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DELIVERABLE 3.6

TRANSFER OF MODEL RESULTS

Work Package 3
Measures & Pathways

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Abstract	Modelled results of scenarios of nutrient reduction measures in demonstrator basins Rhine and Elbe and selected subcatchments within the basins are transferred to other basins contributing to riverine nutrient inputs into the Wadden Sea.
Keywords	Climate change, nitrogen, nutrient reduction, phosphorus

Contents

LIST OF ABBREVIATIONS

C^nANDY .... *Coupled Complex Algal-Nutrient Dynamics*
mHM .... *Mesoscale Hydrologic Model*
mQM .... *Multiscale water Quality Model*
N .... *Nitrogen*
NECD .... *National Emissions Reduction Commitments Directive*
P .... *Phosphorus*
SRP .... *Soluble Reactive Phosphorus*
TP .... *Total Phosphorus*
UWWTD .... *Urban Wastewater Treatment Directive*
WWTP .... *wastewater treatment plant*

1. EXECUTIVE SUMMARY

D3.6 reports on the projected nitrogen (N) and phosphorus (P) exports for all major rivers draining into the Wadden Sea to allow a complete picture of nutrient exports to this valuable coastal ecosystem. These results are based on the mQM model for N and the C^nANDY model for P applied to the Elbe, Rhine and Hunze demonstrator basins, evaluated under different scenarios of measures and under the influence of future climate change (reported in D3.5). The model results for the demonstrator basins are transferred to the basin of the Ems, Weser and Eider by a similarity analysis by the modelled basins and subcatchments. More specifically, percentages of nutrient reductions from Elbe and Rhine compared to the reference conditions (2010-2020) are transferred to report exports and concentrations for the years 2030 and 2050 in all major rivers that are contributing to Wadden Sea eutrophication. We found that Elbe and Rhine basins exports around 70% of the Nitrate-N loads and 90% of the TP loads exported by rivers to the Wadden Sea while the Weser basin is ranked third. The fraction delivered by the Rhine basin will increase under the future climate and nutrient reduction scenarios while the fraction delivered by the Elbe will decrease.

2. INTRODUCTION

To provide a comprehensive understanding of nutrient input into the Wadden Sea, deliverable 3.6 outlines anticipated nitrogen and phosphorus contributions from its major inflowing rivers. These projections utilize the mQM model for nitrogen and the CnANDY model for phosphorus, applied to the Elbe, Rhine, and Hunze demonstrator basins as detailed in deliverable 3.5. By transferring the nutrient reduction scenarios under future climate change conditions, this deliverable allows to rank the different river basin by their exported N and P loads and therefore support water management in their decision processes.

3. METHODS

3.1. Data sources to characterize reference nutrient conditions in additional basins

In this deliverable three basins are considered that have been not explicitly modelled using mQM and C^nANDY (see deliverables D3.2 and D3.5). Table 1 gives an overview of catchment sizes for all basins and data sources for the newly added ones. Figure 1 shows all considered basins and subregions in relation to the Wadden Sea. In total we consider more than 38,000 km^2 of catchment area draining and delivering nutrients into the Wadden Sea. The newly added area of Ems, Weser and Eider represent 13% of this total considered area.

Table 1. Basins and data sources for nutrient concentrations and discharge. Newly added basins are printed in bold. For other basin data sources refer to D3.1.

Name	Area [km^2]	Data source nutrients	Data source discharge
Dutch Maas	7222	See D3.1	See D3.1
Rhine	163141	See D3.1	See D3.1
Dutch Rhine	23526	See D3.1	See D3.1
Ems	9207	UBA, https://gis.uba.de/maps/resources/apps/acp	GR See D3.1DC, https://grdc.bafg.de/
Weser	38455	UBA, https://gis.uba.de/maps/resources/apps/acp	GRDC, https://grdc.bafg.de/
Elbe	138383	See D3.1	See D3.1
Eider	2044	UBA, https://gis.uba.de/maps/resources/apps/acp	Landesamt für Umwelt Schleswig-Holstein, Hochwasser-Sturmflut-Information

