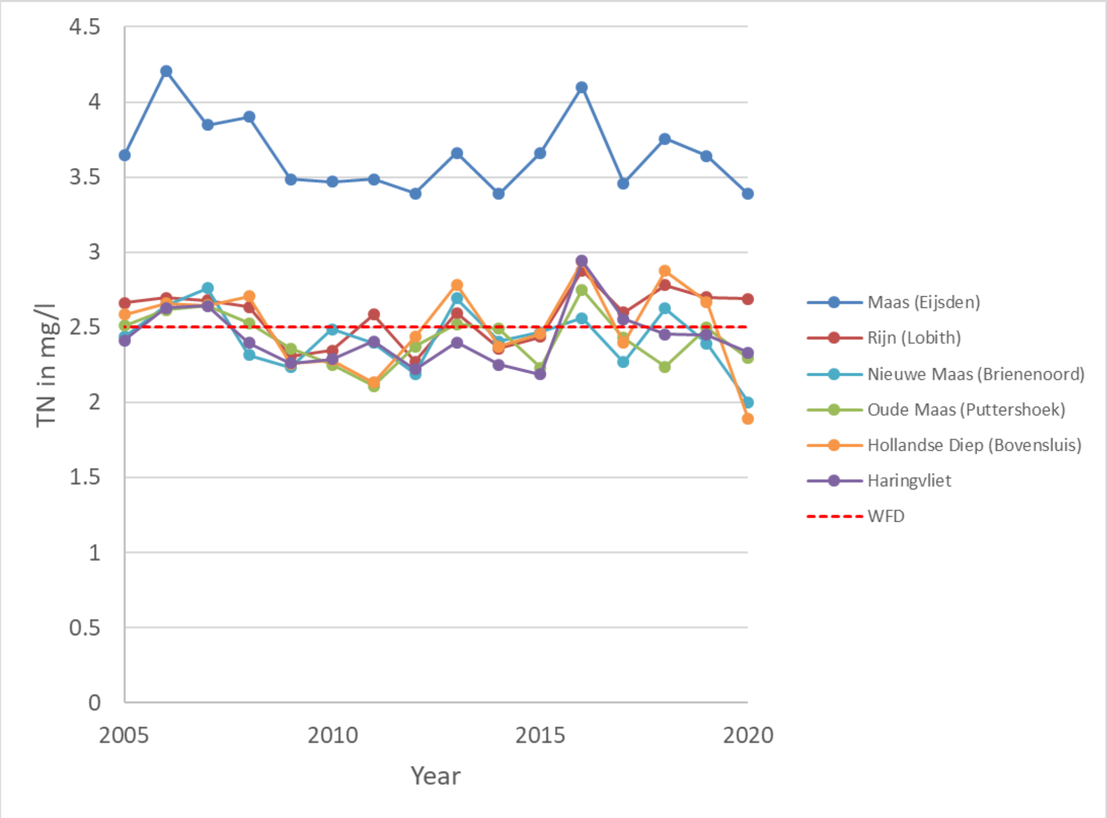

Figure 2.7b Summer average TN concentrations in Rhine and Meuse distributaries, with the Dutch WFD threshold of 2.5 mg/l. Data source: https://waterinfo.rws.nl/.

The average riverine TN load of Haringvliet+Maassluis for the period 2009-2017 was 177 kton/year, with an average discharge of 1854 m^3/s. It should be noted that the discharge of Haringvliet (500 m^3/s) is lower than the discharge of Nieuwe Waterweg (1350 m^3/s), and consequently total loads are dominated by the loads from Nieuwe Waterweg.

A reduction with 25% of the TN loads results in an average annual load of 133 kton/year. To achieve such a reduction, the annual average TN concentration in Meuse and Rhine will need to be 2.3 mg/l if the discharge is 1850 m^3/s.

2.4 Model analysis of the effect of a 25% N-load reduction

In §2.1 the estimated required reduction of riverine nitrogen loads to reach concentrations of chlorophyll below the COMP4 threshold was estimated, using linear relations between riverine TN loads and chlorophyll concentrations in the sea. A reduction of 25% in Dutch river loads (Meuse and Rhine) was selected to use in a model simulation of the effect of reduced loads. In this model simulation, other outflow points in the Rhine river basin (e.g. North Sea Canal, Lake IJssel) were also reduced with 25%.

Here we present the results of a model estimate, using the same model setup of the Deltares Delft3D-GEM model as in the ICG EMO simulations, but with 25% reduction in TN loads.

Due to time constraints, model results are only available for 3 years (2009-2011).

Figure 2.8 visualizes the spatial difference between a 2010 model run with current TN loads and a 2010 model run with 25% reduction in the Rhine/Meuse riverine TN loads, for winter mean DIN (A) and DIP (B) concentrations as well as growing season mean chlorophyll-a concentration (C). Along the Dutch coast a proportional decrease of winter DIN concentrations up to 25% can be seen. Directly along the German coast, the German rivers dominate the winter DIN concentrations and thus, no decrease of winter DIN can be seen along the German coast. The decrease of winter DIN translates into a decrease of summer chlorophyll-a along the Dutch coast. The extent of the area with a >5% decrease is smaller for chlorophyll than for DIN. Riverine phosphate loads were not decreased and thus, there is no visible decrease in winter DIP.

Table 2.5 and 2.6 provide the modelled concentrations for the OSPAR assessment areas and the WFD coastal water bodies, for growing season mean chlorophyll-a and winter mean DIN concentrations. The tables show the mean concentrations for the three modelled years (2009, 2010, 2011) for the two scenarios (current state, 25% reduction in TN loads) and the resulting reduction in concentrations in the 25% scenario. Results for winter mean DIP are not shown as there were no changes in concentrations.

For comparison, the tables include the OSPAR COMP4 and WFD thresholds and the observed average concentrations in 2009-2011 in the COMP4 assessment areas and the WFD water bodies. The last column of the table shows the percentage reduction that is required to lower the observed concentrations of 2009-2011 to meet the COMP4 and WFD thresholds.

No results are shown for the assessment area Southern North Sea, as this is a large area where Rhine and Meuse only influence the most eastern part and changes in riverine fluxes from Rhine and Meuse will have limited effect on the status of the entire area. The assessment areas Dogger Bank and Eastern North Sea are included to illustrate that Rhine and Meuse have a minor contribution to nutrient levels in these areas.

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The model response, in terms of the percentage decrease in concentrations in the 25% reduction scenario in comparison to the model run for the current state, clearly shows a gradient from river mouth to offshore areas. In both the river plume assessment areas of COMP4 (Table 2.5b: Scheldt plume, Meuse plume, Rhine plume) and the WFD water bodies (Table 2.6b), the 25% reduction scenario shows a decrease in DIN concentrations that is proportional to the decrease in riverine TN loads. Obviously, the decrease in winter DIN is highest near the river outflows where the freshwater influence is largest (e.g. water bodies Northern Delta coast and Holland coast, COMP4 areas Meuse and Rhine plume) and small in the offshore areas (e.g. Dogger Bank).

The decrease in chlorophyll concentrations is much smaller than the decrease in DIN concentrations, due to the effect of other limiting factors. The response to the 25% reduction in nitrogen loads is strongest in the Wadden Sea and in the coastal strip along the Dutch coast.

A comparison can be made between the modelled reduction in concentrations and the reduction that is required to reduce the observed (2009-2011) concentrations to a level meeting the COMP4 or WFD thresholds. For DIN, the modelled reduction shows a mixed picture, sometimes lower and sometimes larger than the required reduction derived from the observed concentrations. For chlorophyll, the modelled reduction is in nearly all cases smaller than what is required based on the observations. Exceptions are WFD water bodies Holland coast and Wadden coast where the observed concentrations were below the threshold in 2009-2011.

The interannual variability in concentrations is large. The year 2010 has the highest modelled chlorophyll concentrations in most river plumes and WFD water bodies (but no clear differences in DIN concentrations). This pattern is observed in the chlorophyll satellite observations as well. The year 2010 also shows a larger % reduction than the other years in the river plumes and WFD water bodies. This interannual difference shows that other factors, in addition to nitrogen, have an impact on chlorophyll concentrations.

It is also clear from Figure 2.8 and Table 2.6 that the reduction in DIN loads has a relatively strong impact on chlorophyll concentrations in the Wadden Sea, compared to the coastal water bodies of the North Sea (similar DIN decrease, larger chlorophyll decrease in the Wadden Sea). We have not yet been able to identify the reason for this difference in response. The better light climate in the shallow Wadden Sea probably played a role. In addition, modelled phosphorus release from the sediment in summer seems to be underestimated in the coastal waters. This results in too low DIP concentrations, leading to a stronger P-limitation of phytoplankton in the model and consequently a smaller impact of differences in TN loads on chlorophyll concentrations.

This limited response in the model contrasts with the reductions that are expected based on the statistical correlation between riverine TN loads and chlorophyll concentrations shown in Figure 2.5. To determine if the statistical extrapolations overestimate the effect of TN load reductions on chlorophyll in Dutch coastal waters or whether the model application underestimates the response of chlorophyll to TN load reductions, a more detailed model analysis of reduction scenarios in combination with analysis of monitoring data Is necessary.

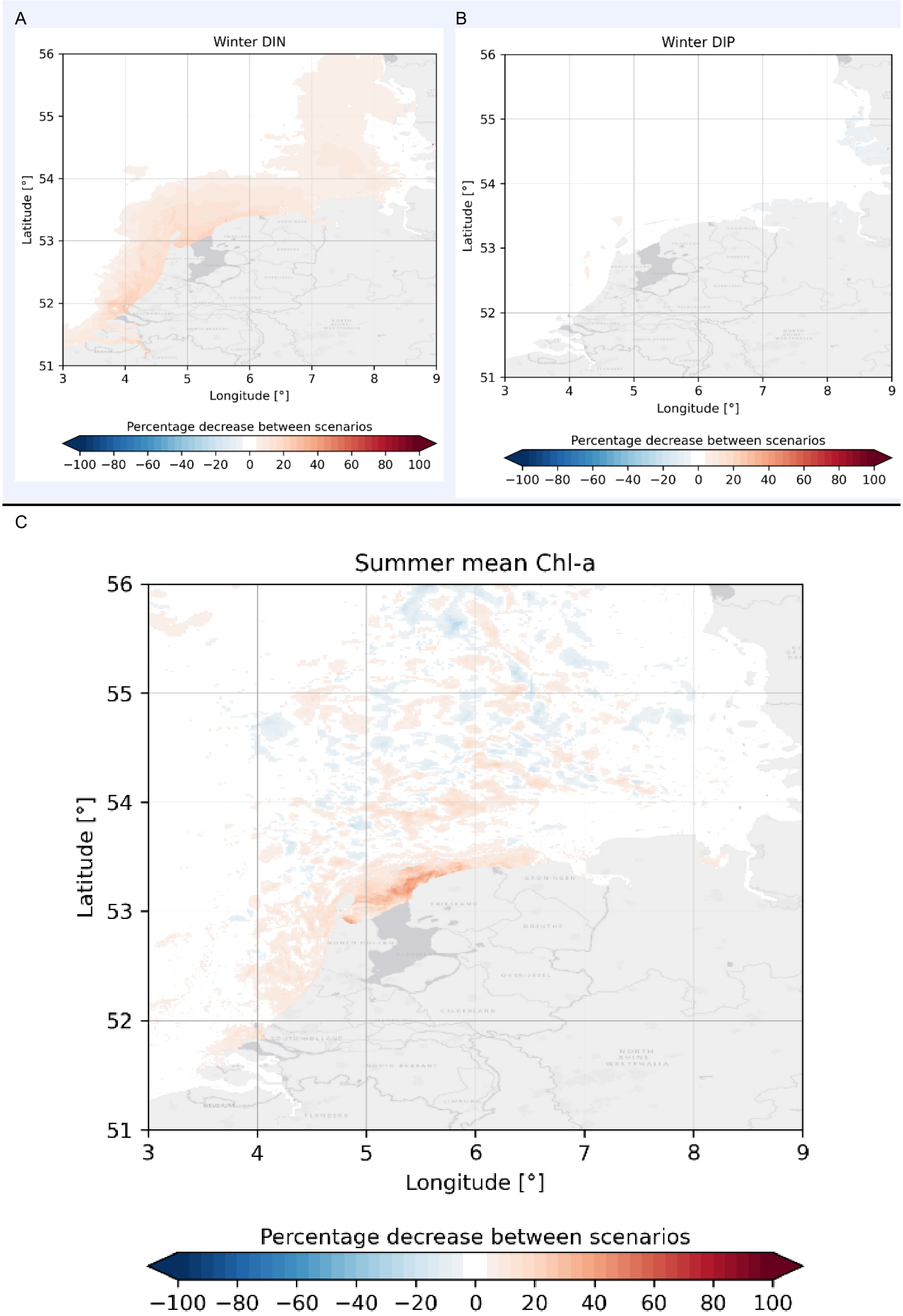

Figure 2.8 Maps visualizing the percentage decrease between the current and the 25% reduction scenario for winter DIN (A), winter DIP (B) and summer chlorophyll-a (C) for the year 2010 in coastal and marine waters. Red: decrease in concentrations in the 25% reduction scenario compared to the current state; Blue: increase in concentrations.

Table 2.5a Chlorophyll-a concentrations for the OSPAR COMP4 assessment areas in the model runs for the current state simulation and for the 25% reduction scenario, for the years 2009, 2010 and 2011. Average concentrations based on monitoring data (combination of in situ and satellite data) and the required reduction calculated from the difference between observed concentrations and COMP4 threshold are shown in the last two columns. See Figure 2.4 for the location of the assessment areas.

		Growing season mean Chlorophyll-a (µg/l)					
		model results			**COMP4 threshold**	**monitoring data (2009-2011)**	
		current state scenario	**-25% scenario**	**decrease in 25% scenario**		**average**	**reduction to meet threshold (%)**
Scheldt plume 1	2009	7.7	7.7		5		
	2010	8.1	8.0				
	2011	7.9	7.8				
	average	**7.9**	**7.9**	**0%**		**13.2**	**-62%**
Scheldt plume 2	2009	9.9	9.8		8.9		
	2010	17.3	16.3				
	2011	9.7	9.6				
	average	**12.3**	**11.9**	**-3%**		**13.3**	**-33%**
Meuse plume	2009	12.0	12.0		8		
	2010	20.2	18.9				
	2011	11.6	11.6				
	average	**14.6**	**14.2**	**-3%**		**9.9**	**-19%**
Rhine plume	2009	9.6	9.6		6.8		
	2010	12.7	11.9				
	2011	8.3	8.3				
	average	**10.2**	**9.9**	**-3%**		**7.6**	**-11%**
Dogger bank	2009	2.7	2.6		1.3		
	2010	2.3	2.3				
	2011	2.3	2.3				
	average	**2.4**	**2.4**	**0%**		**0.9**	**0%**
Eastern North Sea	2009	2.8	2.8		1.2		
	2010	2.7	2.7				
	2011	3.0	3.0				
	average	**2.8**	**2.8**	**0%**		**1.0**	**0%**

Table 2.5b DIN concentrations for the OSPAR COMP4 assessment areas in the model runs for the current state simulation and for the 25% reduction scenario, for the years 2009, 2010 and 2011. Average concentrations based on monitoring data and the required reduction calculated from the difference between observed concentrations and COMP4 threshold are shown in the last two columns. See Figure 2.4 for the location of the assessment areas.

		Winter mean DIN (µmol/l)					
		model results			**COMP4 threshold**	**monitoring data (2009-2011)**	
		current state scenario	**-25% scenario**	**decrease in 25% scenario**		**average**	**reduction to meet threshold (%)**
Scheldt plume 1	2009	37.0	34.2		25.9		
	2010	36.3	33.5				
	2011	37.9	34.7				
	average	**37.0**	**34.1**	**-8%**		**43.6**	**-41%**
Scheldt plume 2	2009	42.5	35.5		33.3		
	2010	38.4	32.3				
	2011	38.0	33.1				
	average	**39.6**	**33.6**	**-15%**		**-**	
Meuse plume	2009	55.8	46.4		40.7		
	2010	57.7	47.0				
	2011	53.4	43.8				
	average	**55.6**	**45.7**	**-18%**		**43.3**	**-6%**
Rhine plume	2009	37.6	31.8		29.7		
	2010	37.1	30.9				
	2011	38.9	32.8				
	average	**37.8**	**31.8**	**-16%**		**45.6**	**-35%**
Dogger bank	2009	8.2	8.1		7.2		
	2010	7.1	7.1				
	2011	7.6	7.5				
	average	**7.7**	**7.6**	**-1%**		**5.3**	**0%**
Eastern North Sea	2009	9.1	9.0		7.3		
	2010	9.3	9.3				
	2011	9.2	9.1				
	average	**9.2**	**9.1**	**-1%**		**6.5**	**0%**

Table 2.6a Chlorophyll-a concentrations for the WFD coastal water bodies in the model runs for the current state simulation and for the 25% reduction scenario, for the years 2009, 2010 and 2011. Average concentrations based on monitoring data and the required reduction calculated from the difference between observed concentrations and WFD threshold are shown in the last two columns.

