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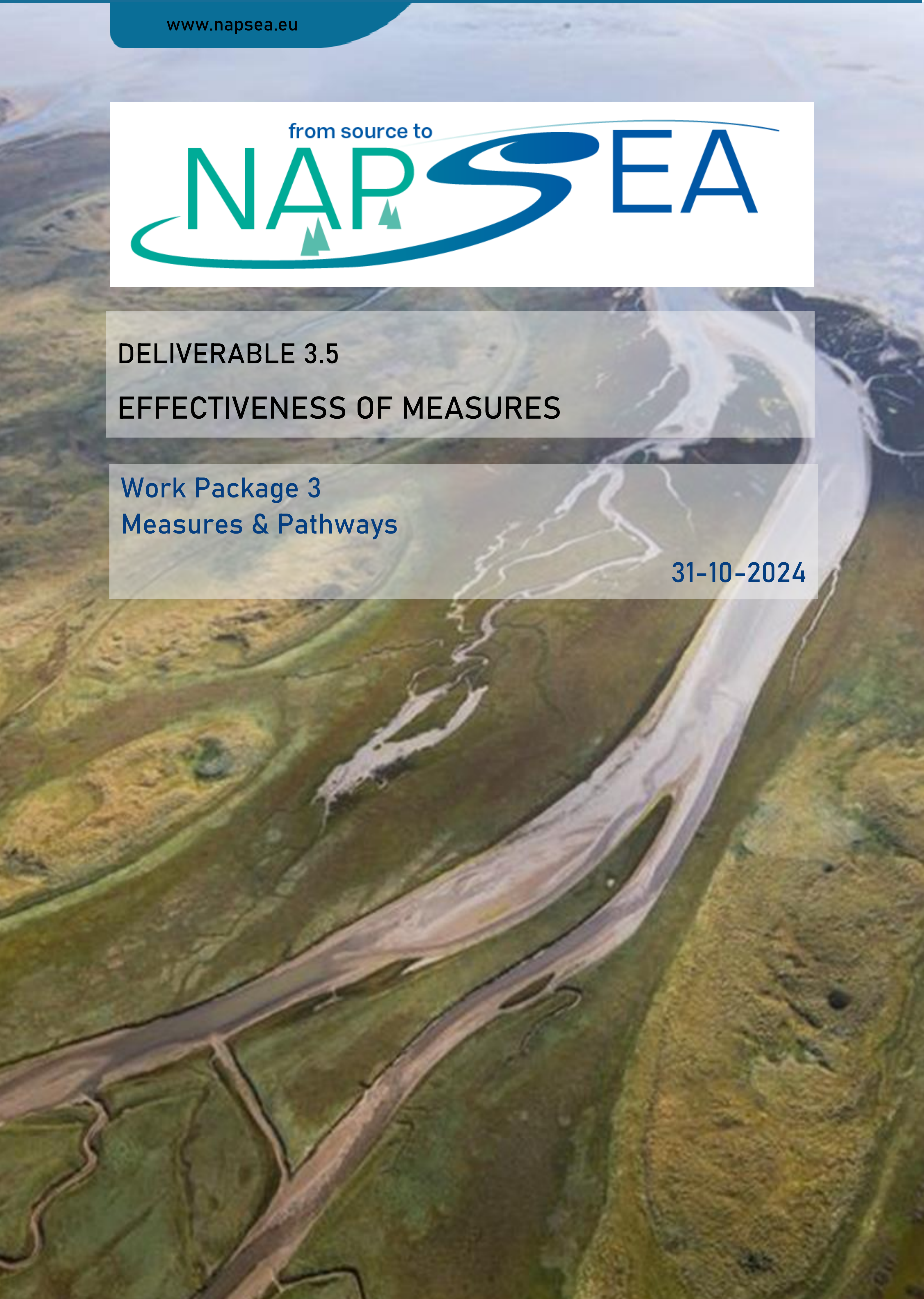
DELIVERABLE 3.5

EFFECTIVENESS OF MEASURES

Work Package 3
Measures & Pathways

31-10-2024



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Abstract	Different scenarios of measures are implemented in demonstrator basins Rhine and Elbe, selected sub-catchments within the basins and for the Hunze catchments. Results are reported for concentrations and exports of nitrogen and phosphorous.
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

D3.5 reports predictive modelling results of nitrogen (N) and phosphorus (P) concentrations and exports for the Elbe, Rhine and Hunze demonstrator basins, evaluated under different scenarios of measures. The foundation of this analysis utilizes the mQM model for N and the CnANDY model for P, with the parameters calibrated to current climatic and nutrient conditions as reported in D3.2. This report follows the set of measures introduced in D3.3 (set of scenarios) and the database of concrete measures provided in D3.4 (model input of selected scenarios). The model results are compared to reference conditions (2010-2020), assessing the effectiveness of each scenario in reducing N and P concentrations in inland waters and the nutrient fluxes exported to the estuaries and the Wadden Sea.

2. METHODS

2.1. Overview of the implemented measures

Table 1 gives an overview on the implemented scenarios and the narrative connected to that measure. Note that scenario 7 will be implemented later with the knowledge of the effectiveness of measures and potential gap to the envisioned safe ecological boundaries of inland waters, estuaries and the Wadden Sea considering the assessment of the social acceptability of additional measures.

Table 1. Set of scenarios (Gericke et al. (2024); D3.3).

Scenario	Target of measures	Narrative
1	Wastewater treatment	The revised Urban Wastewater Treatment Directive is implemented
2	Agricultural input	The Nitrates Directive is implemented, the new Soil Health Law is implemented with a soil erosion ≤ 2 t ha^{-1}, and/or 25% organic farming on agricultural land according to the Farm-to-Fork Strategy
3	Atmospheric deposition	The NECD is implemented, the Dutch atmospheric target for the protection of the Natura 2000 areas is reached.
4	Nature-based solutions for nutrient retention	The Biodiversity Strategy 2030 is implemented in combination with restoration of riparian areas, floodplains, and/or bogs, potentially also fulfilment water-related goals of the EU Nature Restoration Law
5	All measures	All the scenarios 1-4 are implemented together
6	No measures	None of 1-4 is implemented. The projected hydrological states represent the emission scenario RCP4.5.

2.2. Implementation of measures

Here an overview is given, how the different measures have been implemented in the two different models in the different demonstrator basins. Generally, measures have been implemented for the timeframe 2022 to 2050. In the mQM model for N this is done in a temporal continuous way at a resolution of 1 year. In the CnANDY model, which simulates average vegetation period conditions for P this is done in two time-horizons: 2030 and 2050. To avoid a dependency of modelled P-species on the hydrological condition of a specific year for CnANDY we used average hydrological conditions 2027-2032 for the time-horizon 2030 and 2046-2050 for the time-horizon 2050.

All scenarios and both models are using the same projected hydroclimatic conditions (discharge and soil water content) defined in scenario 6.

All scenarios use the model parameterization of the calibration to current climatic and nutrient conditions as reported in D3.2 (Musolff & Ledesma, 2024). The scenarios are mainly implemented by changes in the diffuse and point source inputs of N and P. For the scenario 4 reporting on nature-based solutions, additional nutrient retention in the catchment by was partly removed from the modelled exported fluxes. Changes of inputs are reported in D3.3 (Gericke et al., 2024) and are also part of the Annex I which provides table results_D35_P and results_D35_N.

Scenario 1: Wastewater treatment

For the mQM model we applied the projected new N loads from individual WWTP under the implementation of the UWWTD assuming a linear improvement between 2022 and 2030 and a constant annual load after 2030. Loads of the individual WWTPs have been aggregated to the modelled catchment scale.

For the CnANDY model we applied the projected new P loads from individual WWTP spatially explicitly. Since the UWWTD does not apply to small WWTPs (<10000 population equivalents), P inputs from these sources were held constant from the calibration period.