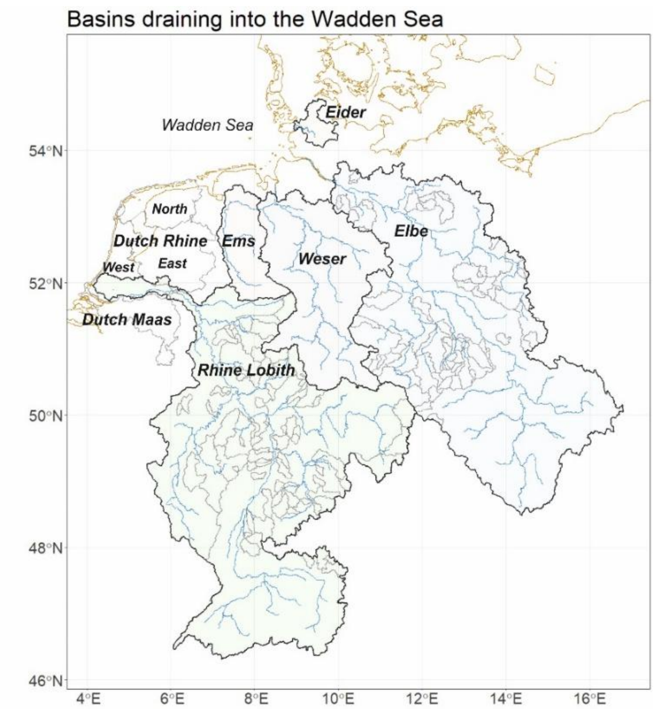


Figure 1. Considered basins contributing to the Wadden Sea eutrophication. Light grey lines are modelled subcatchments in Elbe and Rhine basin and modelled subregions of Rhine and Maas in The Netherlands.

The additional nutrient data were provided by the UBA at an annual averaged basis for Nitrate-N and total phosphorous (TP). Similar to the data handling described in D3.2 and modelling results in D3.5, we refer to a reference period averaged for the years 2010 to 2020. Discharge data from the global runoff data center and Hochwasser-Sturmflut-Information was aggregated from daily to annual values and used to derive annual exported fluxes of Nitrate-N and TP.

3.2. Similarity analysis of new basins and modelled basins and subcatchments

To transfer results for the export of N from the modelled basins to the new basin we performed a similarity analysis based on catchment attributes that are provided in the QUADICA database (Ebeling et al. 2022). More specifically, we used attributes that characterize the nutrient inputs into the catchment (fraction of agricultural land, average nitrogen surplus in the years 2000-2015 representing diffuse nutrient inputs and population density representing wastewater nutrient inputs) on the one hand. On the other hand, we used the fraction of unconsolidated aquifers in the catchment representing nutrient retention. This fraction is the form of the dominant aquifer – being unconsolidated sediments with porous materials or hard-rock aquifers with fissured material. More specifically, this fraction proved to be the best predictor for the subsurface denitrification potential of central European landscapes due to its higher likelihood to contain organic matter and pyrite enabling the denitrification reaction (Ebeling et al 2021).

To transfer the modelling results for P to the new basin, we relied on a different approach than for N. For the reduction of P, the main factor is the fraction of wastewater P inputs into the network as largest part of the reduction is realized by the implementation of the new urban wastewater directive (see deliverable D3.5). As a second factor the size of the catchment is relevant – we prefer transferring from large basins, where pelagic algal developments dominate over benthic processes which is true for stream orders larger than 2 (Yang et al. 2021). We therefore selected the results from the Rhine at Lobith as a blueprint for the P reduction in the Ems (high population density) and the Elbe outlet as a blueprint for the Weser (similar to N) and the Eider.