		Growing season mean Chlorophyll-a (µg/l)					
		model results			**WFD G/M boundary**	**monitoring data (2009-2011)**	
		current state scenario	**-25% scenario**	**decrease in 25% scenario**		**average (2009-2011)**	**reduction to meet G/M boundary (%)**
Zeeland coast	2009	8.1	8.1		7.5		
	2010	10.8	10.5				
	2011	7.7	7.7				
	average	**8.9**	**8.7**	**-1%**		**11.6**	**-35%**
Northern Delta coast	2009	26.4	25.7		8.4		
	2010	32.8	29.3				
	2011	18.1	18.0				
	average	**25.7**	**24.3**	**-5%**		**9.4**	**-11%**
Holland coast	2009	13.5	13.3		8.4		
	2010	17.3	16.0				
	2011	10.8	10.7				
	average	**13.9**	**13.4**	**-4%**		**7.9**	**0%**
Wadden coast	2009	9.1	8.5		7.5		
	2010	10.5	9.4				
	2011	9.0	8.6				
	average	**9.5**	**8.9**	**-7%**		**5.3**	**0%**
Ems Dollard coast	2009	11.4	11.1		5.1		
	2010	9.1	8.9				
	2011	9.4	9.2				
	average	**10.0**	**9.7**	**-2%**		**9.6**	**-47%**
Wadden Sea	2009	16.5	14.2		7.2		
	2010	18.7	15.4				
	2011	13.9	12.6				
	average	**16.4**	**14.1**	**-14%**		**13.1**	**-45%**

Table 2.6b DIN concentrations for the WFD coastal water bodies in the model runs for the current state simulation and for the 25% reduction scenario, for the years 2009, 2010 and 2011. Average concentrations based on monitoring data and the required reduction calculated from the difference between observed concentrations and WFD threshold are shown in the last two columns.

		Winter mean DIN (µmol/l)					
		model results			**WFD G/M boundary**	**monitoring data (2009-2011)**	
		current state scenario	**-25% scenario**	**decrease in 25% scenario**		**average (2009-2011)**	**reduction to meet G/M boundary (%)**
Zeeland coast	2009	34.7	31.1		33		
	2010	34.2	30.2				
	2011	36.5	32.5				
	average	**35.1**	**31.3**	**-11%**		**35.3**	**-7%**
Northern Delta coast	2009	123.3	96.4		33		
	2010	133.5	101.7				
	2011	118.6	93.8				
	average	**125.2**	**97.3**	**-22%**		**46.5**	**-29%**
Holland coast	2009	48.9	40.4		33		
	2010	47.9	38.8				
	2011	51.7	42.1				
	average	**49.5**	**40.4**	**-18%**		**46.9**	**-30%**
Wadden coast	2009	36.6	31.2		33		
	2010	37.0	31.8				
	2011	36.3	31.5				
	average	**36.7**	**31.5**	**-14%**		**29.0**	**0%**
Ems Dollard coast*	2009	55.8	52.3		35.5		
	2010	56.9	50.7				
	2011	61.2	56.0				
	average	**58.0**	**53.0**	**-9%**		**49.9**	**-29%**
Wadden Sea**	2009	57.4	47.2		58.3		
	2010	63.0	51.6				
	2011	60.0	50.2				
	average	**60.1**	**49.7**	**-17%**		**58.5**	**0%**

** Salinity 29.5*

*** Salinity 25.0*

3 Source apportionment of riverine nutrient loads

3.1 Introduction

The new COMP4 thresholds can have implications for measures required to reduce anthropogenic nutrient loads to the North Sea through the rivers (Scheldt, Meuse, Rhine, Ems) and consequently, for nutrient emissions to inland water systems. The main objectives of this chapter are (I) to define the relative contribution of nitrogen and phosphorus sources (both emissions in the Netherlands and via transboundary transport) to the riverine nutrient loads to the North Sea, and (II) compare the 25% reduction in nitrogen emissions (Chapter 2) with the results of the *Ex Ante* evaluation of the WFD river basin management plans (van der Linden *et al.* 2021). Although the focus in the previous chapter is on nitrogen, we included data on phosphorus here, to provide a more complete picture.

To meet these objectives, we performed scenario runs with the Water Framework Directive Explorer (WFD Explorer) applying a “source apportionment” approach. With this approach, emissions from specific sources are tracked through space and time by labelling of the sources. This means that at every location the sources contributing to the load can be identified and quantified. For the labelling we used the Load Composition Tool of the WFD Explorer. With this tool, loads can be broken down into contributions from different source areas and pathways. This allowed us to define the relative contributions and investigate the potential impact of emission reduction measures.

3.2 Methods

3.2.1 Water Framework Directive Explorer

For this study, we used the Water Framework Directive Explorer (WFD Explorer) version 2.5. The WFD Explorer is an analytical tool to gain insight in the effectiveness of programs of measures in relation to WFD objectives by calculating the effects of restoration and mitigation measures on the chemical and ecological quality of surface waters (see Appendix A for more details).

3.2.2 Model schematization

We used the national schematization of the WFD Explorer, version 2.5, as used for the *Ex Ante* evaluation of the WFD river basin management plans (van der Linden *et al.* 2021). This schematization covers the Dutch inland waters, transboundary waters and transitional waters (Figure 3.1). The national schematization contains 14 (large) discharge locations along the Dutch coast. The riverine nutrient loads at these locations are evaluated in this study.

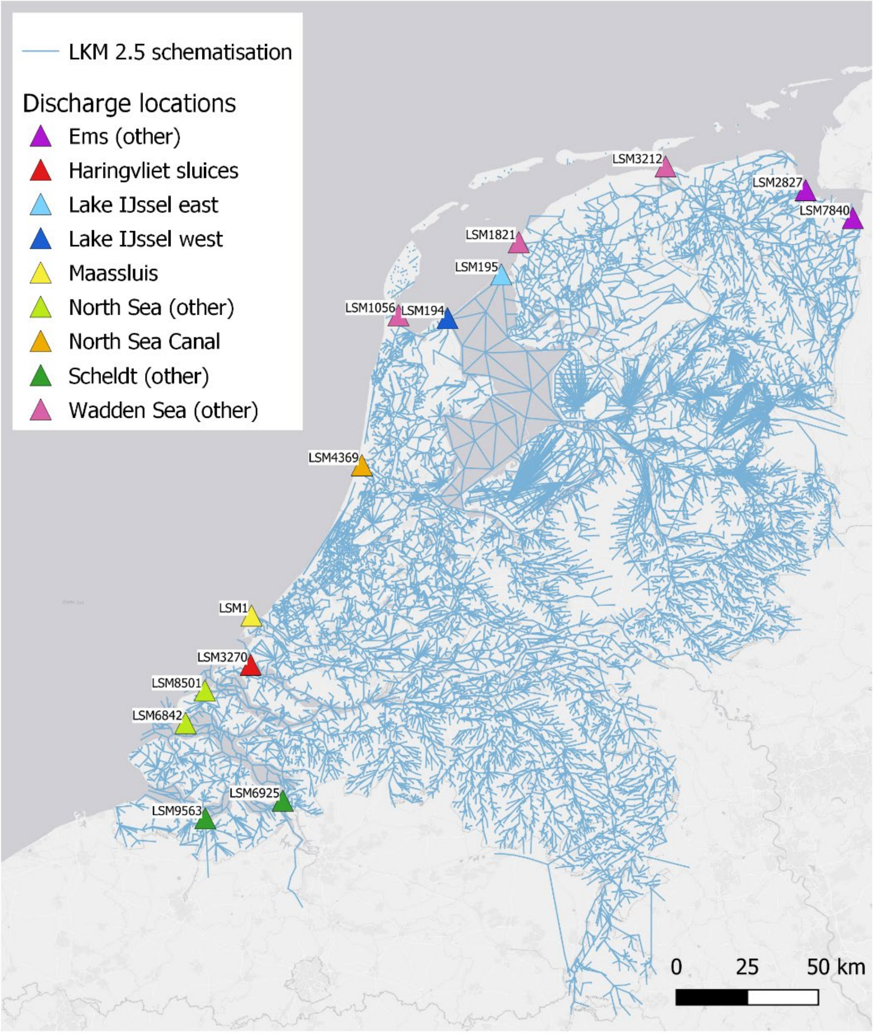

Figure 3.1 National WFD Explorer schematization version 2.5 including the main discharge locations towards the North Sea. Small discharges are lumped together during data analysis. The legend shows the (grouped) discharge locations and names used in this study.

3.2.3 Load Composition Tool

For the “source apportionment” analysis, we used the Load Composition Tool of the WFD Explorer. With this tool we can track emissions from specific sources through space and time by labelling them. At every location the sources contributing to the nutrient load can be identified and quantified.

Users can track down the sources by assigning emissions to a source type and assigning surface water or drainage units to a source area. The source area allows to differentiate between the spatial origin of the nutrient loads. By assigning an area to a node, all point source emissions and diffuse emission are considered to originate from that area. It is not required to define source area, solely defining source types is also possible.

For the labelling, the Load Composition Tool uses so-called tracers. With these tracers the relative contribution of different sources can be defined. When creating tracers, all properties of the represented substances are maintained, e.g. nitrogen tracers maintain the nitrogen properties. These properties are:

- Default retention coefficient;
- Default temperature coefficient;
- Spatially dependent retention and temperature coefficients.

Application of the Load Composition Tool is explained in Appendix C. For the “source apportionment” analysis, we labelled the river basin districts (RBD) and emission sources. The emission sources cover point sources and diffuse sources within the Netherlands as well as the transboundary transport via the large rivers and some other smaller cross-border waters. In order to reduce the number of tracers we clustered the emission sources, as shown in Table 3.1.

Table 3.1 Emission sources included in the model and clusters defined for the “source apportionment” analysis. The emission sources are clustered to improve readability of the pie charts.

Emission source	Cluster
Atmospheric deposition	Other emissions
Transboundary transport Ems river	Transboundary transport Ems river
Transboundary transport Meuse	Transboundary transport Meuse river
Transboundary transport other	Transboundary transport small rivers
Transboundary transport Rhine	Transboundary transport Rhine river
Transboundary transport Scheldt	Transboundary transport Scheldt river
Runoff from farmyards	Agriculture
Greenhouse horticulture	Agriculture
Leaching agriculture areas	Agriculture
Fertilizer spilling into ditches	Agriculture
Leaching nature areas	Agriculture
Industrial emissions	Other emissions
Other diffuse emissions	Other emissions
Rainwater sewers	WWTP
Wastewater Treatment Plants	WWTP
Leaching urban areas	Agriculture

3.2.4 Model runs

Two years were calculated, to assess the relative contribution of the nitrogen and phosphorus sources to the riverine loads discharged into the North Sea and the effect of planned measures. A base year (reference situation) and a scenario year (situation after the planned measures). The year 2019 was used as the base year and 2027 as the scenario year, as was done for the *Ex Ante* evaluation (van der Linden *et al.* 2021). The emissions for the base year are based on water quality data of the year 2019. To determine the emissions in 2027, the so-called “intended measures” set of measures is used, as defined in the *Ex Ante* evaluation. These are the measures which are planned to be carried out and included in the draft RBMPs for the 3rd WFD cycle (2022-2027) by the Dutch water boards and Rijkswaterstaat. The package “intended measures” includes:

- The national implementation of the 7th Nitrate Action Plan (NAP).
- Voluntary agricultural measures of the “Deltaplan Agrarisch Waterbeheer” (DAW).
- Improvement of Urban Waste Water Plants (UWWTPs).
- Hydromorphological and ecological measures.

- Expected nutrient concentrations (delivered by the upstream countries) of the transboundary waters for the year 2027 as a result of the WFD measures in the upstream countries are used. For those transboundary water bodies expected concentrations in 2027 were determined by the upstream partners as the result of measures planned in the 3rd RBMPs (see Van den Roovaart *et al.* 2021).

For the calculation of the reference situation in 2019, we assumed that in practice so-called overfertilization, i.e. application of excess fertilizer (above legal standards), takes place. For the 2027 scenario we assumed that all agricultural holdings uphold a Good Agricultural Practice (GAP) and do not fertilize above application standards. The set-up of the model runs is summarized in Table 3.2. The WFD Explorer calculations of both years are based on a long term 30-year average hydrology, as described in van der Bolt *et al.* (2020). The measures are implemented in the model as load reductions. Applied N and P loads for the base year and 2027 scenario and corresponding reductions, are listed in Table 3.3 per emission source.

Table 3.2 Summary of the model run set-ups, the applied hydrology and measure packages.

Year	**Hydrology**	**RBMPs**	**Nitrate Action Plan and DAW**	**Transboundary concentrations**
2019	Average hydrology (1981-2015)	2nd RBMPs	Initial state 2019 (NAP6) with overfertilization	Present
2027	Average hydrology (1981-2015)	3rd RBMPs	NAP7, DAW intended measures, no overfertilization	Realistic expected concentrations

Table 3.3 Overview of the total nitrogen and total phosphorus loads and emissions used as input data in the WFD-Explorer model runs and computed reductions relative to the base year (2019). For some cross-border waters the upstream countries expect an increase in the nutrient concentrations. See Appendix B for a more detailed overview. The Dutch emissions sources are split into the categories Agriculture, WWTP and Other emissions.

	2019 (kton/year)	**2027 (kton/year)**	**Reduction (%)**
Total nitrogen			
Agriculture	55.9	47.0	16.0*
WWTP	15.8	15.1	4.6
Other emissions	10.8	10.4	4.3
Transboundary load Rhine river	205.9	205.9	0.0
Transboundary load Meuse river	34.5	33.6	2.6
Transboundary load Scheldt river	10.9	11.0	-1.0
Transboundary load Ems river	11.3	6.5	42.3
Transboundary load small rivers	35.5	33.0	7.0
Total	380.6	362.4	5.0
Total phosphorus			
Agriculture	4.6	4.3	7.1
WWTP	2.0	1.9	8.0
Other emissions	0.3	0.3	0.0
Transboundary load Rhine river	4.7	4.5	5.0
Transboundary load Meuse river	1.1	1.1	2.3
Transboundary load Scheldt river	1.0	1.0	-13.0
Transboundary load Ems river	0.2	0.1	31.2
Transboundary load small rivers	2.2	2.3	-6.1
Total	16.1	15.5	4.0

3.3 Results

Figure 3.2 shows the relative contribution of the discharge locations to the total riverine nutrient load towards the North Sea for the year 2019 (base year, no measures). For both nutrients, the contribution of the Rhine *(Maassluis, Lake IJssel east/west*) is the largest. Approximately 65% of the total riverine nutrient load derives from the Rhine (67% for total N and 57.4% for total P). The relative contribution of the Meuse river (*Haringvliet sluices*) is 17.5% for total N and 11.1% for total P.

Scheldt (other) and *Ems (other)* represent smaller rivers that discharge into respectively, the Western Scheldt and Ems-Dollard. The loads of these smaller rivers are grouped in this study. *Scheldt (other)* is the sum of Canal Gent-Terneuzen and other small discharges and *Ems (other)* is the sum of the Ems canal and Westerwoldse Aa. The same applies to *Wadden Sea (other)* and *North Sea (other)*.

The TN load to sea for all sources considered here, was 253 kton/year in 2019, similar to the average TN load in 2009-2017 (256 kton/year). For TP, the load in 2019 was 8.0 kton/year, which is lower than the average for 2009-2017 (9.4 kton/year).

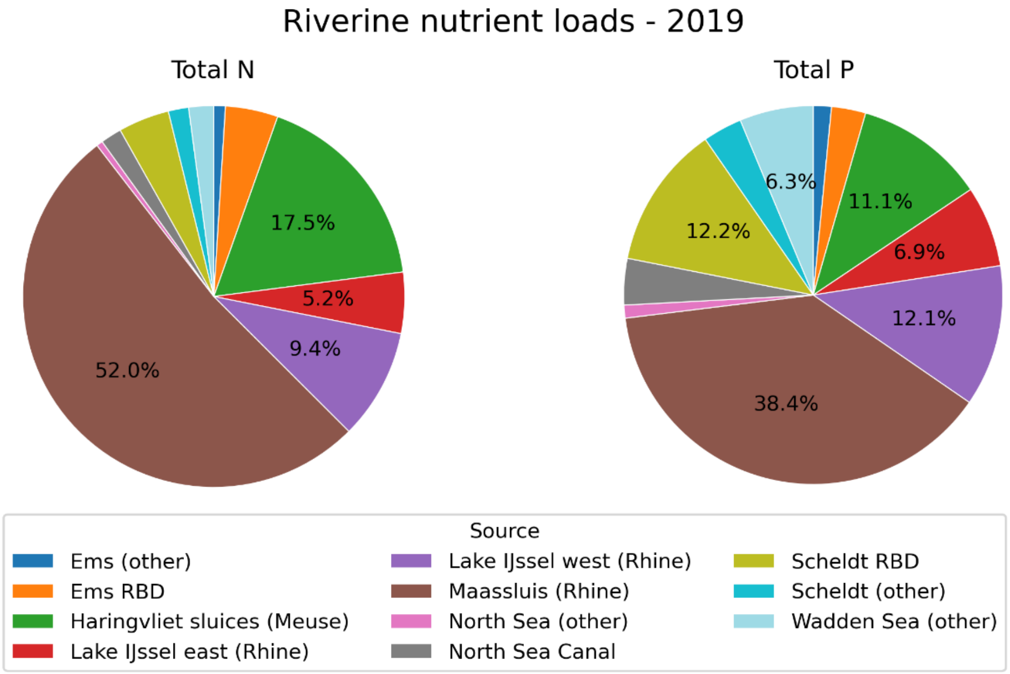

Figure 3.2 Relative contribution to the total riverine nutrient loads to the North Sea for the base year, 2019.