Scenario 2: Agricultural input

For the mQM model we applied the projected new N inputs under the implementation of the new Fertilizer Ordinance is in Germany assuming a linear improvement of nitrogen surplus between 2022 and 2030 and a constant annual input after 2030. Note that this scenario does separate improvement of changed fertilizer inputs from the reduction of atmospheric deposition (see also Annex II for a visualization of the N input change). Thus, the atmospheric deposition was held constant while only N surplus changes due to fertilizer reductions are implemented. For the Hunze catchment within the Netherlands, the measures are based on the anticipated trends in agriculture and implementation of the measures of the 7th Action Program until 2027. According to report D3.4

(Gericke & Leujak, 2024) these measures apply to sandy agricultural soils, while effects of measures on clay soils are neglectable. Within the Hunze catchment agricultural soils are dominantly clay soils with the consequence that no improvement of agricultural N inputs is realized. Results presented for the Hunze are thus similar to scenario 6.

For the CnANDY model, envisioned measures with the implementation of the Soil Health Law and the Farm 2 Fork strategy are directly affecting the input of TP and especially particulate P with a focus on changes in erosion. There is no quantified effect on the input of the dissolved P fraction (SRP) from agricultural sources. The CnANDY model does not consider TP inputs from diffuse sources (land to stream transfer) but only SRP sources that are known to be bioavailable for algae growth. Consequently, effects of both sets of measures are not quantified here. Results presented for CnANDY within this scenario are therefore similar to scenario 6.

Scenario 3: Atmospheric deposition

For the mQM model we applied the projected new N input changes under the implementation of the NECD and reaching the Dutch atmospheric target for the protection of the Natura 2000 assuming a linear improvement between 2022 and 2030 and between 2030 to 2050. Loads of the individual WWTPs have been aggregated to the modelled catchment scale. The base of the implemented scenarios are the cross-nation consistent data from the EMEP MSC-W as described in D3.4 (Gericke & Leujak, 2024).

For the CnANDY model this scenario is not quantified since this pathway is only relevant for N but not for P.

Scenario 4: Nature-based solution

For the mQM model we combined two different sets of measures. First, we modelled the implemented the EU Nature Restoration Law with 20% more active floodplains in Germany until 2030. Second, we modelled the implementation of §38a of the German Federal Water Act (Wasserhaushaltsgesetz), improving riparian buffers with a permanent plant cover of 5 m width on arable land with an average slope of at least 5% within a distance of 20 m from surface waters. For the activation of floodplains, we assumed average soil N retention on the activated floodplain to improve from 200 kg N ha/yr to 250 kg N ha/yr (according to Scholz et al. 2012). This additional retention was subtracted from the areal export fluxed quantified in scenario 6. For the increased area of riparian buffers, we assumed that the additional N retention within these new buffer zones is active for fast and surficial pathways from the land to the river network. Therefore, N-fluxes younger than 1 year have been reduced by 50% in the additional created wide riparian zone provided by D3.4 (Gericke & Leujak, 2024). Similar to the other scenarios implementation was done with a linear increase 2022-2030 and a constant retention afterwards.

For the CnANDY model, similar to scenario 2, we considered measures that affect SRP fluxes to the river network. This is the case for the increase of riparian buffer but not for the floodplain activation. We therefore halved the diffuse agricultural SRP input in the model that flows through additional created wide riparian zones. Note that no improvement was quantified for the Hunze basins so that values presented for this scenario are similar to scenario 6.

Scenario 5: All measures

Here all measures of scenarios 1-4 are combined and implemented as described above.

Scenario 6: No measures

For this scenario, projected total water content in the first meter of the soil column and total discharge was extracted for each catchment and sub catchments from the model mHM. Data was temporally aggregated from daily to annual scale and spatially averaged for each catchment. As forcing, GCM (global climate model) MPI-ESM-LR and RCM (regional climate model) MPI-CSC-REMO2009 was used. Climate forcing (such as precipitation, temperature, etc.) was a-priori downscaled and bias corrected before conducting mHM runs (see also data collection D3.1; Jomaa & Musolff, 2023). The projected hydrological states represent the emission scenario RCP4.5.

3. RESULTS FOR N

3.1. Overview for N

The table in Annex I gives a full overview on the concentrations and loads of NO3-N within the demonstrator catchments and sub catchments and the differences from the reference models (2010-2020). Model results are evaluated by three major metrics that are in line with the ideas of safe ecological limits defined in work package 4: 1. The loads of N exported at the catchment outlet of Elbe and Rhine. 2. The concentration of N at the catchment outlet. 3. The fraction of the sub catchments that do not exhibit a good nitrate status (nitrate-N concentrations >1.9 mg/L).

Projected discharge under climate change scenario RCP4.5 is playing a notable role in the differences between the different scenario time-horizons. Compared to the 2010-2020 reference period, discharge is projected to increase by 2.2% (2028-2032) and 3.1% (2046-2050) in the Rhine. In contrast, discharge in the Elbe is projected to decrease by 15.5% (2028-2032) and increased by 13.4% (2046-2050). In the Hunze, discharge under the RCP4.5 scenario is projected to decrease by 11.8% (2028-2032) and 18.3% (2046-2050). Given that the exported loads are tightly connected to discharge, part of the efficiency of measures may be covered by the variability in discharge. In scenario 6, which only considers climate change and keeps nitrogen inputs the same, nutrient loads by 2030 were reduced by 4.6% at the Rhine outlet and by 15.8% at the Elbe outlet compared to the reference case. For the time horizon 2050 loads were less reduced at the Rhine outlet by 2.8% but increased at the Elbe outlet by 5.1%. The effect on the outlet concentration is relatively small (Figure 1 and 2).

For scenario 5, combining climate change and all measures, strongest reductions in loads and concentrations are reached (Fig. 4-5). Compared to the climate change scenario, exports from the Elbe are reduced by 79% for the time horizon 2030 (82% compared to the reference period). The reduction is not as strong in the sub catchments of the Elbe that do not have the same amount of floodplain areas as the Elbe basin itself and are thus not that strongly affected by the nature-based solution measures (average 18% reduction of exported loads, 2025: 15.6%). Compared to the climate change scenario, exports from the Rhine are reduced by 23% for the time horizon 2030 (26% compared to the reference period) and 25% for the time horizon 2050 (27% compared to the reference period). The reduction is not as strong in the sub catchments of the Rhine (2030: 9% reduction of exported loads compared to the reference, 2050: 16%). Concentrations in the Elbe for scenario 5 improve at the outlet from 1.7 mg N/L in the reference to 0.5 mg N/L (2030) and 0.7 mg N/L and in the sub catchments from 3.6 mg N/L to 2.6 mg N/L (2030) and 2.2 mg/L (2050). Concentrations in the Rhine for scenario 5 improve at the outlet from 2.5 mg N/L in the reference to 1.8 mg N/L (2030 and 2050) and in the sub catchments from 3.7 mg N/L to 2.6 mg N/L (2030 and 2050).

The weakest effects on the exported loads were found for scenario 1 at the Rhine outlet (2030: 3% reduction, 2050: 3%) and for scenario 2 at the Elbe outlet (2030: 3% reduction, 2050: 7%). While nutrient reduction measures effectively reduce the nutrient loads at catchment outlets, they have a minimal effect on the percentage of catchments that surpass the mean annual nitrogen concentration limit of 1.9 mg N/L. Even under the highest nutrient reduction scenario 5, more than 70% of all sub catchments in the Rhine basin (Fig. 6) and more than 55% of all sub catchments in the Elbe basin (Fig. 7) are above the concentration threshold. For the four modeled Hunze catchments, the implemented measures had no significant effect on the metric, as two of the four catchments consistently exceeded the threshold across all scenarios (Fig. 8).

We further note that the scenario 4 for nature-based solutions has particularly high uncertainty. More specifically, the assumption that N retention increase by 50 kg N/ha yr on the reactivated floodplain areas can be discussed. The additional retention can only be realized when there is enough delivery of nitrogen to the floodplain areas. Sub catchments can have large areas of reactivated floodplains (on average 2.4% of the total catchment area). The Elbe catchment has an area of 4.3% of reactivated floodplain, while the Rhine has 2.3%. Within the sub catchments this fraction is much smaller (mean Elbe sub catchment reactivated floodplain area 0.4%) as the large part of floodplain in the downstream Elbe is not part of the selected sub catchments. With these rather large areas changes in the floodplain N retention have a large impact. For the Rhine this difference is less pronounced with a mean of 0.3% of sub catchment area of reactivated floodplains. The uncertainty for this scenario and consequently for scenario 5, including the same nature-based solutions needs further evaluation and discussion.