3.3. Transfer of modelling results

The transfer of modelling results from mQM for Nitrate-N and from C^{n}ANDY for total P has a focus on the exports into the Wadden Sea and the reductions of these exports achieved in the scenarios. We therefore used the percentage reduction of nutrient fluxes relative to the reference years 2010-2020 modelled in different scenarios and applied the average across the similar catchments (section 3.2) to the observed nutrient fluxes 2010-2020 in Ems, Weser and Eider for N and additionally for the Dutch parts of Maas (NLMS) and Rhine (sum of NLRNNO, NLRNOO, NLRNWE) for P. We account for an uncertainty of this transfer for N by using the range of reductions across the selected similar subcatchments. In the case of the Weser catchment, where modelled results of the Elbe outlet are taken as a reference, we used the 5th -95th percentiles among the best 100 modelled solutions for mQM for Nitrate-N but lack a comparable value for C^{n}ANDY and TP. As scenarios the combined effects of measures in scenario 5 (combined planned measures), 7A (strengthening policies), 7B (exploring synergies) and 7C (drastic societal changes) for the time frames 2030 (averaging 2028-2032) and 2050 (averaging 2046-2050) were considered. This selection was made to transfer the combined effect of climate change and combined measures for all relevant nutrient input pathways while not given the details of climate change (scenario 6) and each pathway separately (scenarios 1, 2, 3 and 4).

4. RESULTS

4.1. Results of the catchment similarity analysis

Table 2 gives an overview of the catchment properties of the three new basins and the properties of the choice of similar basins. For the Ems we found four subcatchments of the Rhine with similar catchment properties. For the basin of the Weser, the Elbe basin (outlet) itself has a large similarity while no other comparable catchment was found. Especially catchments with a similar share of unconsolidated aquifers could not be found among the modelled subcatchments. For the basin of the Eider, four subcatchments of the Elbe were found with similar properties.

Table 2. Results of the similarity analysis of new basins with modelled catchments from D3.5. Data are derived from Ebeling et al. (2022). Station – name of the station in Ebeling et al. (2022), f_agric – fraction of agricultural land use, Pdens – population density, N input – nitrogen surplus average 2000-2015, f_unconsol – fraction of unconsolidated aquifers. Note that the Elbe station name refers to the number used by the global runoff data center. Properties of the target basins are printed bold.

River	Station	f_agric [%]	Pdens [inh/km^2]	N input [kg/ha yr]	f_unconsol [%]
Ems	**NW_803182**	**72**	**368**	**74**	**83**
	BW_CSN014	62	136	80	100
	BW_CSN021	65	235	78	100
	BW_CAR028	68	136	78	76
	BW_CAS014	66	152	55	86
Weser	**NI_49112010**	**55**	**189**	**47**	**34**
	6340110	39.7	180	40	32
Eider	**SH_120215**	**83**	**128**	**69**	**100**
	SN_OBF54610	76	132	45	46
	BB_STEP_0040	83	34	48	100
	BB_STEP_0020	84	36	49	100
	ST_2170040	87	126	43	63

The tables 3 and 4 report the percentage of load reduction in 2030 and 2050 under the considered scenarios as reported in deliverable 3.5.

Table 3. Percentage of modelled Nitrate-N load reduction from the catchments of the similarity analysis taken from deliverable 3.5. Mean, minimum and maximum values are given. Note that for the Weser catchment values from the Elbe model are taken where uncertainty refers to 5th and 95th percentiles of 100 best modelled solutions. Numbers in headers refer to scenario number and year. All percentage are relative to the reference year 2010-2020.