Figure 3.3 shows the relative contribution of nitrogen and phosphorus sources to the riverine nutrient loads towards the North Sea. The pie charts show the contribution of the source area (river basin district, RBD), which is further split into the contribution per nutrient emission source, including both emissions in the Netherlands (categories *Agriculture*, *WWTP*, and *Other emission*) and transboundary transport by cross-border waters (see Table 3.1 for specification). In these charts the loads of all discharge locations are summed.

The Rhine river basin is the main source area of nitrogen (76%), followed by the Meuse basin (12%). The contribution of the other source areas is less than 10%. The main emission source is the transboundary transport via the Rhine river, which is 63% of the total riverine load. The transboundary transport of the Meuse river and *Agriculture* in NL contribute respectively 8% and 9% to the total riverine load. The contributions of the other emission sources are less than 6%.

Comparable to nitrogen, the main source area of phosphorus is also the Rhine river basin with a contribution of 69%. The relative contribution of the Meuse and Scheldt area is respectively 10% and 16%. The main emission source of the riverine phosphorus load is the transboundary transport via the Rhine river (37%). Other sources with relatively large contribution are *Agriculture* in NL (23%), *WWTP* in NL(12%) and *transboundary transport Scheldt river* (12%). The contributions of the other emission sources are less than 6%.

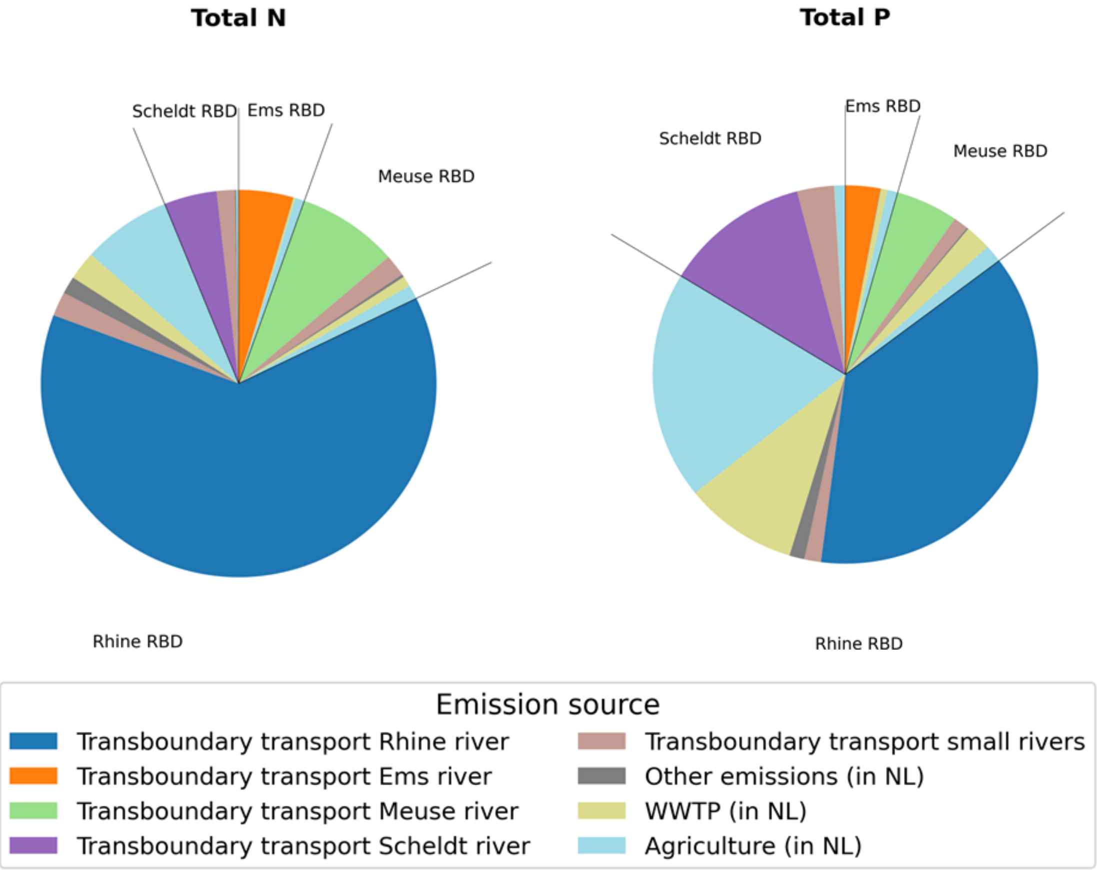

Figure 3.3 Relative contribution of the river basin districts (RBD) and nutrient emission sources (pie wedges) to the total riverine nutrient loads towards the North Sea for the reference situation in 2019. Left: nitrogen; right: phosphorus. Emission sources include point and diffuse sources in the Netherlands (Agriculture, WWTP and Other emissions) as well as transboundary transport (see Table 3.1 *for specification). The pie chart shows the relative contribution of the RBDs and nutrient emission sources to the load from each RBD. See Appendix D for a subdivision of the Rhine RBD into the three sub basins.*

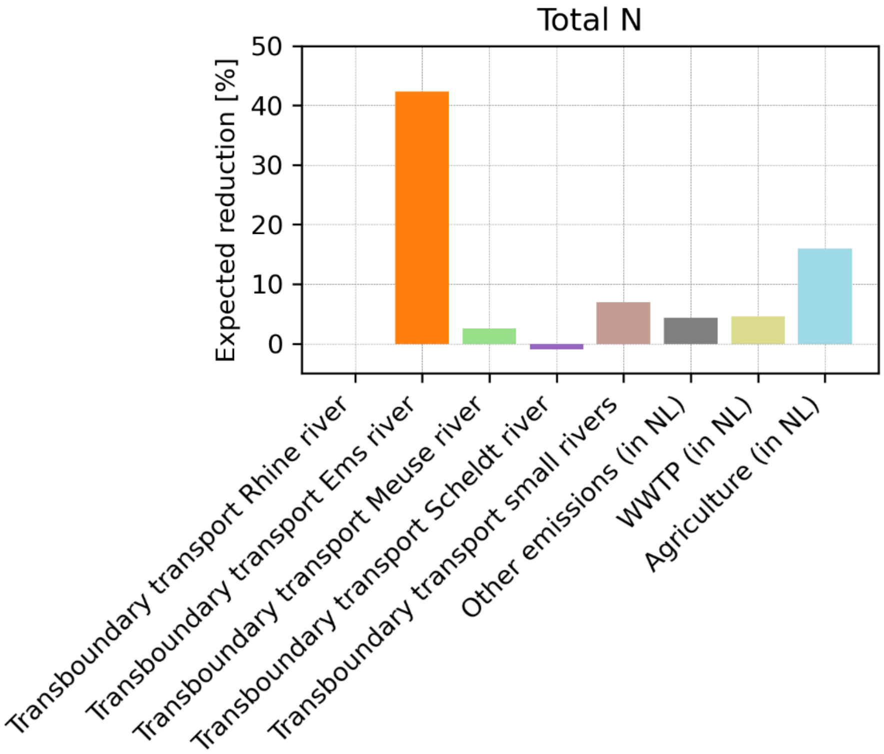

Figure 3.4 Expected reductions in the riverine nitrogen loads per emission source. No bar means the reduction is 0%, i.e. no reduction expected. Negative reduction indicates an expected increase in load. This applies to the transboundary transport of the Scheldt.

Figure 3.4 shows the expected total nitrogen load reduction for 2027 ("intended measures" scenario *Ex Ante*). The expected reductions of all emission sources are less than the required 25%, except for the transboundary transport through the Ems river. For the emission source *Agriculture* (solely includes Dutch emissions), a reduction of 16% is expected. The expected reduction in the transboundary transport via the Rhine is zero, for transboundary transport through the Meuse a small reduction is expected and for the transboundary transport via the Scheldt a small increase of 1% is anticipated. The expected reductions of the other sources (*transboundary transport small rivers*, *WWTP* in NL and *Other emissions in NL*) are less than 10%.

The pie charts in Figure 3.5 illustrate how much the different emission sources contribute to the total riverine nutrient loads in the years 2019 (reference situation) and 2027 (after expected reductions). The relative contribution of the emission sources in 2027 is comparable to 2019. In addition, the charts show the expected reduction of the different emission sources in 2027 after implementation of the "intended measures". As mentioned above, all nitrogen emission sources show reductions lower than 25%, except for the transboundary transport of the Ems river. The nutrient reductions in the Ems and other cross-border waters are based on estimates of the upstream countries. The figure clearly illustrates that transboundary transport forms a major part of the nutrient loads to the North Sea and the sum of the currently expected reductions will only lead to a small reduction in riverine nutrient loads.

Based on the model results we calculate that the expected reduction in the riverine TN load is 4.0% when the "intended measures" are implemented. The riverine TN load will decrease from 253 kton/year in the base year 2019 (reference situation) to 242 kton/year in 2027 (after planned measures). The expected reduction in TP is 3.4%, from 8.0 kton/year in the base year 2019 to 7.8 kton/year in 2027.

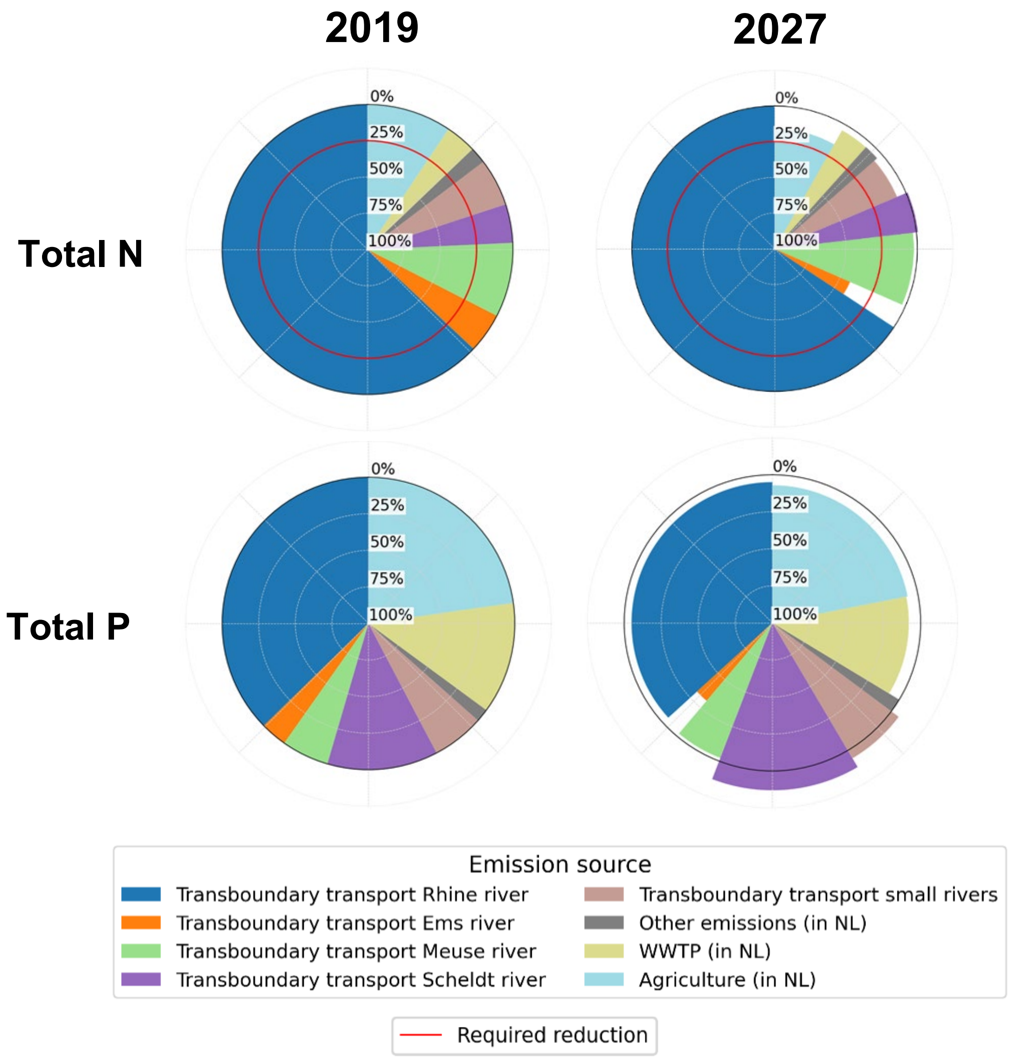

Figure 3.5 Relative contribution of the emission sources to the total riverine nutrient loads towards the North Sea before (2019, left) and after the expected reductions (2027 scenario "intended measures" of Ex Ante, right) for total nitrogen (top) and total phosphorus (bottom). The width of the wedges indicates the contribution to the total load and the height shows the expected reduction. The red line is the required 25% riverine nitrogen load reduction as discussed in Chapter 2. Wedges that extend beyond 0% indicate an expected increase in load. This applies to Transboundary transport Scheldt river and transboundary transport small rivers (only TP).

4 Evaluation of the two pre-eutrophic reference scenarios

4.1 Introduction

To support the development of coherent targets, OSPAR’s Intersessional Correspondence Group on Ecosystem Modelling (ICG EMO) carried out an ensemble modelling approach in 2020-2021 with the aim to propose thresholds for nutrients and chlorophyll based on a common and harmonized approach (Lenhart *et al.* 2022). The thresholds were derived from model simulations describing historic reference (pre-eutrophic) conditions in the North Sea for the year 1900.

Main input data for these historic simulations are the pre-eutrophic nutrient loads into the North Sea. These historic loads were based on model runs simulating the pre-eutrophic nutrient emissions and transports in the European catchments. These simulations were carried out using the E-Hype model (Historic Scenario 1). However, the E-Hype model has some drawbacks especially within the P load estimates. Hence, for TP, also an alternative ‘hybrid’ historic simulation was set up (Historic Scenario 2). In this hybrid approach, P loads of some German and Dutch rivers were adjusted, based on the pre-eutrophic load simulations using the MONERIS model (Venohr *et al.* 2011). Also, Denmark has provided additional national estimates for pre-eutrophic P loads for their coastal areas. The setup, using the two scenarios HS1 and HS2 that only differed in P loads, was supported by OSPAR’s ‘Technical Group for the Common Procedure’ for eutrophication assessments (TG-COMP) and the ICG-EMO model community, since the focus of only changing the P load estimates offers better comparability between the model studies.
Scenario HS2 results in smaller DIP concentrations and thresholds in the North Sea than scenario HS1. Below, the differences between the HS1 and HS2 model set ups are discussed, and it is assessed what could explain their difference regarding TP load.

4.2 Brief model descriptions

Both models are based on estimates of nutrient emissions to inland surface waters, derived from data and emission factors of all relevant point sources and diffuse sources (including, for example, waste water, runoff from agricultural land, atmospheric deposition, etc.) and describe resulting concentrations in water systems throughout the catchment area.

HS1/E-HYPE: E-HYPE is an application of the HYPE model for the entire European continent. HYPE (Hydrological Predictions for the Environment) is an integrated rainfall-runoff and nutrient transport model developed by the Swedish Meteorological and Hydrological Institute (SMHI) under a Creative Commons open source license. HYPE also includes a lake model, which is embedded in the river routing scheme. As an adaptation to nutrient modelling, HYPE explicitly accounts for soil porosity and field capacity/wilting point storage volumes. Data required for setting up the model include spatial data for land management data sources (e.g. point source releases, crop fractions, and land management practices). The pre-eutrophic scenario was set up within the JMP EUNOSAT project (Enserink *et al.* 2019). For this pre-eutrophic scenario, E-HYPE version 3.1.3 (released in August 2016) was used. A description of the detailed model set up used for the historic, pre-eutrophic, scenario is given in the JMP EUNOSAT Activity 1 report (Blauw *et al.* 2019). That report also mentions that, evaluated at a national level, the E-HYPE estimates for (current) nutrient loads into the North Sea are considerably higher than the OSPAR-RID estimates in France, Germany, the Netherlands and the UK. In those cases, a correction factor was applied to the E-HYPE data.

HS2/MONERIS (Modelling Nutrient Emissions in River Systems) is a semi-empirical, conceptual model for the quantification of nutrient emissions from point and diffuse sources in river catchments (Behrendt *et al.* 1999). MONERIS takes into account a wide range of regional characteristics, such as the water supply, soil characteristics, slope, geology, population, and sewage systems; this includes an inventory of wastewater treatment plants. This pre-eutrophic scenario HS2 was set up in 2015 to support the harmonization of the nutrient thresholds in the North Sea. A detailed description of the model set up used for the historic scenario is given in Gadegast & Venohr (2015).

4.3 DIP concentrations in the North Sea

Figure 4.1 shows the modeled DIP concentrations in HS1 (as compared to the current situation) and HS2 (as compared to HS1). Reference scenario HS1 (based on E-HYPE) shows DIP concentrations in the Elbe plume that are only slightly lower than the current situation and surrounding coastal waters (Figure 4.1 left panel). Reference scenario HS2 (based on MONERIS), shows lower DIP concentrations than HS1 (Figure 4.1 right panel). The differences between the two reference scenarios are strongest in the Elbe plume.