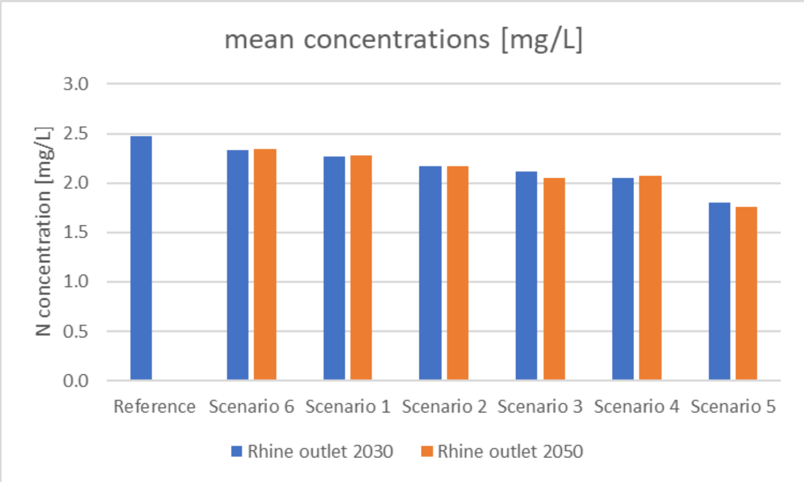

Figure 1. N concentrations the Rhine outlet considering the different scenarios and the reference (2010-2020).

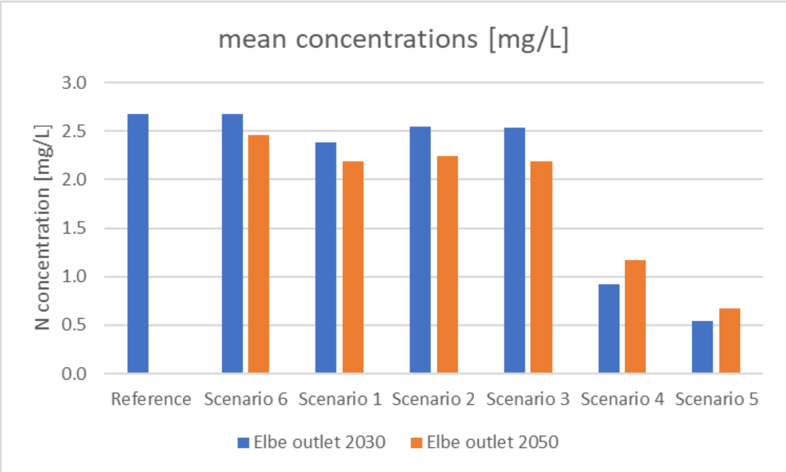

Figure 2. N concentrations the Elbe outlet considering the different scenarios and the reference (2010-2020).

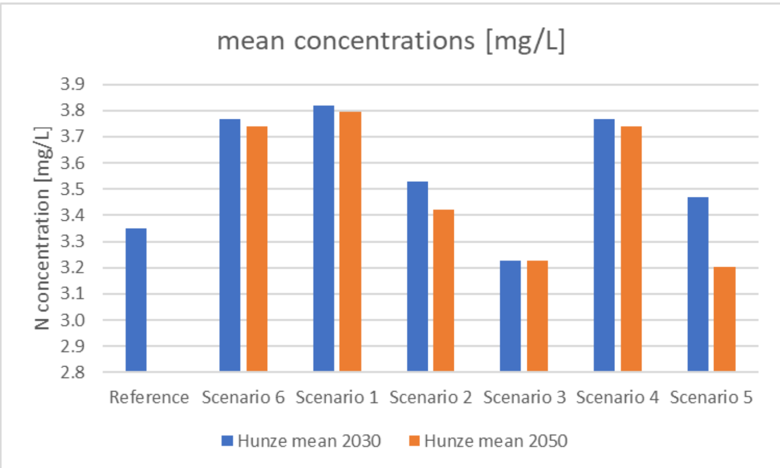

Figure 3. Average N concentrations in the Hunze catchments considering the different scenarios and the reference (2010-2020).

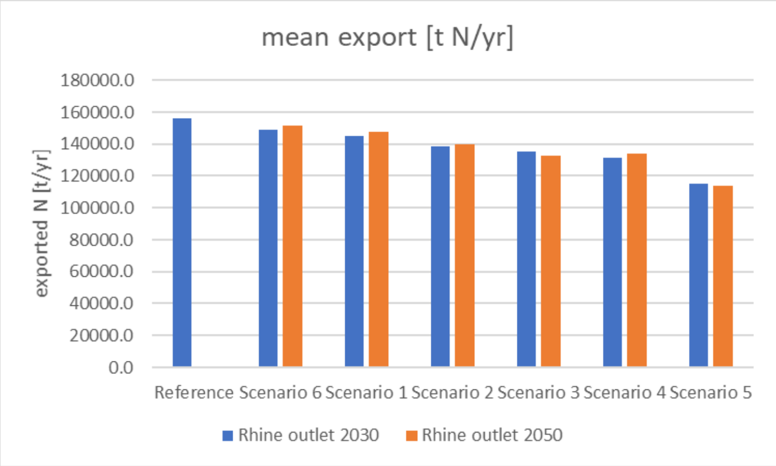

Figure 4. N export the Rhine outlet considering the different scenarios and the reference (2010-2020).

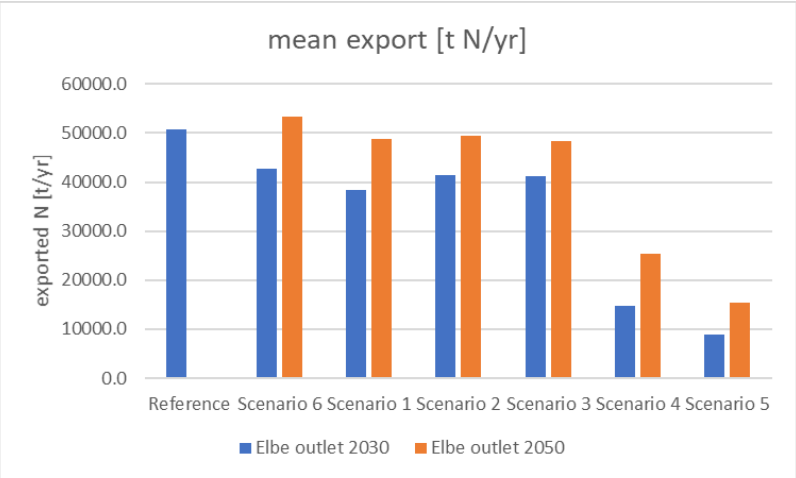

Figure 5. N export the Elbe outlet considering the different scenarios and the reference (2010-2020).

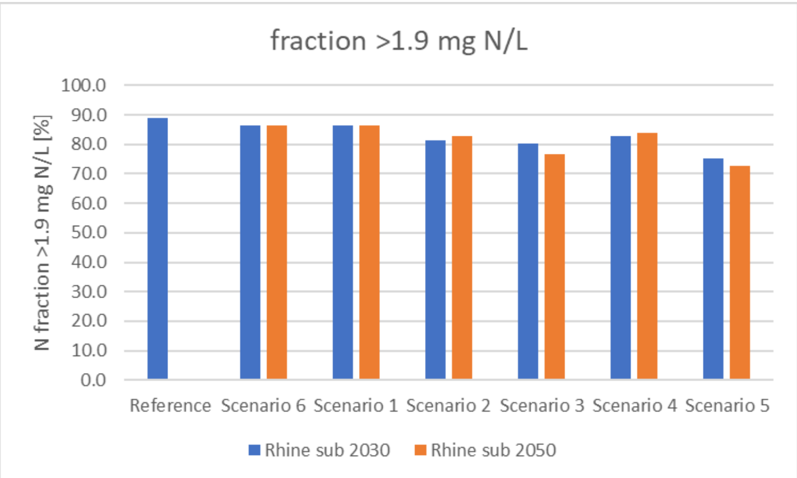

Figure 6. Fraction of sub catchments in the Rhine above the threshold of 1.9 mg N/L considering the different scenarios and the reference (2010-2020).