	Name	**5**	**5**	**7A**	**7A**	**7B**	**7B**	**7C**	**7C**
	Year	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Ems	Best	17.1	16.9	21.4	25.3	21.4	25.3	23.8	35.6
	Min	11.9	1.4	14.2	7.7	14.2	7.7	18.9	5.4
	Max	20.9	26.2	28.3	32.7	28.3	32.7	29.3	42.4
Weser	Best	33.4	20.6	40.8	30.7	57.1	46.9	59.8	61.6
	5th	25.5	16.1	33.3	28.5	49.6	44.8	54.0	61.6
	95th	47.2	25.0	55.1	50.4	71.3	66.7	76.8	84.7
Eider	Best	60.9	48.0	62.1	52.0	62.1	52.0	69.7	73.8
	Min	52.5	44.2	53.2	48.3	53.2	48.3	56.8	70.9
	Max	69.5	53.7	70.7	57.2	70.7	57.2	77.6	75.6

Table 4. Percentage of modelled TP load reduction from the catchments of the similarity analysis (see 3.2) taken from deliverable D3.5. Numbers in headers refer to scenario number and year. All percentages are relative to the reference year 2010-2020.

Name	5	5	7A	7A	7B	7B	7C	7C
Year	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
NLMS	23.7	24.4	29.7	30.4	30.4	31.0	30.4	31.0
NLRN	23.7	24.4	29.7	30.4	30.4	31.0	30.4	31.0
Ems	23.7	24.4	29.7	30.4	30.4	31.0	30.4	31.0
Weser	9.3	38.7	20.0	46.6	21.9	48.1	21.9	48.1
Eider	9.3	38.7	20.0	46.6	21.9	48.1	21.9	48.1

4.2. Transferred results for nitrate-N exports to the Wadden Sea

Table 5 gives an overview of the results of the estimated nitrate-N export reductions achieved in the three additional basins.

Table 5. Estimated Nitrate-N loads for scenarios 5, 7A, 7B and 7C for the three additional basins based on the percentage reductions in Table 3 and the observed reference values (see Table 1) averaged for the years 2010-2020.

	Name	Reference	5	5	7A	7A	7B	7B	7C	7C
	Year	**2010-2020**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Ems	Best	7930	6573	6587	6231	5923	6231	5923	6044	5104
	Max		6983	7820	6805	7322	6805	7322	6428	5747
	Min		6270	5849	5689	5337	5689	5337	5607	4564
Weser	Best	25549	17019	20278	15124	17708	10973	13557	10275	9810
	95th		19026	21429	17031	18261	12880	14110	11763	9813
	5th		13493	19151	11474	12664	7324	8513	5938	3905
Eider	Best	814	318	423	308	391	308	391	247	213
	Max		387	454	381	421	381	421	351	237
	Min		248	377	238	348	238	348	182	199

Among the three additional basins, the river Weser is the biggest contributor to Nitrate-N exports to the Wadden Sea while the river Eider only plays a minor role. The overview on the total amount of Nitrate-N including Elbe and Rhine basin is given in chapter 4.4.

4.3. Transferred results for TP

The Table 6 gives an overview about the results of the estimated TP export reductions achieved in the two additional Dutch regions and the three additional basins.

Table 6. Estimated TP loads for scenarios 5, 7A, 7B and 7C for the two additional regions and the three additional basins based on the percentage reductions in Table 4 and the observed reference values (see Table 1) averaged for the years 2010-2020 (all values in t TP/yr).

Name	Reference	5	5	7A	7A	7B	7B	7C	7C
Year	**2010-2020**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
NLMS	8.9	6.8	6.7	6.3	6.2	6.2	6.1	6.2	6.1
NLRN	34.5	26.3	26.1	24.2	24.0	24.0	23.8	24.0	23.8
Ems	92.0	70.2	69.5	64.6	64.0	64.0	63.5	64.0	63.5
Weser	787.6	714.1	483.0	630.4	420.5	615.3	409.1	615.3	409.1
Eider	155.3	140.8	95.2	124.3	82.9	121.3	80.7	121.3	80.7

Among the three additional basins, the river Weser is the biggest contributor to TP exports to the Wadden Sea while the river Ems and the Eider as well as the Dutch Maas and Rhine regions play a rather minor role. The overview on the total amount of TP exported to the Wadden Sea including Elbe and Rhine basin is given in chapter 4.5.

4.4. All results for Nitrate-N

Table 7 gives an overview of the combined results of the modelled and estimated nitrate-N export reductions achieved in all considered basins and regions contributing to the Wadden Sea.