The small difference in the Elbe plume between the current concentrations and HS1 clearly stands out from the differences in the other river plumes, while the concentrations in the Elbe Plume in HS2 are more in line with those of the other river loads in scenario HS1. At a first glance, this may suggest that the reductions in the Elbe plume in HS1 are underestimated. However, an alternative explanation could be that in 1900 the total population living in the Elbe catchment was relatively large. And indeed, data presented in the MONERIS report show that already in 1880, the total population in the Elbe catchment (15.5 million) was almost as big as in the Rhine catchment at that moment (17.8 million). In contrast, the current population in the Rhine catchment (~60 million[2]) is more than twice as big as in the Elbe catchment (24.4 million[3]). The fact that in 1880 the Elbe catchment contained a relatively large population may explain why the Elbe plume stands out when compared to the current situation, but it does not explain why the two scenarios are so very different.

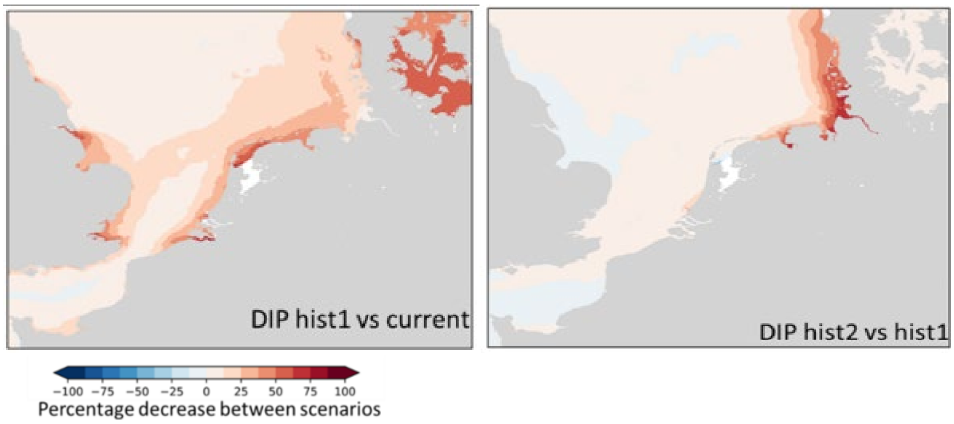

Figure 4.1: Results from the Deltares model for the year 2009, displaying the difference in DIP concentrations between scenario HS1 and the current situation (left panel) and between scenarios HS1 and HS2 (right panel). Red colours indicate concentrations HS1<current concentrations in the left panel; concentrations HS2<HS1 in the right panel. Blue colours indicate the opposite.

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[2] http://nbn-resolving.de/urn:nbn:de:bsz:352-opus-75190
[3] https://en.wikipedia.org/wiki/Elbe

4.4 Differences in TP river concentrations/loads towards the North Sea

The TP river loads in the two scenarios HS1 and HS2 are shown in Figure 4.2, as a percentage of the current loads. Differences between the two scenarios can be found by comparing the two figures. More detailed information on the change in the P loads from scenario HS1 to scenario HS2 is provided in Table 4.1.

The figure and table make clear that, apart from the differences in the Elbe (HS1: 96% to HS2: 26% of current loads), also other river loads show large differences between the two scenarios. This includes other river loads from Germany (e.g. Weser 74% to 24% of current loads), but also river loads from the Netherlands (e.g. Rhine from 72% to 32% of current loads). This suggests that an explanation for these differences is not related to regional phenomena but should be found in more general differences in the model set up.

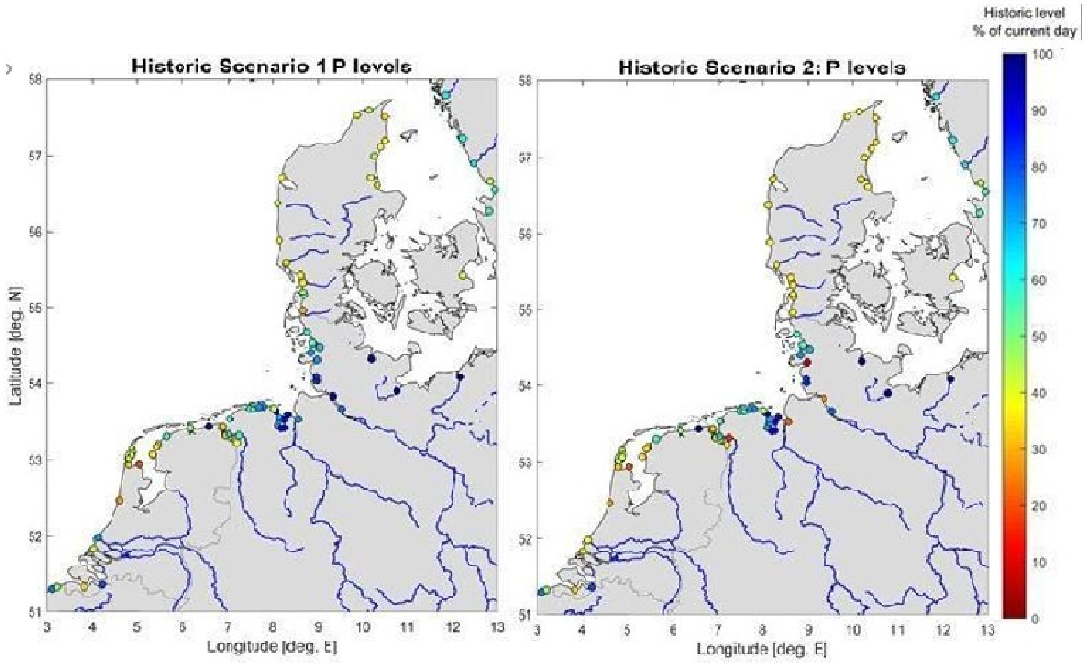

Figure 4.2: Overview of the TP loads in the two pre-eutrophic scenarios as a % of current loads. Source: ICG-EMO 2021

Table 4.1: Estimates of pre-eutrophic condition for a selection of individual rivers for scenario HS1 (TN and TP) and the 2nd scenario HS2 (TP only). When the 2nd scenario has different TP loads (NL, DE, DK), these are highlighted in bold format (source: Lenhart et al. 2022). TN and TP loads show the pre-eutrophic river loads expressed as % of the current (2009-2014) loads.

Contracting Party	**River**	**TN load (%)** Scenario HS1	**TP load (%)** Scenario HS1	**TP load (%) Scenario HS2**
Belgium	IJzer	23	61	61
	Gent-Oostende Canal	17	76	76
	Schipdonk Canal	25	49	49
	Leopold Canal	25	49	49
Denmark	Omme	30	38	**36**
	Skjern	30	38	**36**
	Stora	32	44	**36**
	Vida	30	30	**36**
France	Seine	45	71	71
	Loire	50	92	92
	Garonne	70	74	74
	Dordogne	57	82	82
Germany	Elbe	51	95	**26**
	Ems	26	60	**17**
	Weser	37	74	**24**
	Eider	23	73	**8**
Ireland	Blackwater	35	55	55
	Suir	34	57	57
	Barrow	34	57	57
	Boyne	31	50	50
Netherlands	Meuse	38	44	**32**
	Rhine	43	72	**32**
	Lake IJssel East	22	34	**33**
	Lake IJssel West	21	21	**33**
	North Sea Canal	30	27	27
	Schelde	46	81	81
Norway	Glomma	44	50	50
	Skien	47	76	76
	Otra	48	91	91
	Kvina	37	80	80
Spain	Deba	44	34	34
	Oiartzun	31	21	21
	Urola	44	34	34
	Urumea	31	21	21
Sweden	Gota alv	56	62	62
	Lagan	48	57	57
	Nissan	48	45	45
	Atran	48	66	66
United Kingdom	Tweed	56	83	83
	Humber	34	33	33
	Thames	35	38	38
	Tay	63	100	100

4.5 Differences in model set up of the pre-eutrophic scenarios (focus, concepts, assumptions and values)

Per capita P production and atmospheric deposition

A comparison between the model set ups for HS1 and HS2 has been carried out by UBA (pers. comm. Julian Mönnich and Wera Leujak, 2021). They found two main differences between the models (see Table 4.2) but could not compare all assumptions between the two models because information on many of the E-HYPE assumptions was not available.

The first main difference found by UBA concerned the per capita P production, which in MONERIS ranged from 1-1.5 g P capita^{-1} day^{-1}, while in E-HYPE it was set to a value of 1 gP capita^{-1} day^{-1}. The estimated emission for the Netherlands is 1.34 g P capita^{-1} day^{-1} (data CBS). The second main difference concerned the atmospheric deposition, which in MONERIS ranged from 5-50 kg km^{-2}, while in E-HYPE it was not considered at all. Both differences would however lead to *higher* nutrient loads in MONERIS than in E-HYPE, and thus do not explain why it is E-HYPE that has the higher P-loads in NL and GE (not in 3 out of 4 in DK) except for Lake IJssel East/West.

Table 4.2: main differences between E-HYPE and MONERIS as found by UBA

Input pathway	Assumption MONERIS 1800s	Assumption EHYPE 1990s	Observed differences MONERIS vs. EHYPE
Sewage system and sewage treatment plants	The information about the connection rate to the sewage system and sewage treatment plants was adopted from Gadegast et al. 2014.	Per-capita production: 1 g P/(capita day) 5.5 g N/(capita day) based on Schmidt 2000 and Smil 2000.	MONERIS: 1-1.5 g P/(capita day) 10-15 g N/(capita day) EHYPE: 1 g P/(capita day) 5.5 g N/(capita day) **Difference:** **0-0.5 g P/(capita day)** **4.5-9.5 g N/(capita day)**
Atmospheric deposition	The current value for the deposition of TP varies between 5 and 40 kg/km²/a in Northern Europe (Ruoho-Airola et al. 2012) and between 5 and 50 kg/km²/a in the whole of Europe (EEA 2005). Like nitrogen oxides (NOx), the deposition of phosphorus is strongly influenced by combustion processes. From 1880 to 1980 the NOx deposition in the North Sea catchment area increases from 85 to 1130 kg/km²/a and decreases to 674 kg/km²/a by the year 2000.	Atmospheric N deposition reduced to 1/3 of current levels, according to Engardt et al. (2017). P deposition not considered in EHYPE.	MONERIS: TP deposition 5-50 kg/km²/a EHYPE: P deposition not considered **Difference:** **TP deposition 5-50 kg/km2/a**

Simulated year
The two scenarios focus on different years. For HS1 (E-HYPE) the year 1900 was used as a reference year representing natural background concentrations. According to Lenhart *et al.* (2022), it represents a period before industrialization and agricultural intensification and before the establishment of the Haber-Bosch process (industrial production of inorganic nitrogen fertilizer, 1913).

For HS2 (MONERIS), the year 1880 was used as a reference year. Gadegast & Venohr (2015) do not discuss why the year 1880 is chosen, but they cite EC (2000) (WFD) which states that the reference conditions for nutrients in surface waters correspond to high ecological status and contain only very minor disturbing human influences with no or very little ecological effects. However, when discussing the model results, Gadegast & Venohr (2015) make a comparison to the literature review of Topcu *et al.* (2011) regarding the nutrient concentrations of the inflows into the German Bight under undisturbed or original conditions. They state that the values calculated around 1880 are many times higher than those of Topcu *et al.* (2011) and conclude that this supports the assumption that the results of the nutrient calculations for the North Sea catchment area around 1880 do not correspond to the (almost) undisturbed conditions of a river, but describe an early industrial state due to anthropogenic influences.

Although different years are used, there is no fundamental difference between the historic scenarios: both HS1 and HS2 consider the pre-eutrophic scenario at an early industrial state with small anthropogenic influences.

Population density
In HS2 (MONERIS), data on the total population, population in cities with 10,000 inhabitants or more and land use, are based on official state statistics in the North Sea catchment area around 1880 (Gadegast & Venohr 2015). A digital map of the regions of Europe around 1900 provided by the Mosaic Project (Historical GIS Data) was used for the transmission of the historical statistical data. The total population in the catchment area of the North Sea around 1880 was approx. 45 million inhabitants (2005: 104 million) with an average population density of 103 inhabitants/km² (2005: 239 inhabitants/km²).
In HS1 (E-HYPE), HYDE data on urban and rural population in 1900 was used to estimate the number of people living in urban and rural settings in each catchment (Klein Goldewijk *et al.* 2011). However, the paper provides data on the total population in Europe (300 million) but we could not retrieve the population numbers for the North Sea river catchments. Hence, we cannot confirm or refute that differences in assumed population densities may have caused the differences between model results of HS1 and HS2.

4.6 Historic data on nutrient concentrations in the river Rhine

A comparison of the estimates in the two scenarios with data on historic nutrient concentrations is useful for an evaluation. There are very limited data available for the period before World War II. Several scientific publications (e.g. Van Bennekom *et al.* 1975, Laane 1992, Van Raaphorst *et al.* 2000, van Raaphorst & de Jonge 2004), all referring to the same, limited number of data sources, provide estimates of background nutrient concentrations. The data show limited differences in TP and TN between the 19th century and early 20th century (Van Bennekom *et al.* 1975, Van Bennekom & Wetsteijn 1990, van Raaphorst & de Jonge 2004).
Laane (1992), Laane *et al.* (2005) and Topcu *et al.* (2011) give summaries of estimated natural background concentrations. There is a large range of values for the estimates of natural background concentrations, as there are many geochemical, hydrological and biological processes that influence those concentrations.

For the Rhine, several Dutch studies gave estimates of approximately 0.06 mg/l TP and 0.6 mg/l TN (Laane 1992, Van Raaphorst *et al.* 2000). In the two scenarios, annual average TP concentrations in the Rhine are 0.06 mg/l (HS1) and 0.03 mg/l (HS2), which indicates that the TP concentrations in HS2 are about a factor 2 lower than published estimates of natural background concentrations. For TN, the concentration in both scenarios is 1.09 mg/l, which is 1.8 times higher than the estimated natural background concentrations.

4.7 Conclusions

The differences in P loads between HS1 and HS2 lead to differences in modelled DIP concentrations in the North Sea, especially in the Elbe plume. Closer examination of the model results however shows that also large differences exist in the river loads of other (Dutch and German) rivers. This suggests that the difference lies in a general aspect of the model set up, instead of in a local/regional issue.

When looking into the model set up, it turns out to be difficult to find out what is causing the differences in model results between HS1 and HS2.

UBA did a comparison between the two model set ups, but could not compare all assumptions between the two models because they could not get information on many of the EHYPE assumptions. The two main differences that they found concerned the per capita P production and the atmospheric N deposition. Both differences would however lead to *higher* nutrient loads in MONERIS than in E-HYPE, and thus do not explain why it is E-HYPE that has the higher P-loads in most German and Dutch rivers.

A possible explanation for the differences in model results lies in their assumed population density, if only because MONERIS focuses on the year 1880 and E-HYPE on the year 1900. However, this hypothesis could not be confirmed because the population density used in E-HYPE could not be retrieved on basis of the available documents.

Although they are using different years, there is no fundamental or conceptual difference between the pre-eutrophic scenarios: both HS1 and HS2 consider the scenario as an early industrial state with minor anthropogenic influences.

TP concentrations in scenario HS2 are a factor 2 lower than literature values for natural background concentrations in the Rhine. This seems unrealistic and for this reason the Netherlands chose HS1 as the preferred scenario.

5 Effect of riverine nutrient loads on near-bottom oxygen concentrations in the North Sea

Oxygen is a prerequisite for life in ecosystems. In aquatic ecosystems, oxygen diffuses from the atmosphere or is produced during photosynthesis (Diaz, 2001). Through mixing processes, the whole water column is oxygenated. However, waters can become oxygen depleted when the supply of oxygen is too low and/or the rate of oxygen consumption is too high (see reviews by Diaz & Rosenberg (2008); Middelburg & Levin (2009)). The regional sea conventions for the Northeast Atlantic and the Baltic Sea (OSPAR and HELCOM) defined dissolved oxygen (DO) concentrations under 2 mg l^{-1} to be acutely lethal and concentrations between 2-6 mg l^{-1} as oxygen deficient (OSPAR Commission, 2017).

In systems such as the North Sea, oxygen depletion can occur during summer stratification when the thermocline isolates the bottom mixed layer (BML) from the surface mixed layer (SML) and the spring bloom in the SML and the deep chlorophyll maximum at the thermocline provide ample organic matter for degradation (Peeters et al., 1995; Topcu & Brockmann, 2015; Weston et al., 2008). Oxygen depleted waters can result in a decrease of biodiversity, a decrease in fisheries catch and an increase in species mortality (e.g., Dethlefsen & von Westernhagen (1983) and review by Díaz & Rosenberg (2011)).

In a model study by Grosse *et al.* 2017 the influence of nitrogen inputs (riverine loads, atmospheric deposition, Atlantic Ocean inputs) on the oxygen dynamics in the southern North Sea was studied. Figure 5.1 (modified from Große et al. (2017)) displays the simulated minimum bottom O_2 concentrations for the North Sea averaged over a 10 year time period (2004 to 2014). In terms of oxygen dynamics, Große et al. (2016) determined three different zones for the North Sea. Zone A occurs along the continental coast and is a highly productive, non-stratified coastal zone that is not prone to oxygen depletion due to strong tidal mixing (Große et al., 2017). Zone B occurs in the central southern North Sea and is a productive, seasonally stratified zone with a small sub-thermocline volume. Zone B is prone to oxygen depletion (Große et al., 2016). Zone B is located between 54.5-56.5 °N and 4-7.5 °E. Oyster Grounds and Dogger Bank lie in that zone and quite some publications deal with the oxygen dynamics at those locations (Greenwood et al., 2010; Peeters et al., 1995; Queste et al., 2016). Zone C comprises the area of the deep Northern North Sea which is less productive and seasonally stratified with a large sub-thermocline volume. Due to its depth, less organic matter reaches the bottom resulting in less oxygen depletion (Große et al., 2017) and thus zone C is not prone to oxygen depletion.