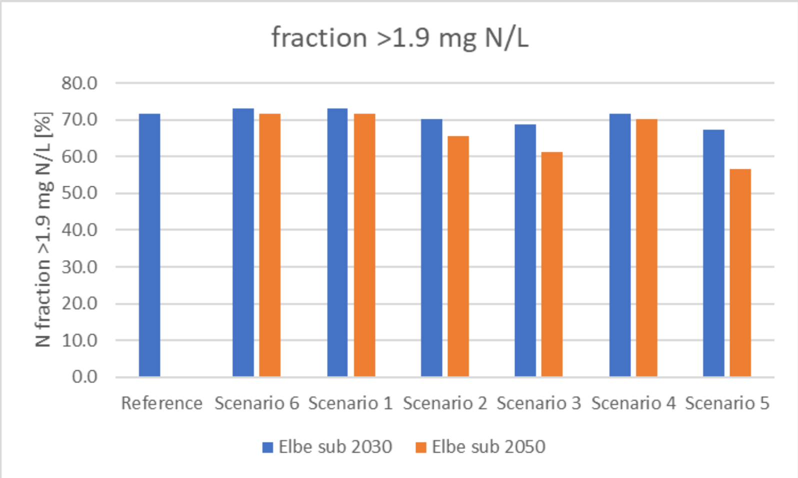

Figure 7. Fraction of sub catchments in the Elbe above the threshold of 1.9 mg N/L considering the different scenarios and the reference (2010-2020).

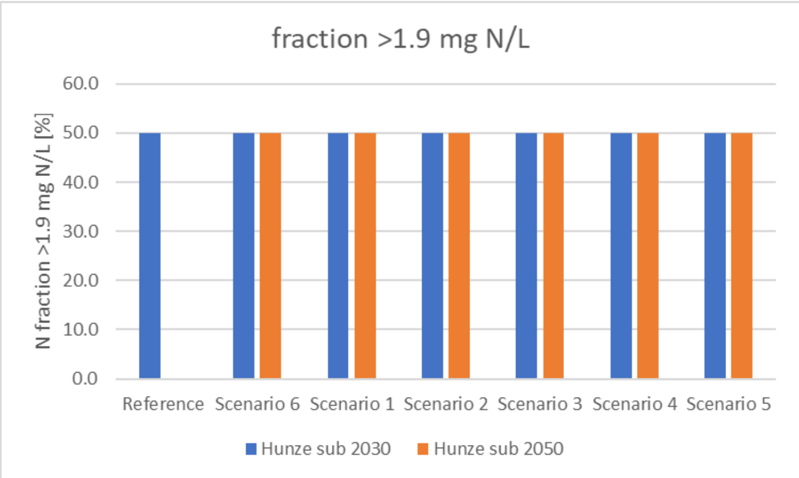

Figure 8. Fraction of sub catchments in the Hunze above the threshold of 1.9 mg N/L considering the different scenarios and the reference (2010-2020).

3.2. N evolution at the catchment outlet

The temporal evolution of N at the outlet is of special interest since N typically shows delayed effects of stream concentrations and fluxes when the diffuse input into the catchment is changed (Lutz et al. 2022). This is due to legacy N stores that have built up in the catchment soils and long (multi-years) travel time of N within the groundwater bodies. Figure 9 shows the temporal evolution of N input and modelled for scenarios 6 at the catchment outlets for Elbe and Rhine including uncertainty as a result of the calibration process. Figure 10 shows the temporal evolution of the combined scenario 5. All other scenario figures are provided as supplements in Annex II. Model results for P are evaluated by three major metrics that are in line with the ideas of safe ecological limits defined in work package 4: 1. The loads of TP exported at the catchment outlet of Elbe and Rhine. 2. The concentration of SRP at the catchment outlet. 3. The fraction of the river network that does not exhibit a good SRP status (SRP concentrations >55 µg/L).

The figures 9 and 10 also show that the uncertainty introduced by the model calibration is in an acceptable range compared to the temporal variability introduced by the projected discharge and the nutrient reduction measures.

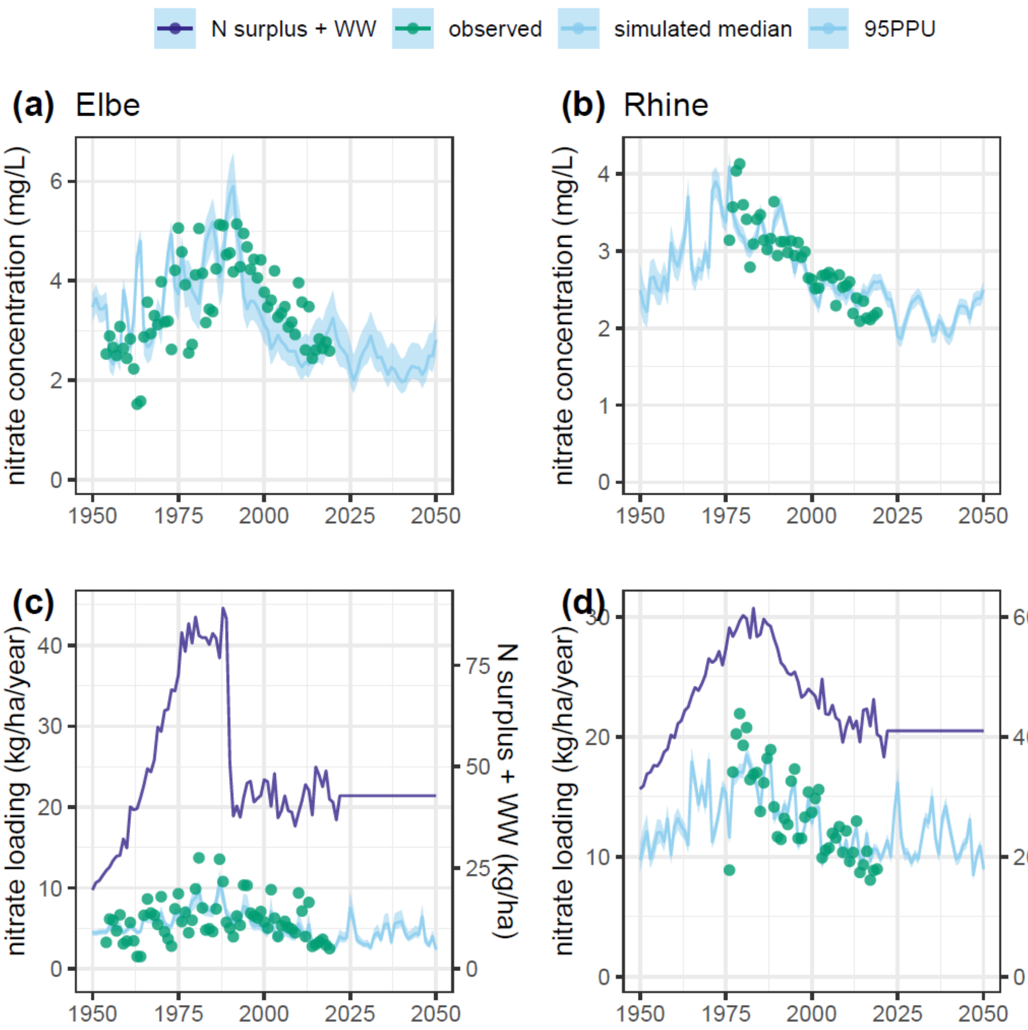

Figure 9. Scenario 6, depicting climate change effects without changes of the nutrient inputs and retention. (a): Elbe outlet concentrations, (b) Rhine outlet concentrations, (c) N loading at the Elbe outlet and N inputs by diffuse and wastewater point sources, (d) N loading at the Rhine outlet and N inputs by diffuse and wastewater point sources. Dots display observed values in the past that have been used for model calibration (D3.2; Musolff & Ledesma, 2024).