Table 7. Estimated Nitrate-N loads for scenarios 5, 7A, 7B and 7C from all considered basins and regions draining into the Wadden Sea based on the percentage reductions in Table 3 and the observed reference values (see Table 1) averaged for the years 2010-2020 as well as the direct model outputs (all values in t N/yr).

	Name	Reference 2010-2020	5 2030	5 2050	7A 2030	7A 2050	7B 2030	7B 2050	7C 2030	7C 2050
NLMS	Best	7213	6155	5186	5614	4219	5548	4153	5437	3851
	95th		4663	3991	4115	2767	4050	2702	3858	2257
	5th		6156	5186	5615	4219	5550	4154	5437	3852
Rhine Lobith	Best	156075	128329	126617	119813	113410	113149	106747	105005	88253
	95th		120608	116991	111343	102563	104680	95899	95566	74857
	5th		133293	130908	125427	118854	118763	112191	111831	96164
NLRN	Best	12571	9644	8176	9416	7399	9106	7089	8425	5687
	95th		8297	7349	7790	6455	7481	6145	7110	5238
	5th		11784	10030	11542	9219	11233	8910	10520	7435
Ems	Best	7930	6573	6587	6231	5923	6231	5923	6044	5104
	Max		6983	7820	6805	7322	6805	7322	6428	5747
	Min		6270	5849	5689	5337	5689	5337	5607	4564
Weser	Best	25549	17019	20278	15124	17708	10973	13557	10275	9810
	95th		19026	21429	17031	18261	12880	14110	11763	9813
	5th		13493	19151	11474	12664	7324	8513	5938	3905
Elbe	Best	50687	33764	40231	30004	35131	21769	26896	20386	19463
	95th		26769	30567	22764	25124	14529	16889	11781	7747
	5th		37746	42009	33787	36228	25553	27993	23338	19468
Eider	Best	814	318	423	308	391	308	391	247	213
	Max		387	454	381	421	381	421	351	237
	Min		248	377	238	348	238	348	182	199

The main contributor of all considered basins and regions is the river Rhine with 60% of the total nitrate-N exports to the Wadden Sea under reference conditions. While the river Elbe is contributing 19% and the river Weser 10%, all other basins and regions are below 5% each (Fig. 2). Under the future scenarios of nutrient load reduction the general ranking of basins and regions does not change. However, the relative contribution of the river Rhine to Wadden Sea nitrate-N imports is increasing to 67% under scenario 7C while the contribution of the river Elbe is decreasing to 15% (Fig. 2). This is a result of a higher efficiency of the anticipated measures in the Elbe compared to the Rhine basin. The spatial pattern of nitrate-N exports for the different scenarios in the year 2050 is visualized in Figure 3.

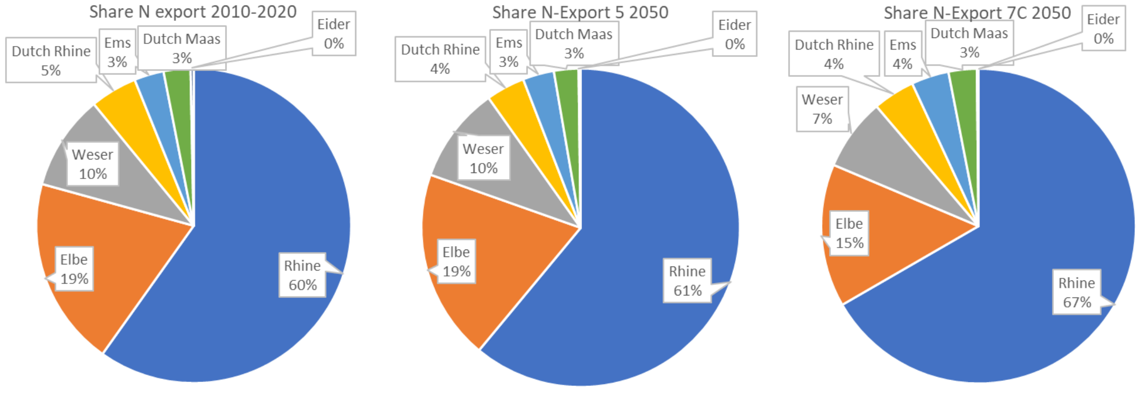


Figure 2. Share of Nitrate-N exports to the Wadden Sea from all basins and regions for the reference conditions 2010-2020 (left), scenario 5 in 2050 (middle) and for scenario 7C in 2050 (right).