Große et al. (2016) used (model) data on stratification (duration and intensity), depth and nutrient availability to define the three different zones of oxygen dynamics in the North Sea. Those three parameters (stratification, depth and nutrient availability) are the three most important drivers of O_2 dynamics in the North Sea. Of those three drivers, nutrient availability is the only one that can be directly influenced by ecosystem management.

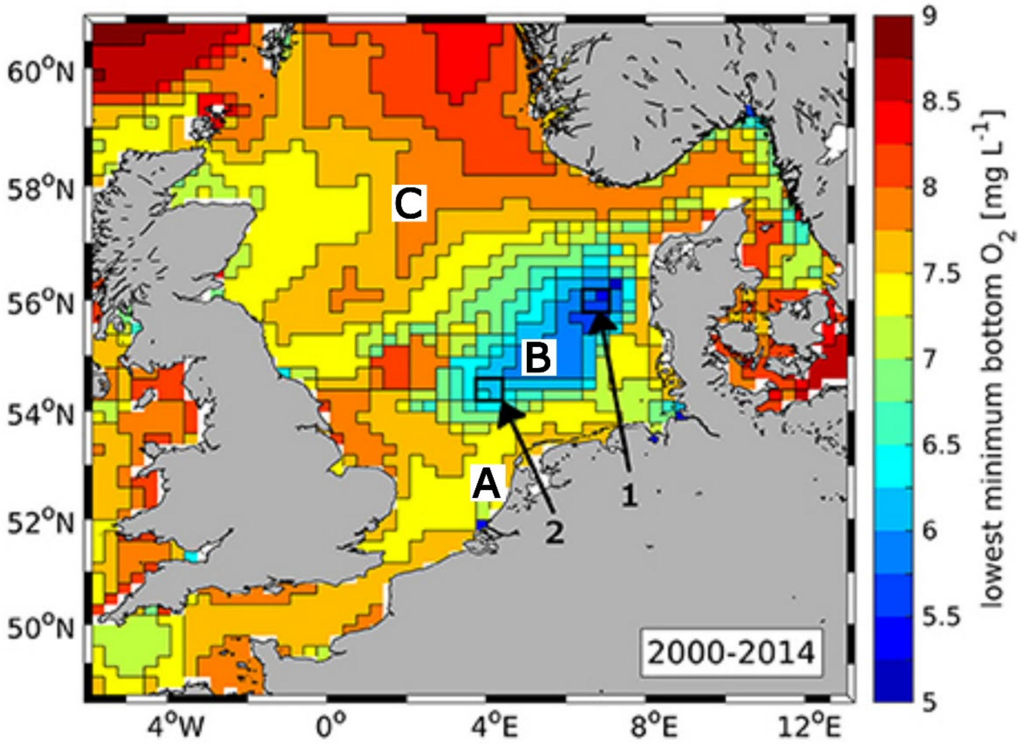

Figure 5.1 Spatial distribution of lowest simulated O_2 concentrations averaged over a 10 year period (2004-2014). Boxes 1 and 2 indicate regions used by Große et al. (2017) for time series, which are shown in the following section. Letters A, B and C denote the different zones of oxygen dynamics in the North Sea derived from Große et al. (2016). Adapted and modified from Große et al. (2017) under CC BY 4.0

5.1 Nutrient availability as a driver for oxygen dynamics

5.1.1 Literature review

The concentration of winter nutrients determines the magnitude of the spring bloom. The larger the initial concentration of nutrients, the larger the bloom will be (under non-light limiting conditions). Once the spring bloom dies off, the organic matter sinks to the bottom and is remineralized which consumes oxygen (Greenwood et al., 2010). Thus, the availability of nutrients affects the depletion of oxygen in the BML. Due to this important link between nutrient availability and oxygen depletion, OSPAR determined oxygen depletion to be a Category III indirect effect of nutrient enrichment (OSPAR Commission, 2017).

The nutrient sources for the North Sea differ per region. Figure 5.2 (from Große et al. (2017)) illustrates the contribution of nitrogen from the different national rivers and the North Atlantic to the gross oxygen consumption of the North Sea. North of Dogger Bank (see Figure 5.2D) most of the nutrients originate from the North Atlantic inflow (Greenwood et al., 2010; Große et al., 2016; Thomas et al., 2005). South of the Dogger Bank (see Figure 5.2 A, B and C), the riverine inputs from the continental coasts and the Southern Bight provide the bulk of the nutrients (Greenwood et al., 2010; Große et al., 2016). The area of the North Sea that is most prone to oxygen depletion (Zone B determined by Große et al. (2017)) lies within the region of influence of riverine nutrients supplied by Germany, the Netherlands and the UK. The authors estimated the contribution of various nutrient sources to net primary production and, consequently, oxygen consumption caused by the degradation of the organic matter produced by phytoplankton growth. For region 1 in zone B (see Figure 5.1) Große et al. (2017) determined that riverine nutrient loads, mainly from Dutch, German and British rivers are the cause of 39%

of the total annual oxygen consumption in that area, while for region 2 in zone B (see Figure 5.1), located at the Oyster Grounds, the contribution of rivers is 40 %. This is similar to the contribution of the North Atlantic which is 39 %.

Figure 5.3 by Große et al. (2017) shows the contribution of the different nutrient sources to the gross oxygen consumption for region 1 of zone B over the 10 year model period 2004-2014. The higher the gross oxygen consumption, the lower the oxygen concentrations at the bottom under sufficiently long stratified conditions (Große et al., 2017). In the years 2002 and 2011, the contribution of riverine input was particularly high due to the intense Elbe floods that occurred in those years. This additional input of riverine nutrients from the German rivers leads to a high gross oxygen consumption. This illustrates the importance of decreasing anthropogenic nutrient loads, especially nitrogen, to combat hypoxia in the North Sea.

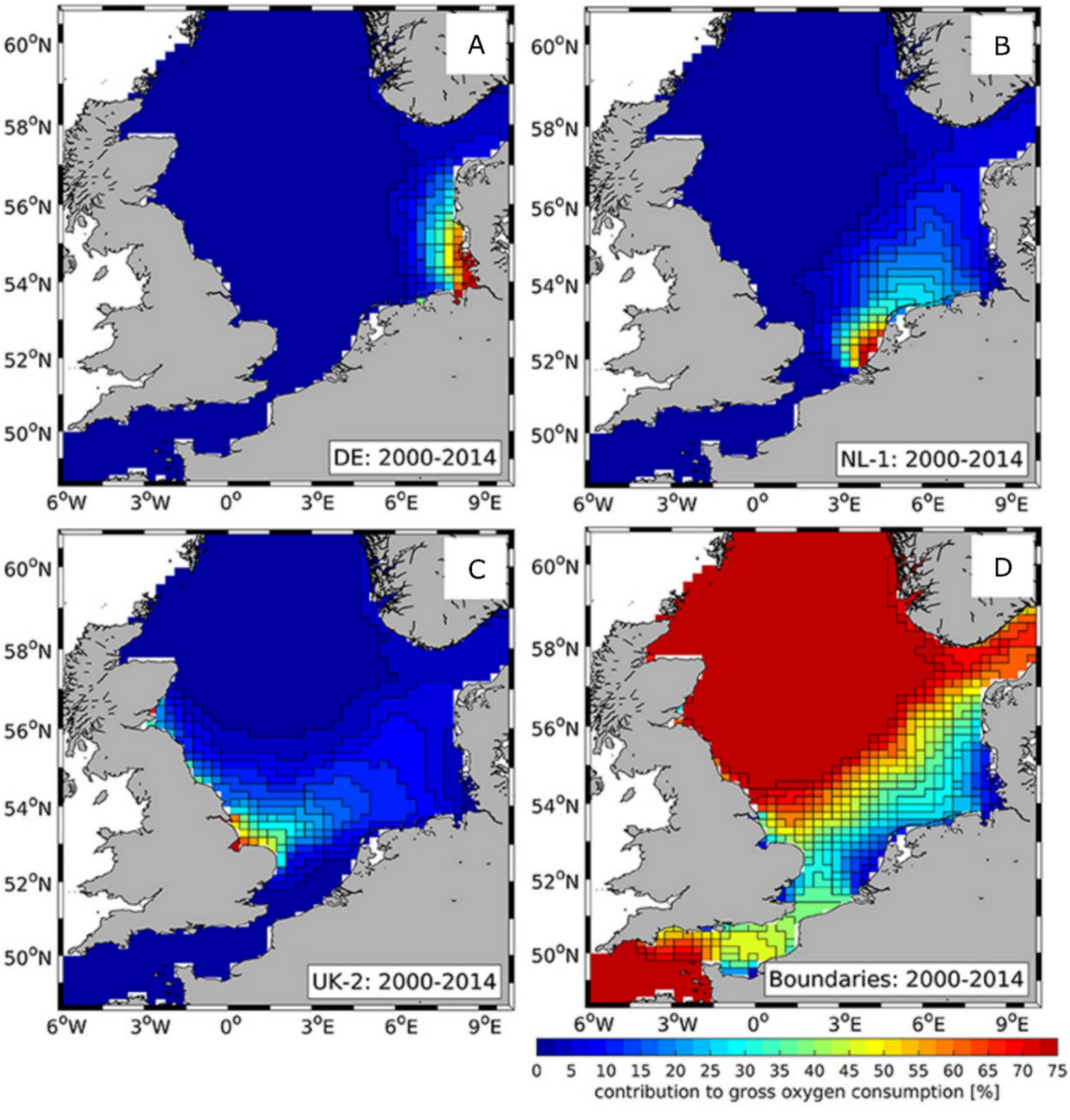

Figure 5.2 Spatial distribution of the relative contributions due to N from the different sources during 2000-2014. A) German rivers, B) Dutch river group 1, C) UK river group 2 and D) boundaries from the North Atlantic, English Channel and the Baltic Sea. For more information on the different sources, please see table 1 in Große et al. (2017). Adapted and modified from Große et al. (2017) under CC BY 4.0

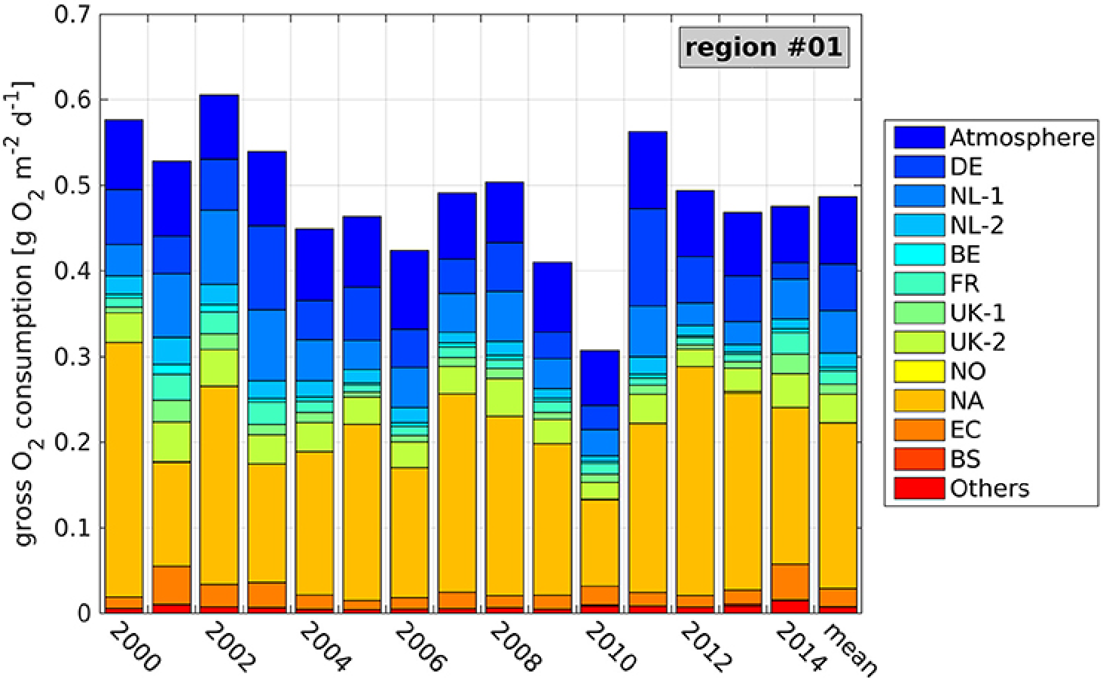

Figure 5.3 Averaged daily, near-bottom, gross O_2 consumption during seasonal stratification and the contributions of the different N sources for region 1 (see Figure 5.1) for the years 2000-2014. DE: Germany, NL-1, NL-2: Dutch rivers, BE: Belgium, FR: France, UK-1, UK-2: British rivers, NO: Norwegian rivers; NA: North Atlantic; EC: English Channel, BS: Baltic Sea. For more information on the different sources, see table 1 in Große et al. (2017). From Große et al. (2017) under CC BY 4.0

5.1.2 Model scenario comparisons

Model studies (e.g. Troost & Los 2014, Lenhart & Große 2018, Lenhart *et al.* 2022) show that reductions in riverine nutrient loads will have an impact on nutrient levels and on chlorophyll levels, particularly in the coastal waters of the North Sea. This decrease in chlorophyll-a concentrations in turn can have a positive effect on the oxygen dynamics in the North Sea. Decreasing the anthropogenic input to riverine and atmospheric nutrient loads can have a relevant positive effect on the O_2 levels in the southern North Sea (Greenwood et al., 2010; Große et al., 2017; Lenhart & Große, 2018).

To test whether a decrease in riverine nutrient loads influences the near-bottom oxygen levels of the North Sea, three model scenarios were compared. For the model scenario “current state” the current (2009-2014) riverine nutrient loads were used. For the historic reference scenarios HS1 and HS2 the riverine nutrient loads were decreased as shown in Table 4.1, atmospheric deposition was reduced (Lenhart *et al.* 2022), while all other factors (like weather and hydrodynamic conditions) were kept the same as in the current state model run. For this analysis we compared the scenarios using the modelled time series of oxygen dynamics and looking at the relative change in oxygen concentrations, minimum oxygen concentrations and duration of oxygen depletion.

5.1.2.1 Near-bottom oxygen concentrations

Figure 5.4 shows yearly averaged maps of the bottom oxygen concentrations for the current model scenario (left column) as well as maps of the relative difference in bottom oxygen concentrations between the current state and HS1 model scenario. The difference between the current state and HS2 model scenario is not shown here. The results for Scenario HS2 are nearly identical to those of Scenario HS1 as differences in nutrient and chlorophyll concentrations in the offshore areas are small. The left column of Figure 5.4 shows that the minimum oxygen concentrations for the current state model scenario occur in the central North Sea (as would be expected from literature). The extent of these minimum concentrations varies between years. The right column of Figure 5.4 shows that in zone B described in Figure 5.1 the minimum bottom oxygen concentrations in the current state model scenario are on average 10-30 % lower compared to the HS1 scenario.

Figure 5.5 visualizes the near-bottom oxygen concentrations for the stations Terschelling 4, 100, 135 and 175 for the three different model scenarios. The difference between the historic and the current scenarios is most pronounced at the stations Terschelling 100, 135 and 175. Compared to station Terschelling 4, the other stations are located further offshore and in the zone that is most prone to summer oxygen depletion due to stratification. Figure 5.5 also clearly shows that the difference between current state and the historic reference scenarios is larger than the difference between the two reference scenarios.