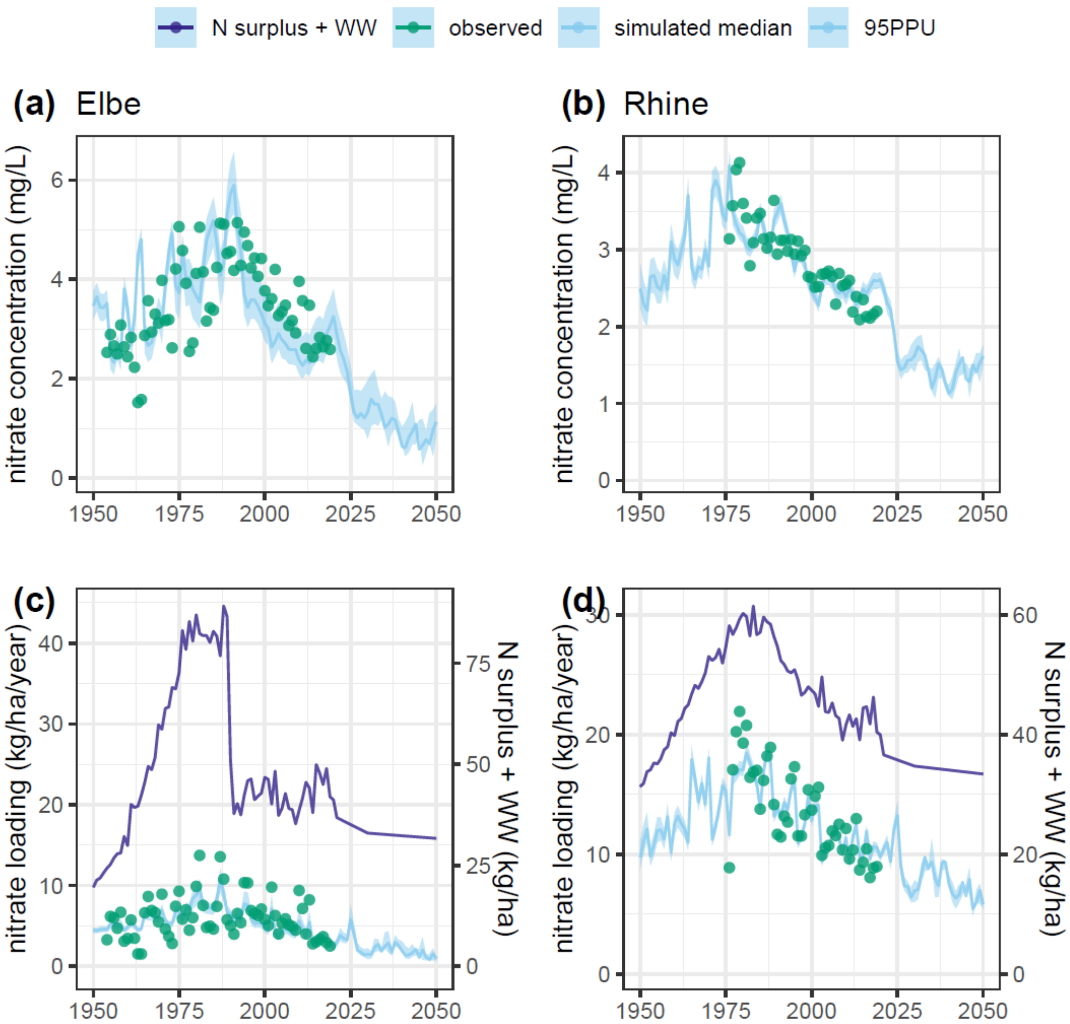

Figure 10. Scenario 5, depicting maximum nutrient reduction and climate change effects. (a): Elbe outlet concentrations, (b) Rhine outlet concentrations, (c) N loading at the Elbe outlet and N inputs by diffuse and wastewater point sources, (d) N loading at the Rhine outlet and N inputs by diffuse and wastewater point sources. Dots display observed values in the past that have been used for model calibration (D3.2; Musolff & Ledesma, 2024).

4. RESULTS FOR P

4.1. Overview for P

The table in Annex I provided as a supplement gives a full overview on the concentrations and loads of P at the demonstrator catchment outlets and the entire river network and the differences from the reference models (2010-2020).

Similar to N (chapter 3.1) projected discharge is playing a notable role for P as well in the differences between the different scenario time-horizons and in the difference to the reference period. This is true for the exported TP flux (Fig. 11-12) to a much larger extent to the concentrations at the outlet (Fig. 13-14). Especially exported TP fluxes are partly more variable between the three different modelled time horizons (reference, 2030 – 2028-2032 average and 2050 – 2046-2050 average) than between different nutrient reduction scenarios within one time horizon.

For scenario 5, combining climate change, wastewater input reductions and the effect of nature-based solutions, strongest reductions in loads and concentrations are reached (Fig. 11-12, 14-15). Compared to the climate change scenario, exports from the Elbe reduced by 22% for the time horizon 2030 (16% compared to the reference period) and by 23% for the time horizon 2050 (43% compared to the reference period). Exports from the Rhine reduced by 31% for the time horizon 2030 and 2050 (27% compared to the reference period). The weakest effects on the exported loads were found for scenario 4 in both, Elbe and Rhine outlet. The additional retention by enhanced retention in buffer strips only reduced exported loads from the Elbe and Rhine by less than 1%. Consequently, the main effect of measures in scenario 5 in the modelled catchments is the effect of the implementation of the new UWWTD from scenario 1. While the loads at the catchment outlet are reduced by the nutrient reduction measures, effects on the fraction of catchments that are not in compliance with the mean annual SRP concentration threshold of 0.055 mg P/L, are not as strong though compliance was much better than for nitrate in the reference period already. Under the highest nutrient reduction scenario 5, in 2050 still more than 15% of all river sections in the Rhine basin (Fig. 16) and more than 34% of all river sections in the Elbe basin (Fig. 17) are above the concentration threshold. For the seven modelled Hunze catchments, all stream sections have been in line with this threshold under reference conditions. For the scenarios with changed discharge conditions 1 out of 7 catchments was projected to be not in line with the threshold in all the scenarios (Fig. 18).

We note that the inability of the CnANDY model to model the consequences of planned measures in the agricultural sector is not sufficient at the moment. More specifically, we need a better understanding of what effect measures that aim at reduced inputs of particle bound P into the river network (i.e. soil erosion) would have on the dissolved SRP inputs. This needs further evaluation and discussion in the consortium.

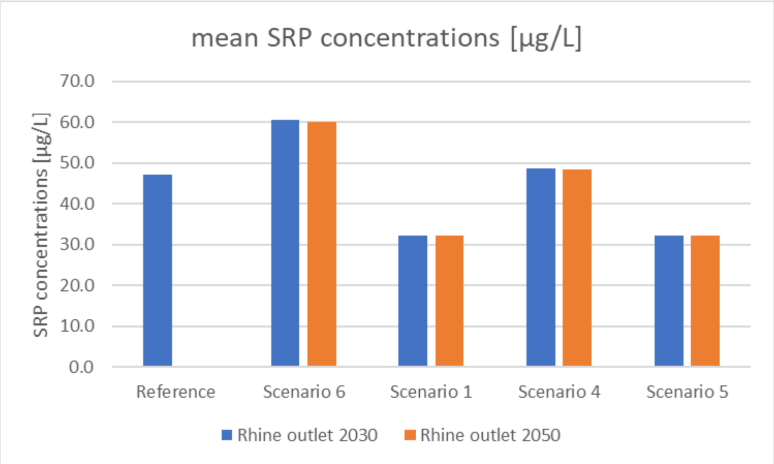

Figure 11. SRP concentrations the Rhine outlet considering the different scenarios and the reference (2010-2020).

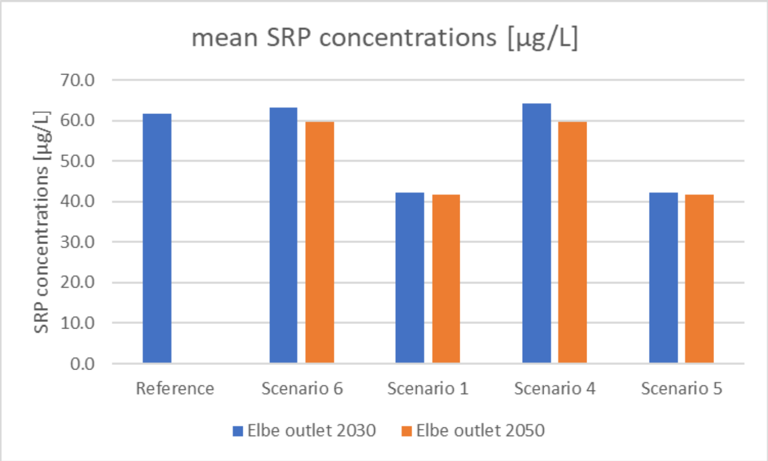

Figure 12. SRP concentrations the Elbe outlet considering the different scenarios and the reference (2010-2020).