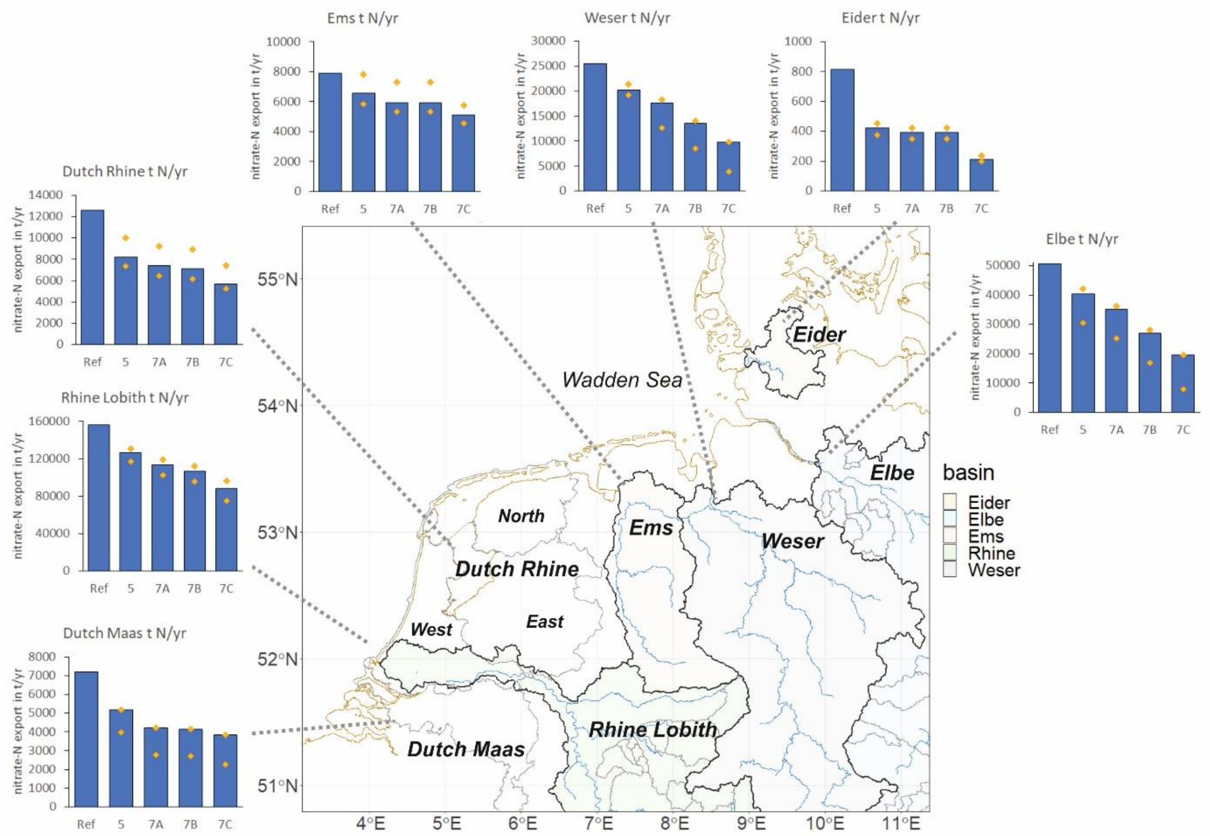


Figure 3. Nitrate-N exports from the different basins and regions contributing to the Wadden Sea eutrophication. Light grey lines are modelled subcatchments in Elbe and Rhine basin and modelled subregions of Rhine and Maas in The Netherlands. The blue bars are based on the best modelled realizations, the yellow dots depict the 5th and 95th percentiles of solutions or the min and max of estimated solutions (see Table 7).