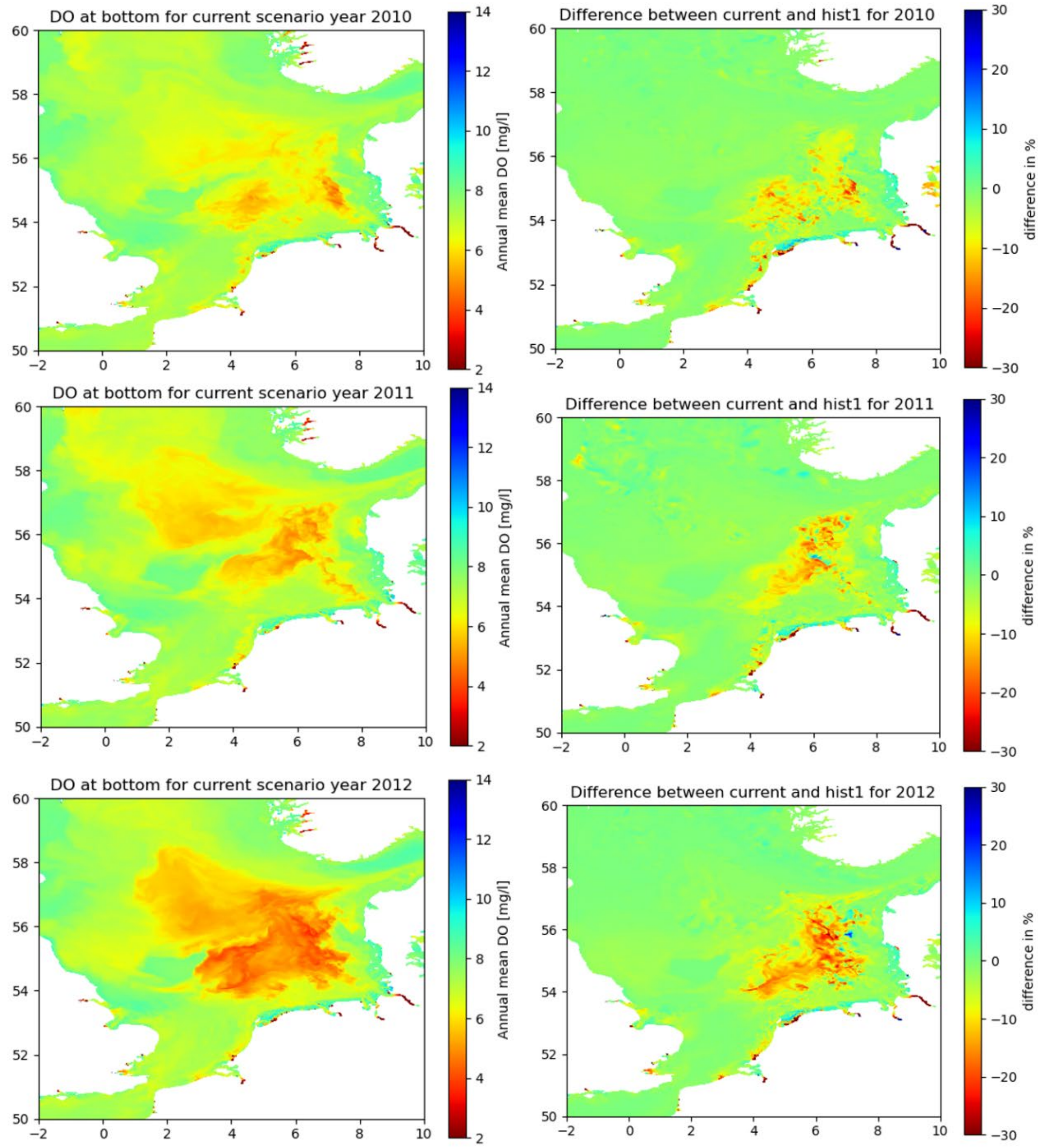

Figure 5.4 Maps visualizing the annual-mean near-bottom oxygen concentrations in the current state (left column) and the relative difference between the current state and HS1 scenario (right column) for the years 2009, 2010, 2011. Red colors indicate lower concentrations in the current state compared to the reference HS1. Blue colors indicate higher concentrations in the current state.

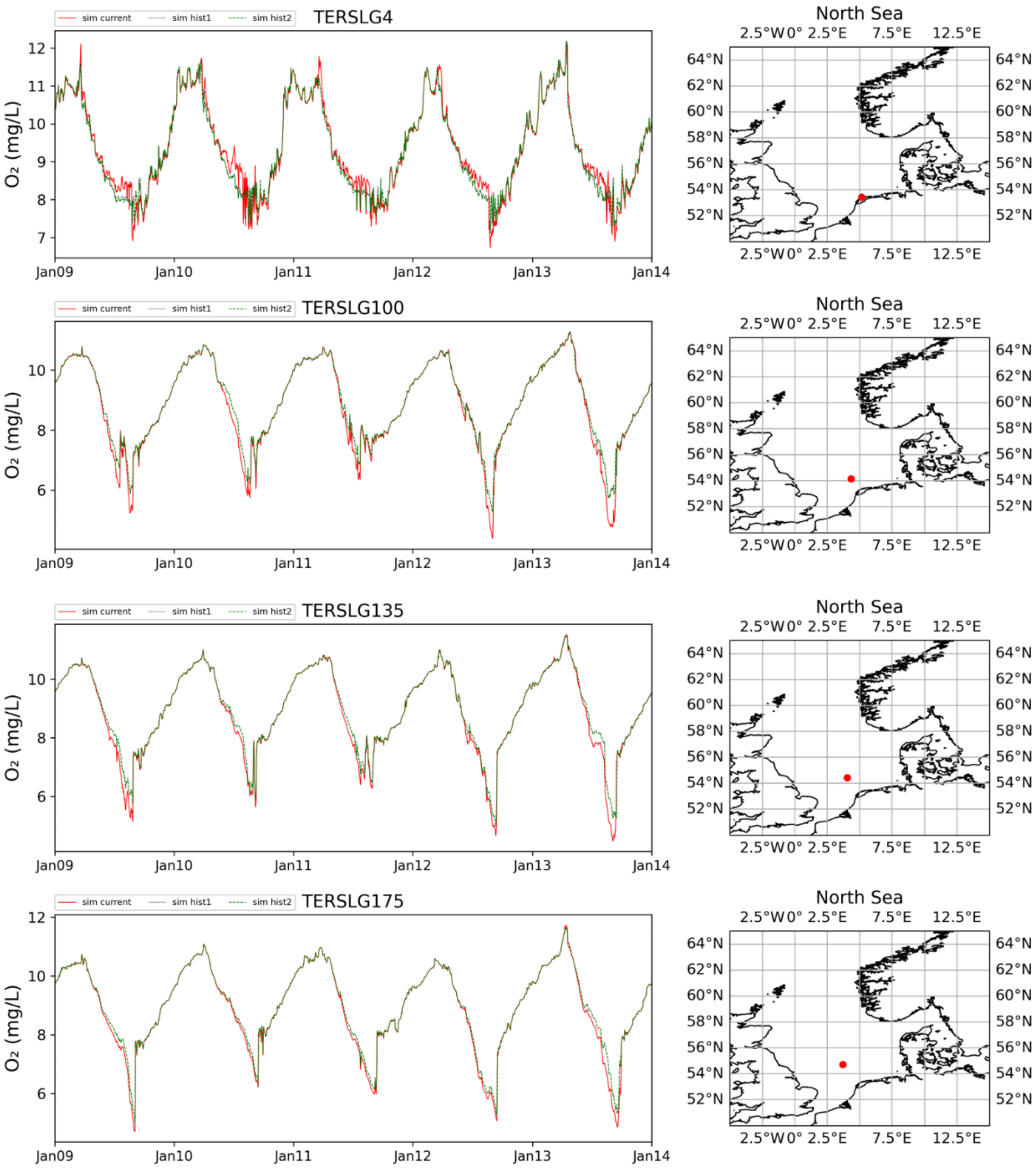

Figure 5.5 Five year time series of near-bottom oxygen concentrations at the stations Terschelling 4, 100, 135, 175 km off the coast for the current state scenario (red), HS1 scenario (black) and HS2 scenario (green).

5.1.2.2 Minimum oxygen concentrations

Figure 5.6 shows the minimum bottom oxygen concentrations for the stations Terschelling 100, 135 and 175 for each year and model scenario. These three stations in the Oyster Ground area were selected as these are the stations that are most sensitive to oxygen depletion.
For all years and stations the minimum bottom oxygen concentrations are the lowest in the current state scenario. The minimum bottom oxygen concentrations do not differ between the two historic reference scenarios.

5.1.2.3 Duration of reduced oxygen concentrations

Figure 5.7 shows the duration of the period with bottom oxygen conditions lower than 6 mg l^{-1} for the stations Terschelling 100, 135 and 175, for each year and model scenario.

For all years and stations the duration of reduced bottom oxygen conditions is the longest in the current state. With the exception of 2013 for Terschelling 100, the duration of reduced bottom oxygen conditions does not differ between the two historic references.
The difference between years, with longest duration of the period with oxygen concentrations below 6 mg/l in the years 2012 and 2013, illustrate the effect of physical factors such as stratification and weather conditions, in addition to the effects of nutrient loading.

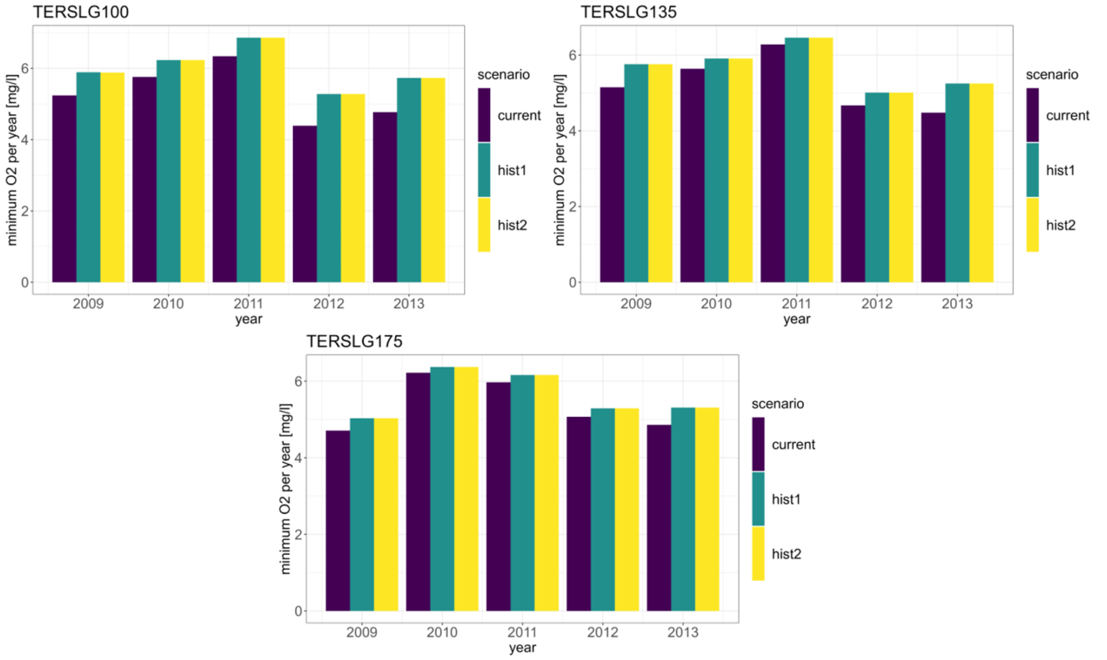

Figure 5.6 Bar charts of the minimum near-bottom oxygen concentration per year and per model scenario for the stations Terschelling 100, 135 and 175.

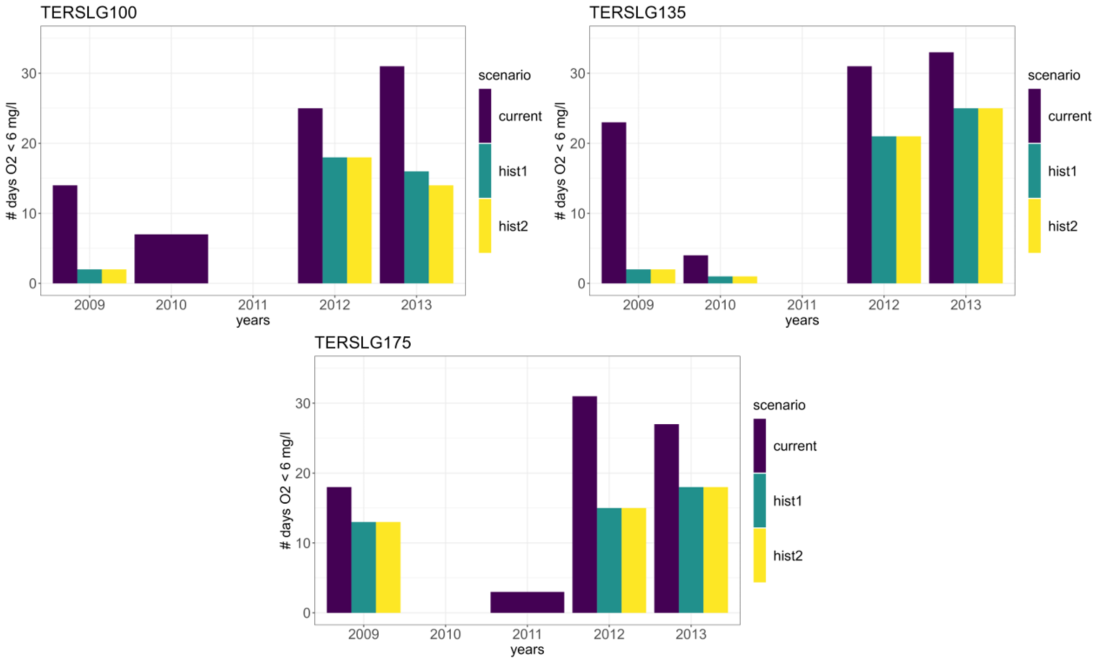

Figure 5.7 Bar charts of the duration of reduced oxygen conditions (<6 mg/l) per year and model scenario, for the stations Terschelling 100, 135 and 175.

Table 5.1 summarizes the results, showing the average and maximum duration of the occurrence of oxygen concentrations below 6 mg/l in the current state and in scenario HS1. The results show that the reduced riverine nitrogen loads in scenario HS1 (compared to current state) result in a shorter duration of the period with reduced oxygen concentrations. However, also in the reference scenario periods with reduced oxygen concentration occur. This again points at the fact that reduced oxygen concentrations are the combined effect of riverine nutrient loads and physical factors (weather conditions, stratification). Reducing nutrient loads will not entirely prevent the occurrence of reduced oxygen concentrations, but it will reduce the duration of the period with low oxygen.

Table 5.1 The average and maximum number of days per year with oxygen concentrations <6 mg/l, for the Terschelling stations in the current state scenario and in the historic reference scenario HS1.

	current state		**HS1**	
	average	maximum	average	maximum
Terschelling 70	4	12	0	0
Terschelling 100	14	30	6	16
Terschelling 135	17	32	9	24
Terschelling 175	14	28	9	17
Terschelling 235	0	1	0	1

5.2 Conclusion

The model scenarios show that decreasing riverine nutrient concentrations has a positive effect on the oxygen dynamics and concentrations at the Oyster Grounds. This is in line with literature reviewed in this section. The model scenarios also show that the difference between historic scenario 1 and historic scenario 2 is very small, as the differences in nutrient and chlorophyll concentrations between HS1 and HS2 at the Oyster Grounds are very small as well.

6 Discussion

OSPAR has agreed on new threshold values for nutrients and chlorophyll that are applied in the eutrophication assessment in the 4th application of the Comprehensive Procedure (COMP4). This report addresses the questions on the potential implications of those new thresholds for the need for reduction of riverine nutrient loads and hence, the need for further emission reduction in the catchment areas.

A linear regression of chlorophyll concentrations against riverine nitrogen loads was done for four MWTL monitoring stations and for the Rhine plume assessment area. Based on this regression, it was assumed that a further reduction of nitrogen loads is required to achieve good status for chlorophyll. The estimates for the required reduction show a considerable range. To arrive at a maximum allowable load, the average estimated necessary reduction in TN loads is 18-20% of current loads. This load reduction was translated into a nutrient concentration threshold for the rivers, using the average water discharge volume. A threshold for nutrient concentrations is probably easier in terms of monitoring and assessment. However, in terms of ecosystem response it is more logical to set a threshold for the load as it is the loads that are determining the nutrient enrichment of the coastal waters. With a fixed threshold for concentrations, loads will vary with variations in water discharge, .and years may occur where concentrations do not exceed threshold concentrations whereas loads are higher than the maximum allowable load.

In an application of the Deltares model Delft3D GEM the effects of a 25% reduction of riverine TN loads from Meuse and Rhine on nutrient and chlorophyll concentrations in the Dutch part of the North Sea were calculated. The results were compared to results from a previous model application in the framework of OSPAR ICG EMO. The results show that a 25% reduction of riverine TN loads leads to a proportional reduction in DIN concentrations in the areas near the river discharge points (WFD coastal water bodies and COMP4 river plumes) and no reductions in offshore areas with limited freshwater influence, like the Dogger Bank or areas with limited influence from Meuse and Rhine, like the Eastern North Sea.

The response of chlorophyll concentrations to a reduction in nitrogen loads is much smaller than the DIN reduction, with a 3-7% reduction in water bodies and river plumes. The explanation for the more limited response of chlorophyll is the fact that phytoplankton growth in Dutch coastal waters in the model is influenced by light conditions, P-limitation and possibly shellfish grazing, which consequently leads to a limited effect of changes in N loads. It is likely that this is not simply a model artefact as observations also indicate that light limitation determines the timing of the spring bloom and P-limitation is an important factor during the spring bloom in the coastal stretch of the Dutch North Sea whereas N-limitation prevails in offshore waters (see e.g. Peeters & Peperzak 1990, De Vries *et al.* 1998, Loebl *et al.* 2009, Burson *et al.* 2016).