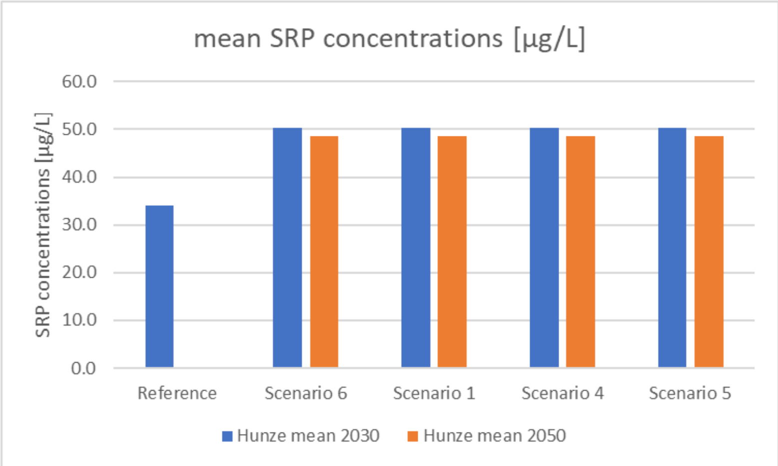

Figure 13. Average SRP concentrations in the Hunze catchments considering the different scenarios and the reference (2010-2020).

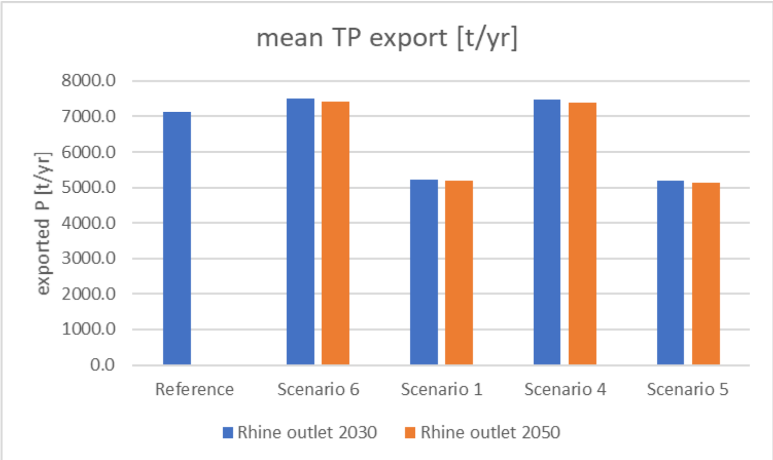

Figure 14. TP export at the Rhine outlet considering the different scenarios and the reference (2010-2020).

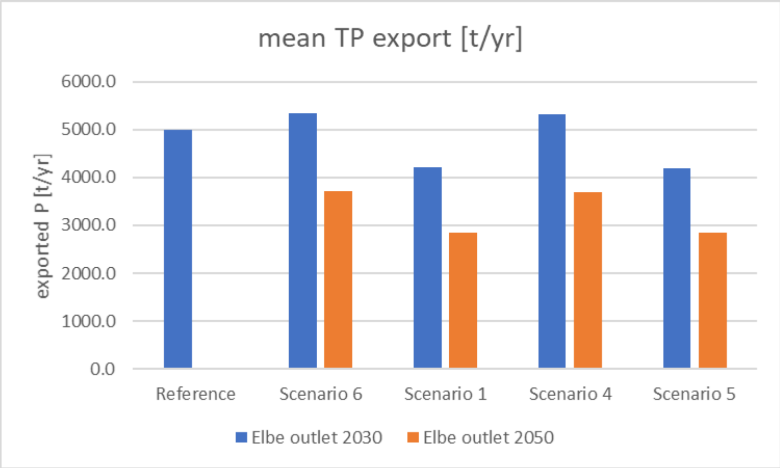

Figure 15. TP export at the Elbe outlet considering the different scenarios and the reference (2010-2020).

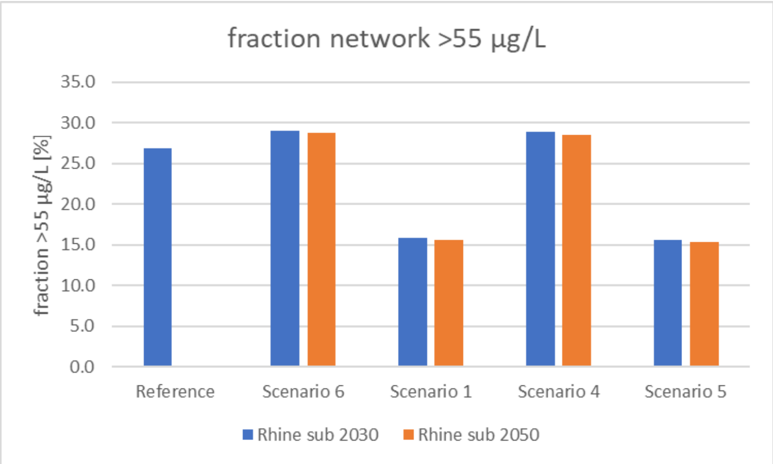

Figure 16. Fraction of river network in the Rhine above the threshold of 0.055 µg/L SRP considering the different scenarios and the reference (2010-2020).

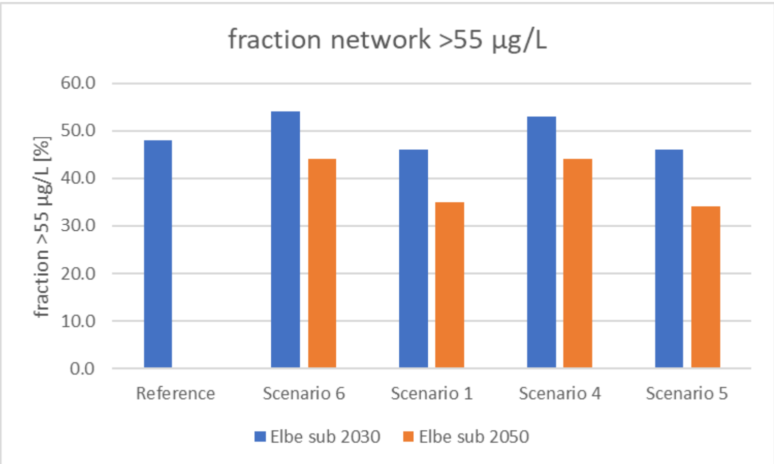

Figure 17. Fraction of river network in the Elbe above the threshold of 0.055 µg/L SRP considering the different scenarios and the reference (2010-2020).

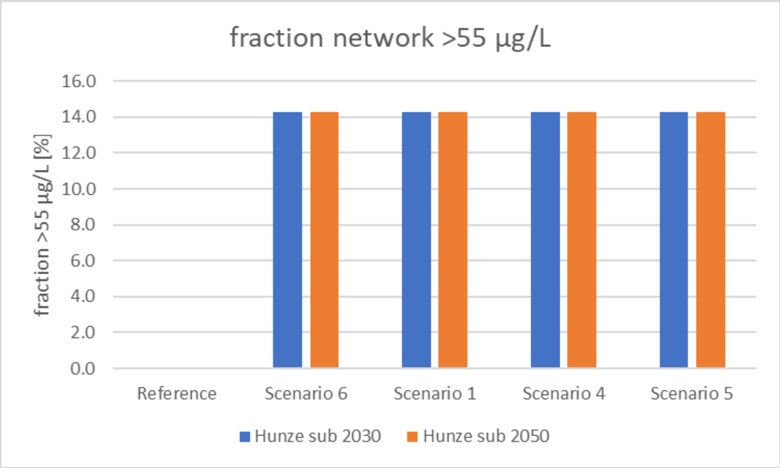

Figure 18. Fraction of river network in the Hunze above the threshold of 0.055 µg/L SRP considering the different scenarios and the reference (2010-2020).