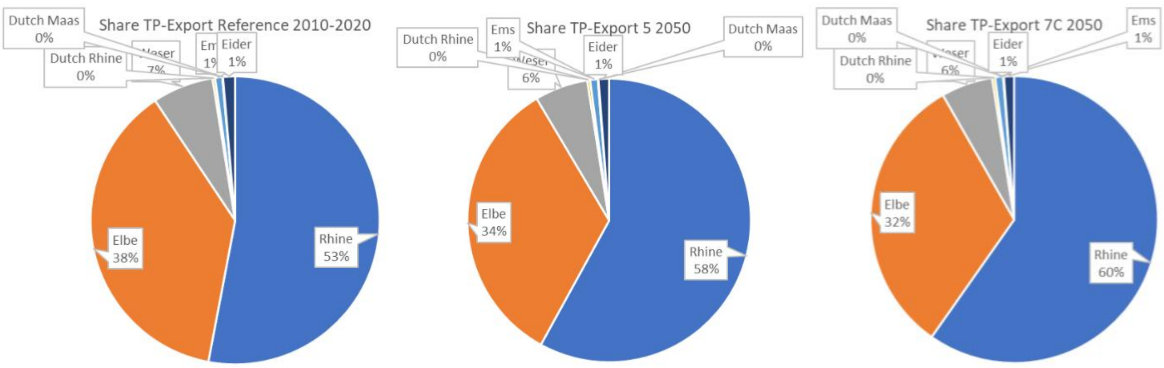
4.5. All results for TP

Table 8 gives an overview of the combined results of the modelled and estimated TP export reductions achieved in all considered basins contributing to the Wadden Sea.

Table 8. Estimated TP loads for scenarios 5, 7A, 7B and 7C from all considered basins draining into the Wadden Sea based on the percentage reductions in Table 4 and the observed reference values (see Table 1) averaged for the years 2010-2020 as well as the direct model outputs for Rhine and Elbe (all values in t TP/yr).

Name	Reference 2010-2020	5 2030	5 2050	7A 2030	7A 2050	7B 2030	7B 2050	7C 2030	7C 2050
NLMS	8.9	6.8	6.7	6.3	6.2	6.2	6.1	6.2	6.1
NLRN	34.5	26.3	26.1	24.2	24.0	24.0	23.8	24.0	23.8
Rhine Lobith	6113.8	4667.1	4622.4	4296.5	4257.3	4256.9	4218.2	4256.9	4218.2
Ems	92.0	70.2	69.5	64.6	64.0	64.0	63.5	64.0	63.5
Weser	787.6	714.1	483.0	630.4	420.5	615.3	409.1	615.3	409.1
Elbe	4348.0	3942.2	2666.4	3480.2	2321.3	3396.6	2258.6	3396.6	2258.6
Eider	155.3	140.8	95.2	124.3	82.9	121.3	80.7	121.3	80.7

The main contributor of all considered basins and regions is the river Rhine with 53% of the TP exports to the Wadden Sea under reference conditions. While the river Elbe is contributing 38% and the river Weser 7%, the two other basins are below 2% each and the two Dutch regions below 0.3% (Fig. 4). Under the future scenarios of nutrient load reduction, the general ranking of basins and regions does not change. However, the relative contribution of the river Rhine to Wadden Sea nitrate-N imports is increasing to 60% under scenario 7C (2050) while the contribution of the river Elbe is decreasing to 32% (Fig. 4). The spatial pattern of TP exports for the different scenarios in the year 2050 is visualized in Figure 5.