A preliminary analysis of monitoring data supports the notion of a complex interaction of multiple limiting factors with differences between different parts of the coastal and marine waters. Appendix E shows the seasonal pattern in the concentrations of DIP, DIN, silicate and chlorophyll for a selection of monitoring stations: Noordwijk 2 and Noordwijk 20 in the coast to offshore transect downstream from the Meuse/Rhine discharges, Doove Balg west in the western part of the Dutch Wadden Sea and Dantziggat in the eastern part of the Dutch Wadden Sea. All stations show roughly a similar seasonal pattern: with the onset of the phytoplankton spring bloom DIP and silicate concentrations decrease sharply. DIP concentrations start to increase again after spring, due to remobilization of phosphate in marine sediments. DIN concentrations decrease more gradually towards a minimum in summer. The seasonal pattern in concentrations and in N:P ratios point towards a tendency for P- and/or Si-limitation in spring/early summer and N- and/or Si-limitation during summer. The eastern Wadden Sea shows an earlier drop in DIN concentrations and N:P ratios, which suggests that N-limitation could be more dominant than at the other sites. This may be an explanation for the stronger response of chlorophyll to the 25% nitrogen load reduction in §2.4. The comparison between decades shows clearly lower DIP concentrations after 2000 at the Noordwijk transect and a more gradual decline in DIN concentrations. This may have resulted in a stronger P-limitation, although chlorophyll concentrations do not show a difference between 1990-1999 and 2000-2009. In the western Dutch Wadden Sea, DIP concentrations are clearly lower after 2010 but show significant sediment release after May. While there are indications for P-limitation during spring in the western Wadden Sea and coastal North Sea (Peeters & Peperzak 1990, De Vries *et al.* 1998, Ly *et al.* 2014, Burson *et al.* 2016), P recycling may be a significant source of regenerated P and reduce the effect of P-limitation in shallow waters (Leote *et al.* 2016). This also stresses the need to improve model performance with respect to P release from the sediment. Some efforts for model improvement of sediment P-release have been done in the Interreg project Water quality Wadden Sea[4], but this could not yet be implemented in the Deltares model.

The observed correlations of chlorophyll concentrations with riverine nitrogen loads are stronger than correlations with riverine phosphorus loads, suggesting a stronger influence of N-loads on chlorophyll. Most probably, in addition to light limitation both P- and N-limitation play a role, with P-limitation mainly occurring during the spring bloom and N-limitation occurring during summer and a decreasing coastal-offshore gradient in P-limitation and an increasing gradient in N-limitation.

The results indicate that there is considerable uncertainty about the magnitude of the effect of reducing N loads on the reduction of chlorophyll concentrations at sea. The question could be raised if it would be more efficient to reduce P loads? Phosphate concentrations in the Rhine are already near background values, as discussed in Chapter 4, so a further reduction of P loads would require a large effort. In addition, further reduction of P loads would result in a larger surplus of N further offshore, potentially enhancing eutrophication problems in those areas.

The results should be considered as a first estimate of the effects of nitrogen load reductions. Only reductions in the Meuse and Rhine riverine loads were considered and a more extensive analysis of monitoring data and of the model response would be necessary to improve our understanding of the response of phytoplankton concentrations in coastal and marine waters to nutrient load reductions.

Source apportionment of the riverine nutrient loads to the North Sea shows that transboundary transport (import from Germany via the Rhine) has the largest contribution to the nutrient loads through Rhine and Meuse to the sea. Other important sources are agriculture (in the Dutch part of the river basins) and transboundary transport through the Meuse. The total effect of the foreseen measures to reduce nutrient emissions is approximately 4% reduction in riverine nitrogen loads and 3% reduction in riverine phosphorus loads. This limited effect is to a large extent due to the fact that transboundary transport through the Rhine is a major source and the present assumption is that this load will not decrease.

In the model studies to develop the new COMP4 thresholds, two historic (pre-eutrophic) scenarios were used. A comparison of the assumptions underlying the two pre-eutrophic

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[4] https://deutschland-nederland.eu/nl/project/wasserqualitaet-waterkwaliteit-2/

scenarios HS1 (based on E-HYPE) and HS2 (based on Moneris) was made. Based on the available information, no fundamental conceptual differences between both approaches was found. Differences between the models (in particular in the estimates of P loads) cannot be explained from differences in model setup, but detailed information on the models is not available. A comparison with observations in the Rhine, shows that the concentrations in scenario HS2 are lower than concentrations assumed to represent natural background values.

The model result from the ICG EMO application was used to analyze the effects of riverine nutrient loads on oxygen conditions in parts of the North Sea. Some parts of the North Sea, in particular the Oyster Grounds, are sensitive to oxygen depletion due to a combination of physical factors like stratification, a relatively small volume below the pycnocline and organic matter supply caused by primary production driven by nitrogen loads. Reducing riverine nutrient loads will reduce the duration of the period with lower oxygen concentrations, but it will not entirely prevent those events. Recent model applications show that those areas that already experience occasional oxygen depletion such as the Oyster Grounds and eastern North Sea may have extended periods of stratification and oxygen depletion in the future, as a consequence of climate change (Wakelin *et al.* 2020). Reducing nitrogen loads would therefore reduce the risk of oxygen depletion.

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A Water Framework Directive Explorer

The WFD Explorer is a lumped, steady state catchment water quality model comprising of three building blocks:

- Hydrology module (water balance);
- Water quality module (substance balance);
- Ecological module (which is not used in this project).

The WFD Explorer is developed as an analytical tool to support the implementation of the Water Framework Directive (WFD). With this tool users can gain insight in the effectiveness of programmes of measures in relation to WFD objectives by calculating the effects of restoration and mitigation measures on the chemical and ecological quality of surface waters. Measures can be defined in relation to both point sources, such as wastewater treatment plants (WWTPs), and diffuse sources, such as agriculture and traffic. Likewise, it is possible to calculate the effectiveness of restoration measures such as stream re-meandering or the construction of near-natural riparian zones.

The WFD Explorer can be applied on both national as well as regional scales. It has a user-friendly interface which makes it easy to set up a model structure and perform analyses. Users can easily import or adjust a river basin schematization, emission data and area specific characteristics.

A.1 Modules and processes

The three main building blocks of the WFD Explorer can be used either concurrently or as stand-alone modules (Figure A1). The Hydrology module routes the water through the nodal network using the forcing flows from sinks and sources such as waste water treatment plants, industry, border-crossing streams, etc. as main input. Water quality is subsequently calculated using the flows from the Hydrology module, forcing loads on the nodes, and substance-related retention coefficients. The applied retention coefficients are generally generic in space and time. At present, coefficients are used for the Pleistocene and the Holocene parts of the Netherlands and split up for the summer and winter half years. The Ecology module provides an ecological score per identified water body usually made up of one or more nodes.

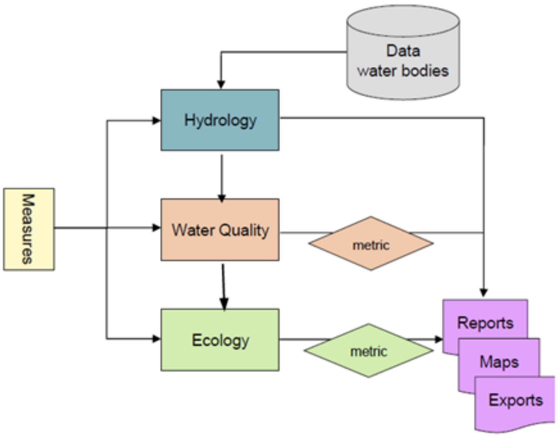

Figure A1 Schematic overview of the WFD Explorer.

A.2 Input data

For the national set up of the WFD Explorer model, the hydrology is derived from the Dutch National Hydrological Model and consists of the following inputs:

1 Spatial schematization:
    a Local Surface Waters (LSWs) acting as the principal 2-D rainfall-runoff unit;
    b Distribution Model (DM), a 1-D nodal network for the national waters;
    c District Water (DW) nodes linking the LSWs to the DM nodes;
2 Flow data:
    a Routing distribution fractions per individual node per unit time for the discharge situation;
    b Network routed nodal supplies per unit time (mainly for coping with summer droughts, but also to provide uptake points with enough water);
3 Hydrological forcing:
    a Sink and source flows per node per unit time: drainage, infiltration, water level conservation, industry, agriculture, drinking water, flushing requirements, etc.

To properly represent the local water network and to properly deal with water quality processes (i.e. to prevent excessive numerical dispersion), the WFD Explorer pre-processor converts 2D-LSW data into multiple nodes, one or more for the network and one representing the aggregated water volume within an LSW. Building the network and necessary conversions into WFD Explorer formats are fully supported by a Windows® GUI.

The water quality data consists of the nutrients; total nitrogen and total phosphorus, derived from the following sources:

- Diffuse sources (agriculture) on the LSW aggregation node derived from the ANIMO model (van der Bolt *et al.* 2020);
- Industry and WWTPs on the DM and LSW network nodes derived from the national Emission Registration (ER) database (www.emissieregistratie.nl);
- Wet and dry airborne depositions of nitrogen on all nodes taken from the national Emission Registration (ER) database (www.emissieregistratie.nl).

B Overview total nitrogen and phosphorus emissions in WFD Explorer

	2019 (kton/year)	**2027 (kton/year)**	**Reduction (%)**
Total nitrogen			
Leaching agriculture	43.34	36.22	16.4
Leaching nature	5.09	4.82	5.2
Leaching urban	5.42	5.20	4.1
WWTP	13.65	12.93	5.3
Atmospheric deposition	7.87	7.41	5.9
Runoff from farmyards	0.77	0.45	41.2
Fertilizer spilling into ditches	0.84	0.00	100.0
Greenhouse horticulture	0.49	0.32	33.5
Rainwater sewers	2.19	2.19	0.0
Other emissions	2.94	2.94	0.0
Transboundary transport Ems river	11.26	6.52	42.3[a]
Transboundary transport Meuse river	34.45	33.55	2.6
Transboundary transport Rhine river	205.89	205.89	0.0
Transboundary transport Scheldt river	10.92	11.03	-1.0[b]
Transboundary transport small rivers	35.45	32.89	7.0[a,c]
Total	**380.57**	**362.36**	**5.0**
Total phosphorus			
Leaching agriculture	3.38	3.21	5.2
Leaching nature	0.37	0.37	-0.3
Leaching urban	0.50	0.50	-0.1
WWTP	1.68	1.52	9.7
Runoff from farmyards	0.26	0.15	41.2
Fertilizer spilling into ditches	0.03	0.00	100.0
Greenhouse horticulture	0.06	0.04	33.6
Rainwater sewers	0.35	0.35	0.0
Other emissions	0.31	0.31	0.0
Transboundary transport Ems river	0.23	0.15	32.1[a]
Transboundary transport Meuse river	1.08	1.06	2.3
Transboundary transport Rhine river	4.69	4.46	5.0
Transboundary transport Scheldt river	0.97	1.01	-13.0[b]
Transboundary transport small rivers	2.20	2.33	-6.1[a,c]
Total	**16.11**	**15.46**	**4.0**

[a] Niedersachsen did not deliver expected reduction percentages. In accordance with the *ex ante*, the reductions are calculated based on the assumption that the waterbodies will meet the WFD thresholds.

[b] Flanders is expecting an increase in the nutrient concentrations in the Scheldt river.

[c] An increase in nutrient concentrations is expected for some cross-border waters.

C Source apportionment approach

Figure C1 shows the steps to convert a simple conceptual model with a few nitrogen emissions to a tracer model with tracers per emission source. In this example nitrogen is derived from two sources:

- Agriculture (AGR);
- WWTP.

For each source we create a unique tracer, for example:

- N-AGR;
- N-WWTP.

The original nitrogen emission is subsequently converted to tracer emissions. The sum of the tracer loads in the downstream node equals the nitrogen load. The ratio between the different tracer loads indicates the ratio of the different emission sources.

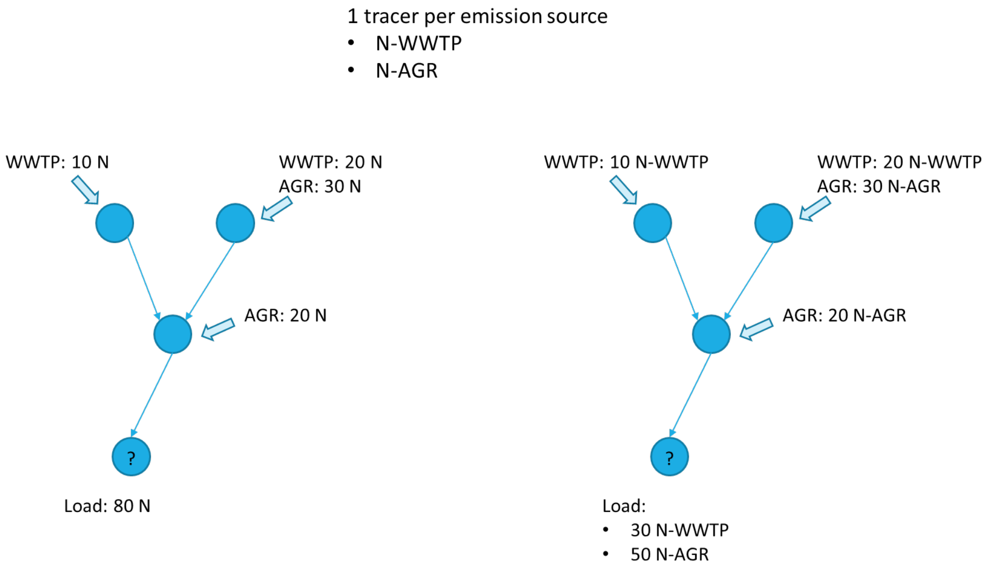

Figure C1 Schematic illustration of nitrogen loads (left) converted to tracer loads per emission source (right).

The same approach can be used to distinguish sources spatially. You can create a unique tracer for every substance/region/source combination. The conceptual schematization in Figure C2 consists of two regions: R1 and R2. R1 only contains one node and R2 contains two.

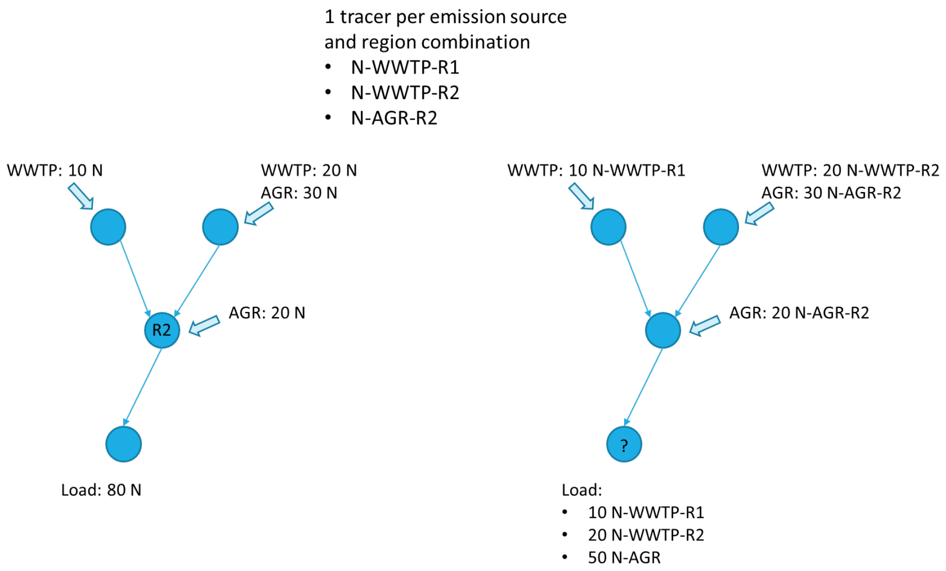

Figure C2 Schematic illustration of nitrogen loads (left) converted to tracer loads per emission source and region (right).