4.2. P spatial patterns

In comparison to N, there is a special interest of the spatial pattern of SRP concentrations in the river network that is driven the interaction of spatially distributed sources, water travel time in the river network and algae competition for light and nutrients (Yang et al., 2021).

The following figures illustrate the spatial pattern of SRP in the Elbe river network under the climate change scenario 5 and the maximum P reduction within this scenario. We observe that the spatial pattern is mainly driven by the distribution of population density and wastewater inputs, with the highest concentrations as around the major cities like Berlin and Prague for the Elbe. The spatial SRP concentration pattern persists across the different scenarios. However, the general pattern persists, the proportion of the river network matching the 0.055 mg/L concentration threshold changes between scenarios and time horizons (see 4.2).

All other figures for Elbe and Rhine SRP distribution are enclosed in Annex III.

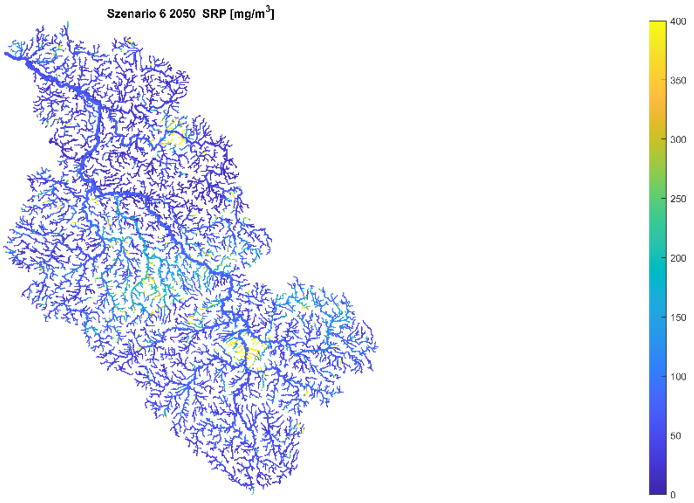

Figure 19. River network SRP concentrations in µg/L (=mg/m³) of the Elbe river under climate change conditions while sources are kept constant (scenario 6, year 2050).

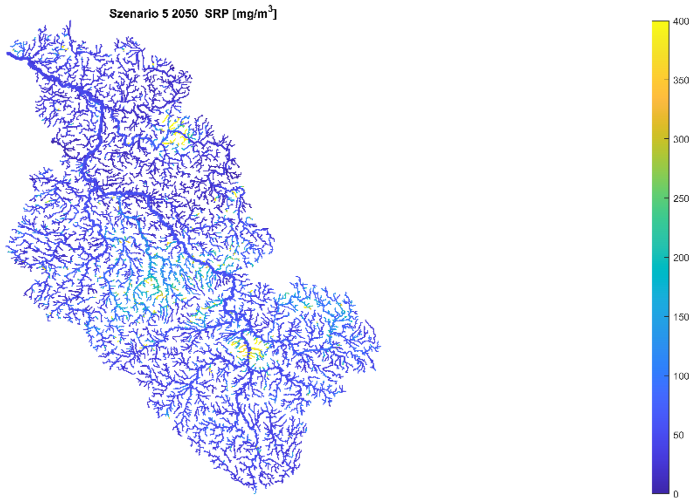

Figure 20. River network SRP concentrations in µg/L (=mg/m^3) of the Elbe river under climate change conditions while wastewater sources are reduced and buffer strips are enhanced (scenario 5, year 2050).

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ANNEX I

Tables for phosphorus (results_D35_P) and nitrogen (results_D35_N) provided below :

Reference	diffuse P [kg/ha yr]	wastewater P [kg/ha yr]	mean concentrations SRP [µg/L]	mean concentrations TP [µg/L]	mean export TP [t/yr]	network > 55 µg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	0.246	0.285	47.2	98.2	7118.8	-	-	-
Elbe outlet	0.156	0.140	61.7	218.8	4982.9	-	-	-
Rhine subcatchments	0.246	0.285	57.8	-	-	26.9	-	-
Elbe subcatchments	0.156	0.140	82.7	-	-	48.0	-	-
Hunze subcatchments	0.100	0.053	34.1	88.0	-	0.0	-	-

Scenario 6 2030	diffuse P [kg/ha yr]	wastewater P [kg/ha yr]	mean concentrations SRP [µg/L]	mean concentrations TP [µg/L]	mean export TP [t/yr]	network > 55 µg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	0.246	0.285	48.8	106.6	7501.6	-	-5.4	-
Elbe outlet	0.156	0.140	63.2	323.2	5339.1	-	-7.1	-
Rhine subcatchments	0.246	0.285	60.5	-	-	29.1		-
Elbe subcatchments	0.156	0.140	95.3	-	-	54.0	-	-
Hunze subcatchments	0.100	0.053	50.2	104.3	-	14.3	-	-

Scenario 6 2050	diffuse P [kg/ha yr]	wastewater P [kg/ha yr]	mean concentrations SRP [µg/L]	mean concentrations TP [µg/L]	mean export TP [t/yr]	network > 55 µg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	0.246	0.285	48.6	104.4	7404.7	-	-4.0	-
Elbe outlet	0.156	0.140	59.7	167.0	3703.6	-	25.7	-
Rhine subcatchments	0.246	0.285	60.0	-	-	28.7		-
Elbe subcatchments	0.156	0.140	74.7	-	-	44.0	-	-
Hunze subcatchments	0.100	0.053	48.6	93.2	-	14.3	-	-

Scenario 1 2030	diffuse P [kg/ha yr]	wastewater P [kg/ha yr]	mean concentrations SRP [µg/L]	mean concentrations TP [µg/L]	mean export TP [t/yr]	network > 55 µg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	0.246	0.128	32.3	74.3	5227.8	-	26.6	30.3
Elbe outlet	0.156	0.073	42.2	254.4	4202.4	-	15.7	21.3
Rhine subcatchments	0.246	0.128	45.2	-	-	15.8		
Elbe subcatchments	0.156	0.073	79.5	-	-	46.0	-	-
Hunze subcatchments	0.100	0.053	50.2	104.3	-	14.3	-	-

Scenario 1 2050	diffuse P [kg/ha yr]	wastewater P [kg/ha yr]	mean concentrations SRP [µg/L]	mean concentrations TP [µg/L]	mean export TP [t/yr]	network > 55 µg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	0.246	0.128	32.2	73.0	5178.0	-	27.3	30.1
Elbe outlet	0.156	0.073	41.7	128.5	2851.3	-	42.8	23.0
Rhine subcatchments	0.246	0.128	44.9	-	-	15.6		
Elbe subcatchments	0.156	0.073	62.7	-	-	35.0	-	-
Hunze subcatchments	0.100	0.053	48.6	93.2	-	14.3	-	-

Scenario 4 2030	diffuse P [kg/ha yr]	wastewater P [kg/ha yr]	mean concentrations SRP [µg/L]	mean concentrations TP [µg/L]	mean export TP [t/yr]	network > 55 µg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	0.245	0.128	48.7	106.0	7459.4	-	-4.8	0.6
Elbe outlet	0.155	0.140	64.1	322.1	5321.9	-	-6.8	0.3
Rhine subcatchments	0.245	0.285	60.3	-	-	28.8		
Elbe subcatchments	0.155	0.140	94.96	-	-	53.0	-	-
Hunze subcatchments	0.100	0.053	50.2	104.3	-	14.3	-	-

Scenario 4 2050	diffuse P [kg/ha yr]	wastewater P [kg/ha yr]	mean concentrations SRP [µg/L]	mean concentrations TP [µg/L]	mean export TP [t/yr]	network > 55 µg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	0.245	48.500	48.5	104.2	7394.8	-	-3.9	0.1
Elbe outlet	0.155	0.140	59.6	166.4	3690.9	-	25.9	0.3
Rhine subcatchments	0.245	0.285	59.8	-	-	28.5		
Elbe subcatchments	0.155	0.140	74.5	-	-	44.0	-	-
Hunze subcatchments	0.100	0.053	48.6	93.2	-	14.3	-	-