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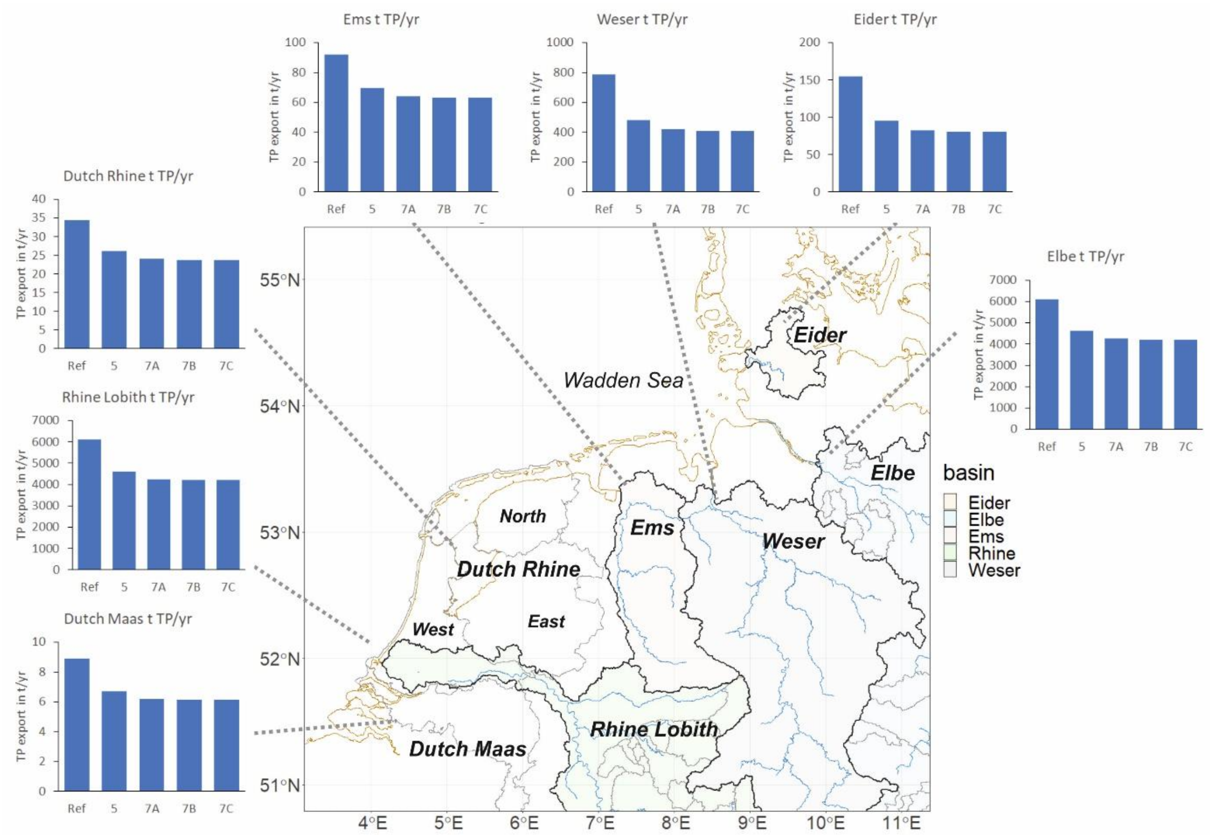

Figure 5. TP exports from the different basins and regions contributing to the Wadden Sea eutrophication. Light grey lines are modelled subcatchments in Elbe and Rhine basin and modelled subregions of Rhine and Maas in The Netherlands. The blue bars are based on the best modelled realizations (see Table 7).

5. CONCLUSIONS

The presented results of deliverable D3.6 give a complete overview on the transfer of Nitrate-N and TP by rivers to the Wadden Sea. The results indicate that under reference conditions as well as under the scenario 5 and 7A-C the rivers Rhine and Elbe are the largest contributors for the land-to-sea transfer of nutrients to the Wadden Sea while other basins are of subordinate importance for the entire budget. These results can give a guideline to prioritize future management activities along the option space of nutrient reduction scenarios presented here.

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