D Source apportionment results

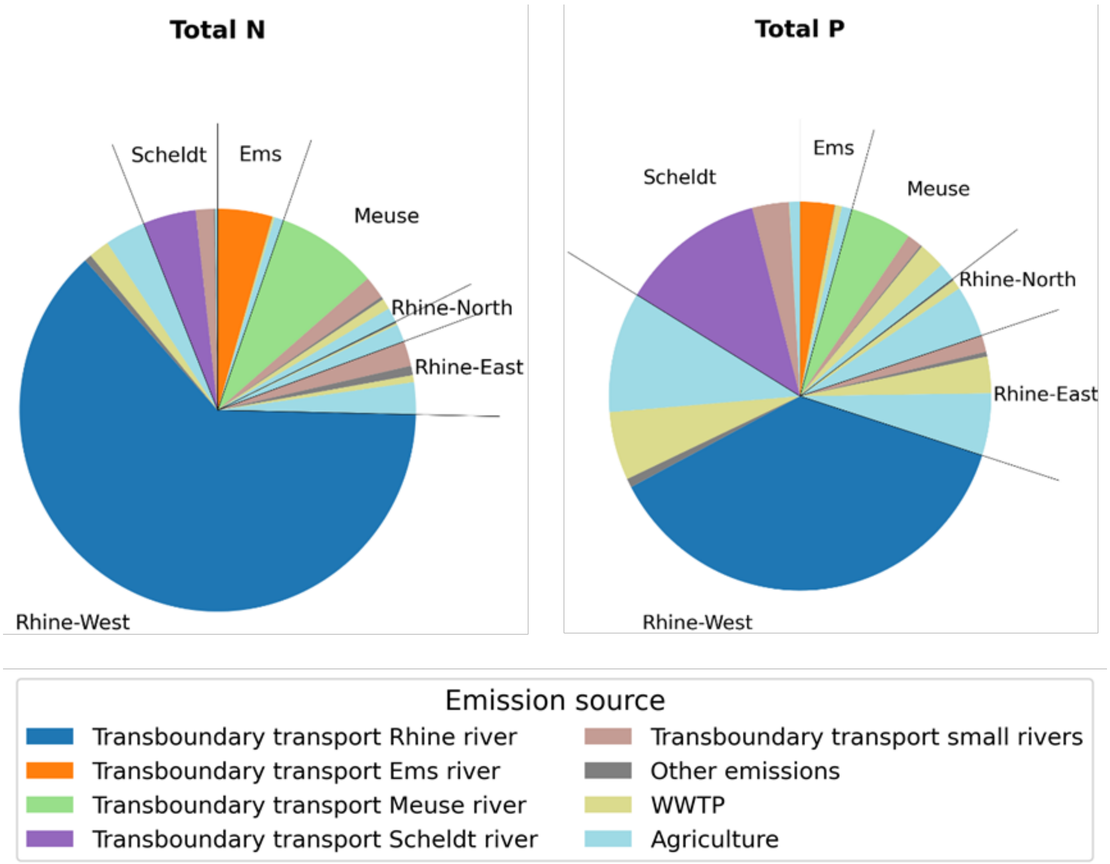

Figure D1 Relative contribution of various emission sources (pie wedges) to the total riverine nutrient loads towards the North Sea for the reference situation in 2019. Left nitrogen and right phosphorus. The emission sources are further subdivided by the river sub basins

E Seasonal and decadal patterns in concentrations at a selection of monitoring stations

Coastal waters North Sea; Noordwijk 2

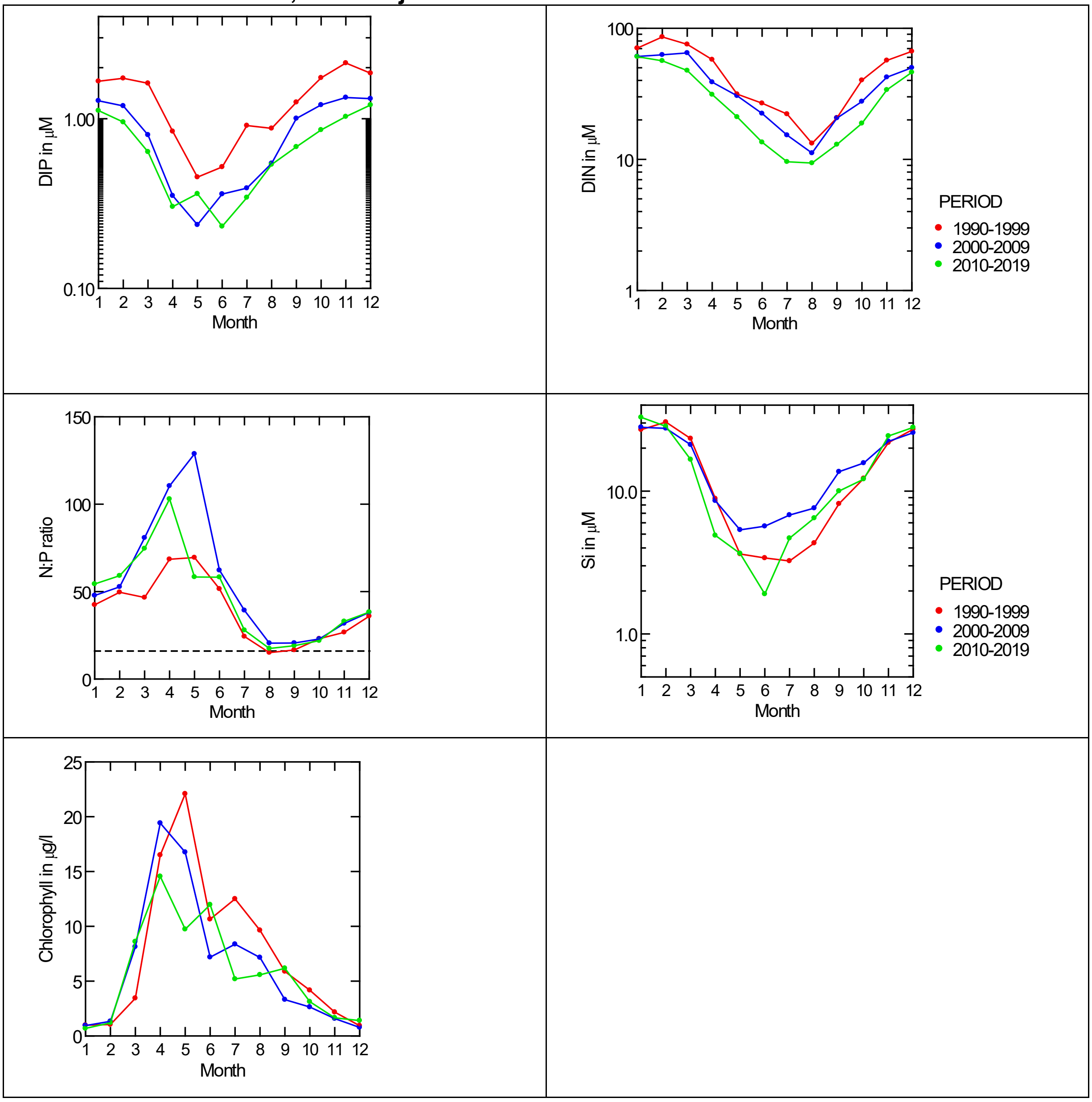

Figure E1.DIP, DIN, Si and chlorophyll concentrations and N:P ratio, averaged per month and decade, for station Noordwijk 2. The broken line shows the N:P ratio 16:1, indicative of a higher chance of P-limitation with ratios>16 and a higher chance of N-limitation with ratios<16

Coastal waters North Sea; Noordwijk 20

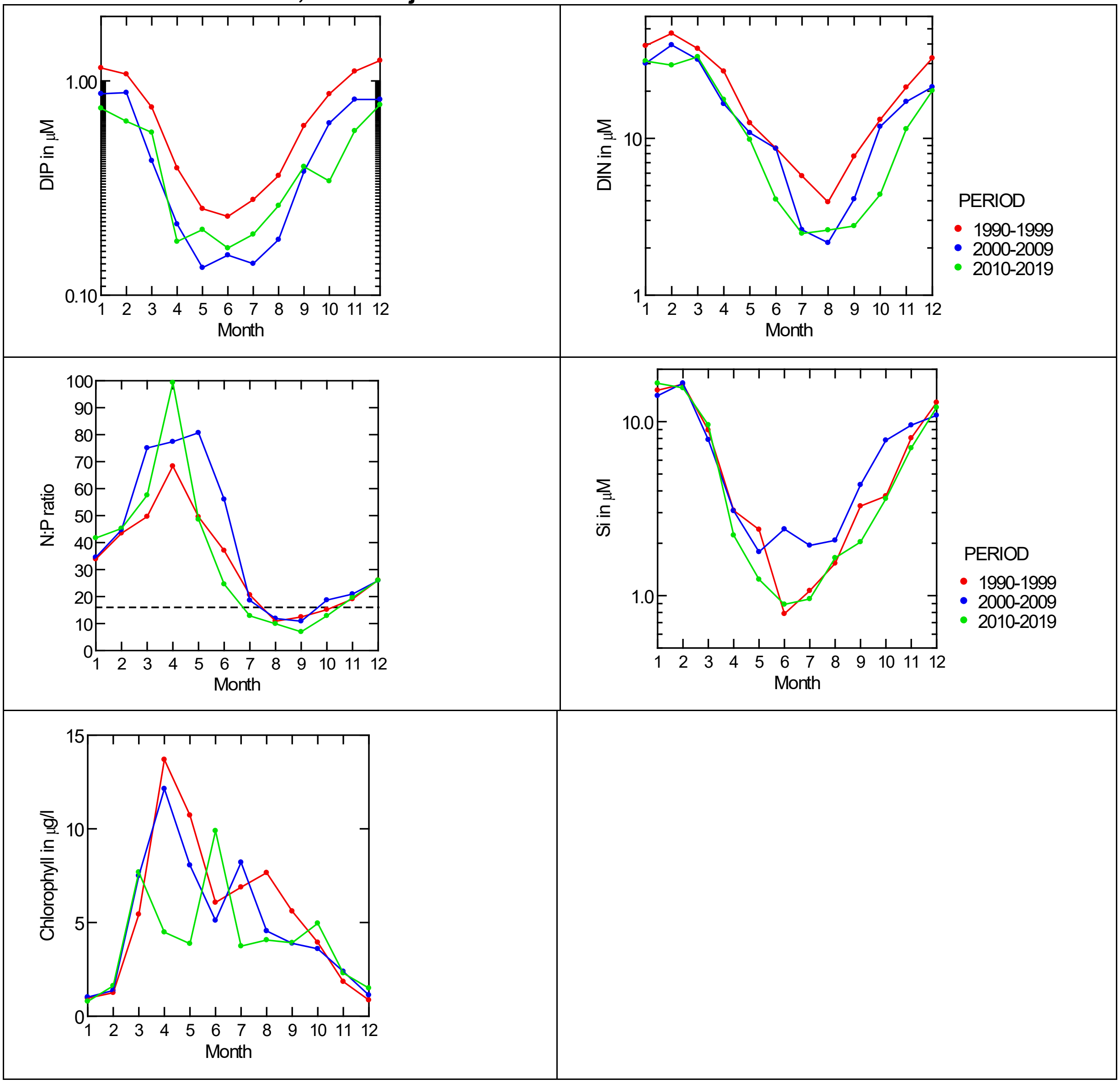

Figure E2.DIP, DIN, Si and chlorophyll concentrations and N:P ratio, averaged per month and decade, for station Noordwijk 20. The broken line shows the N:P ratio 16:1, indicative of a higher chance of P-limitation with ratios>16 and a higher chance of N-limitation with ratios<16

Western Dutch Wadden Sea; Doove Balg west

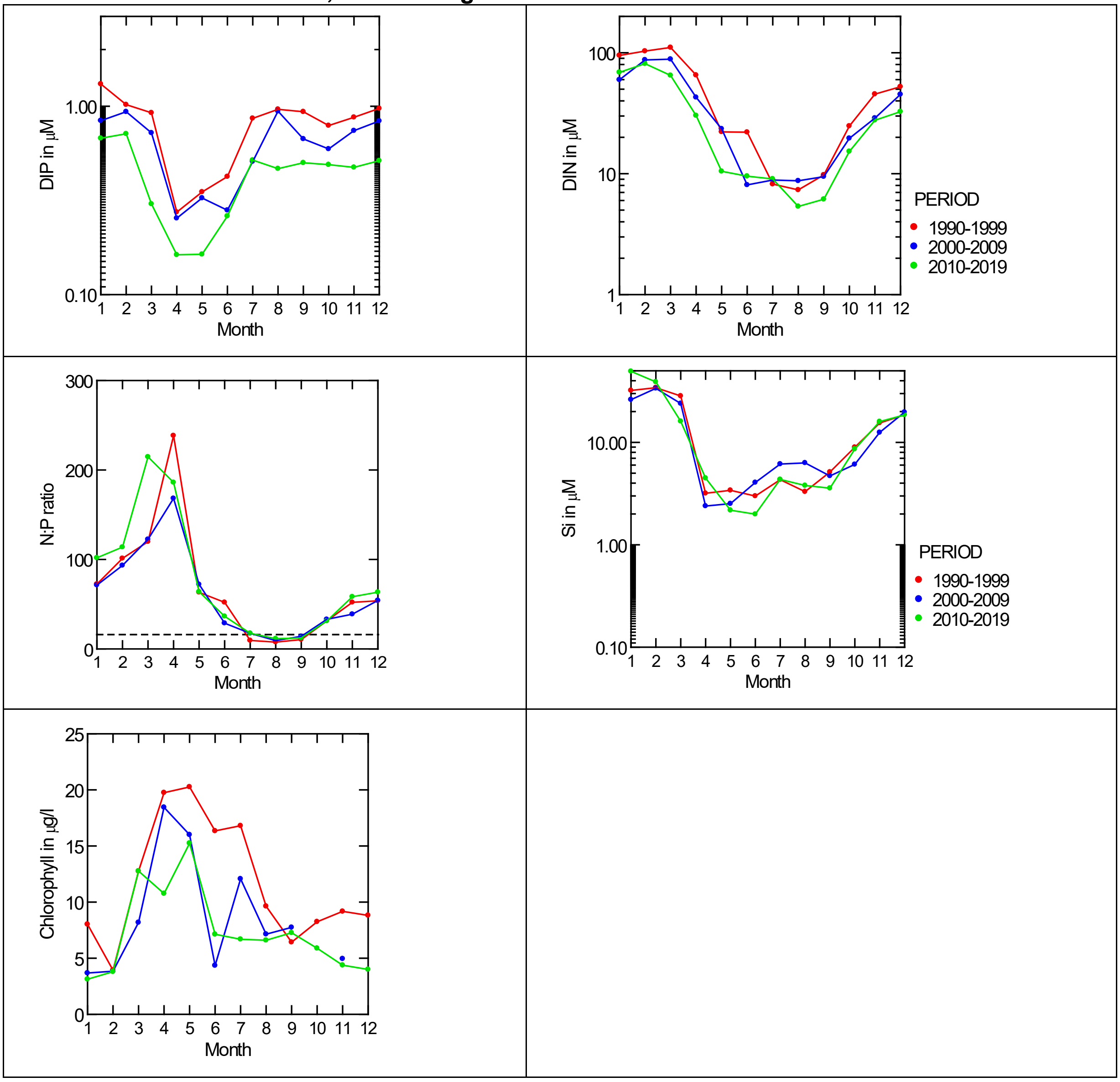

Figure E3.DIP, DIN, Si and chlorophyll concentrations and N:P ratio, averaged per month and decade, for station Doove Balg west. The broken line shows the N:P ratio 16:1, indicative of a higher chance of P-limitation with ratios>16 and a higher chance of N-limitation with ratios<16

Eastern Dutch Wadden Sea; Dantziggat

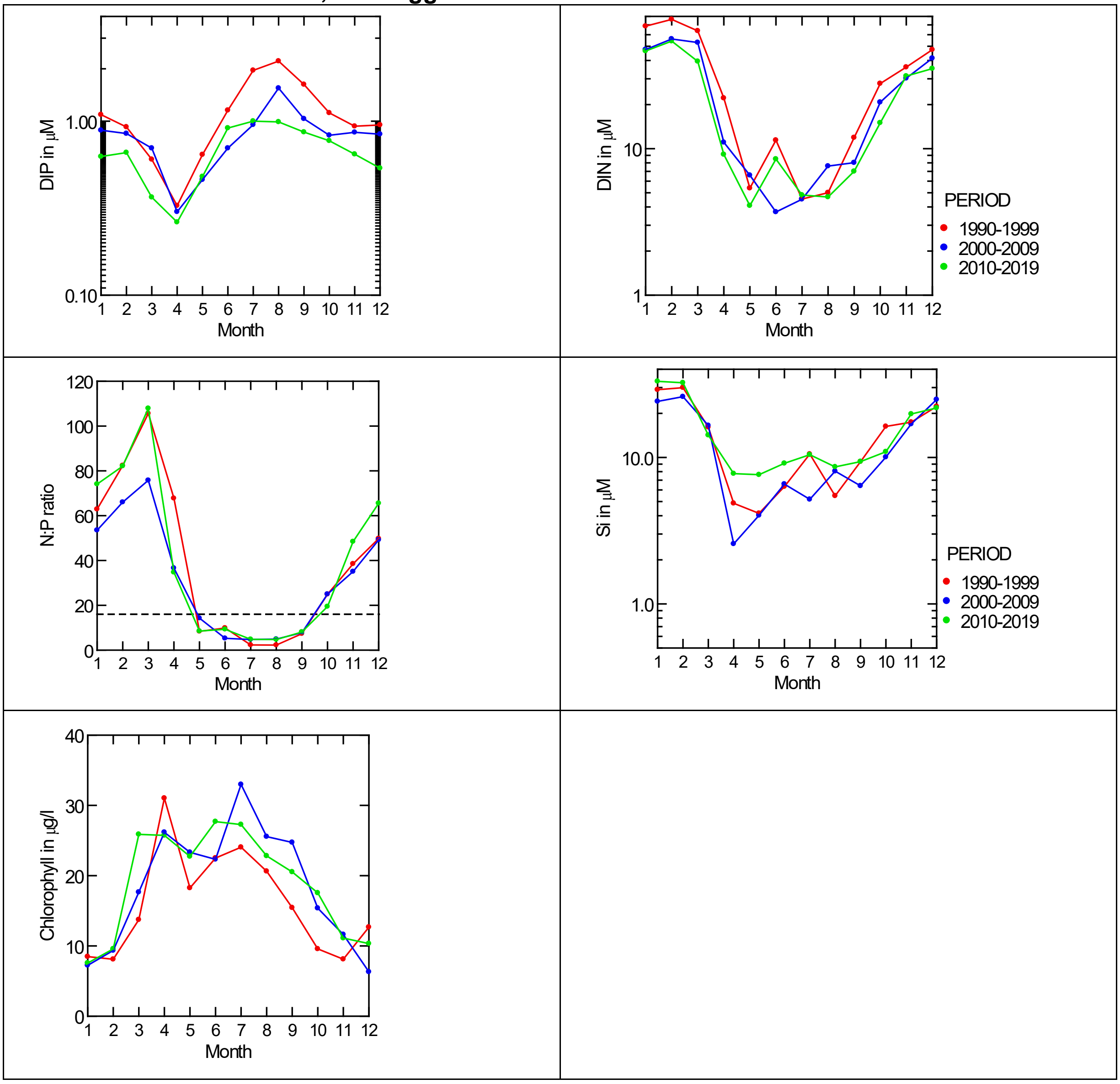

Figure E4.DIP, DIN, Si and chlorophyll concentrations and N:P ratio, averaged per month and decade, for station Dantziggat. The broken line shows the N:P ratio 16:1, indicative of a higher chance of P-limitation with ratios>16 and a higher chance of N-limitation with ratios<16.