Scenario 5 2030	diffuse P [kg/ha yr]	wastewater P [kg/ha yr]	mean concentrations SRP [µg/L]	mean concentrations TP [µg/L]	mean export TP [t/yr]	network > 55 µg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	0.245	0.128	32.2	73.7	5186.3	-	27.1	30.9
Elbe outlet	0.155	0.073	42.2	253.3	4184.4	-	16.0	21.6
Rhine subcatchments	0.245	0.128	45.0	-	-	15.6		
Elbe subcatchments	0.155	0.073	79.16	-	-	46.0	-	-
Hunze subcatchments	0.100	0.053	50.2	104.3	-	14.3	-	-

Scenario 5 2050	diffuse P [kg/ha yr]	wastewater P [kg/ha yr]	mean concentrations SRP [µg/L]	mean concentrations TP [µg/L]	mean export TP [t/yr]	network > 55 µg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	0.245	0.128	32.1	72.4	5136.8	-	27.8	30.6
Elbe outlet	0.155	0.073	41.7	128.0	2838.7	-	43.0	23.4
Rhine subcatchments	0.245	0.128	44.7	-	-	15.4		
Elbe subcatchments	0.155	0.073	62.5	-	-	34.0	-	-
Hunze subcatchments	0.100	0.053	48.6	93.2	-	14.3	-	-

Reference	N surplus [kg N/ha yr]	N wastewater [kg N/ha yr]	mean concentrations [mg/L]	mean export [kg N/ ha yr]	mean export [t N/yr]	stations > 1.9 mg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	39.2	3.2	2.5	10.8	156074.8	-	-	-
Elbe outlet	42.5	1.4	2.7	3.9	50686.5	-	-	-
Rhine subcatchments	40.3	3.3	3.7	11.3	-	88.9	-	-
Elbe subcatchments	40.3	1.7	3.6	8.2	-	71.6	-	-
Hunze subcatchments	79.5	1.0	3.4	7.8	-	50.0		

Scenario 6 2030	N surplus [kg N/ha yr]	N wastewater [kg N/ha yr]	mean concentrations [mg/L]	mean export [kg N/ ha yr]	mean export [t N/yr]	stations > 1.9 mg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	37.8	3.2	2.3	10.3	148879.0	-	-4.6	-
Elbe outlet	41.4	1.4	2.7	3.3	42665.9	-	-15.8	-
Rhine subcatchments	38.5	3.4	3.1	11.5	-	86.4	2.4	-
Elbe subcatchments	37.5	1.7	3.3	7.3	-	73.1	-11.8	-
Hunze subcatchments	77.0	1.1	3.8	10.7	-	50.0		

Scenario 6 2050	N surplus [kg N/ha yr]	N wastewater [kg N/ha yr]	mean concentrations [mg/L]	mean export [kg N/ ha yr]	mean export [t N/yr]	stations > 1.9 mg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	37.8	3.2	2.3	10.5	151728.1	-	-2.8	-
Elbe outlet	41.4	1.4	2.5	4.1	53291.5	-	5.1	-
Rhine subcatchments	38.5	3.4	3.2	11.2	-	86.4	-0.6	-
Elbe subcatchments	37.5	1.7	3.0	7.8	-	71.6	-5.1	-
Hunze subcatchments	77.0	1.1	3.7	9.7	-	50.0		

Scenario 1 2030	N surplus [kg N/ha yr]	N wastewater [kg N/ha yr]	mean concentrations [mg/L]	mean export [kg N/ ha yr]	mean export [t N/yr]	stations > 1.9 mg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	37.8	2.9	2.3	10.0	145051.0	-	-7.1	-2.6
Elbe outlet	41.4	0.9	2.4	3.0	38366.1	-	-24.3	-10.1
Rhine subcatchments	38.5	3.1	3.0	11.3	-	86.4	0.3	-2.0
Elbe subcatchments	37.5	1.4	3.2	7.1	-	73.1	-14.4	-3.0
Hunze subcatchments	77.0	1.3	3.8	10.9	-	50.0		

Scenario 1 2050	N surplus [kg N/ha yr]	N wastewater [kg N/ha yr]	mean concentrations [mg/L]	mean export [kg N/ ha yr]	mean export [t N/yr]	stations > 1.9 mg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	37.8	2.8	2.3	10.2	147634.7	-	-5.4	-2.7
Elbe outlet	41.4	0.9	2.2	3.8	48686.6	-	-3.9	-8.6
Rhine subcatchments	38.5	3.0	3.1	11.0	-	86.4	-2.8	-2.3
Elbe subcatchments	37.5	1.4	2.9	7.6	-	71.6	-7.9	-2.9
Hunze subcatchments	77.0	1.3	3.8	9.9	-	50.0		

Scenario 2 2030	N surplus [kg N/ha yr]	N wastewater [kg N/ha yr]	mean concentrations [mg/L]	mean export [kg N/ ha yr]	mean export [t N/yr]	stations > 1.9 mg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	32.9	3.2	2.2	9.6	138446.2	-	-11.3	-7.0
Elbe outlet	34.3	1.4	2.5	3.2	41402.5	-	-18.3	-3.0
Rhine subcatchments	32.0	3.4	2.8	10.8	-	81.5	-4.4	-6.6
Elbe subcatchments	28.4	1.7	2.9	6.5	-	70.1	-21.4	-10.9
Hunze subcatchments	71.4	1.1	3.5	10.1	-	50.0		

Scenario 2 2050	N surplus [kg N/ha yr]	N wastewater [kg N/ha yr]	mean concentrations [mg/L]	mean export [kg N/ ha yr]	mean export [t N/yr]	stations > 1.9 mg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	32.9	3.2	2.2	9.7	140074.0	-	-10.3	-7.7
Elbe outlet	34.2	1.4	2.2	3.8	49346.3	-	-2.6	-7.4
Rhine subcatchments	32.0	3.4	2.9	10.2	-	82.7	-9.3	-8.7
Elbe subcatchments	28.4	1.7	2.6	6.6	-	65.7	-19.5	-15.2
Hunze subcatchments	71.4	1.1	3.4	8.9	-	50.0		

Scenario 3 2030	N surplus [kg N/ha yr]	N wastewater [kg N/ha yr]	mean concentrations [mg/L]	mean export [kg N/ ha yr]	mean export [t N/yr]	stations > 1.9 mg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	31.0	3.2	2.1	9.4	135207.3	-	-13.4	-9.2
Elbe outlet	33.0	1.4	2.5	3.2	41268.6	-	-18.6	-3.3
Rhine subcatchments	29.4	3.4	2.7	10.5	-	80.2	-6.5	-8.6
Elbe subcatchments	26.2	1.7	2.8	6.3	-	68.7	-23.1	-12.9
Hunze subcatchments	68.3	1.1	3.5	9.9	-	50.0		

Scenario 3 2050	N surplus [kg N/ha yr]	N wastewater [kg N/ha yr]	mean concentrations [mg/L]	mean export [kg N/ ha yr]	mean export [t N/yr]	stations > 1.9 mg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	29.6	3.2	2.1	9.2	132892.0	-	-14.9	-12.4
Elbe outlet	31.7	1.4	2.2	3.8	48406.1	-	-4.5	-9.2
Rhine subcatchments	27.9	3.4	2.7	9.7	-	76.5	-14.1	-13.6
Elbe subcatchments	24.8	1.7	2.4	6.2	-	61.2	-24.5	-20.5
Hunze subcatchments	66.5	1.1	3.2	8.5	-	50.0		

Scenario 4 2030	N surplus [kg N/ha yr]	N wastewater [kg N/ha yr]	mean concentrations [mg/L]	mean export [kg N/ ha yr]	mean export [t N/yr]	stations > 1.9 mg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	37.8	3.2	2.1	9.1	131124.5	-	-16.0	-11.9
Elbe outlet	41.4	1.4	0.9	1.1	14737.7	-	-70.9	-65.5
Rhine subcatchments	38.5	3.4	3.0	11.3	-	82.7	0.0	-2.3
Elbe subcatchments	37.5	1.7	3.1	7.0	-	71.6	-14.8	-3.4
Hunze subcatchments	77.0	1.1	3.8	10.7	-	50.0		

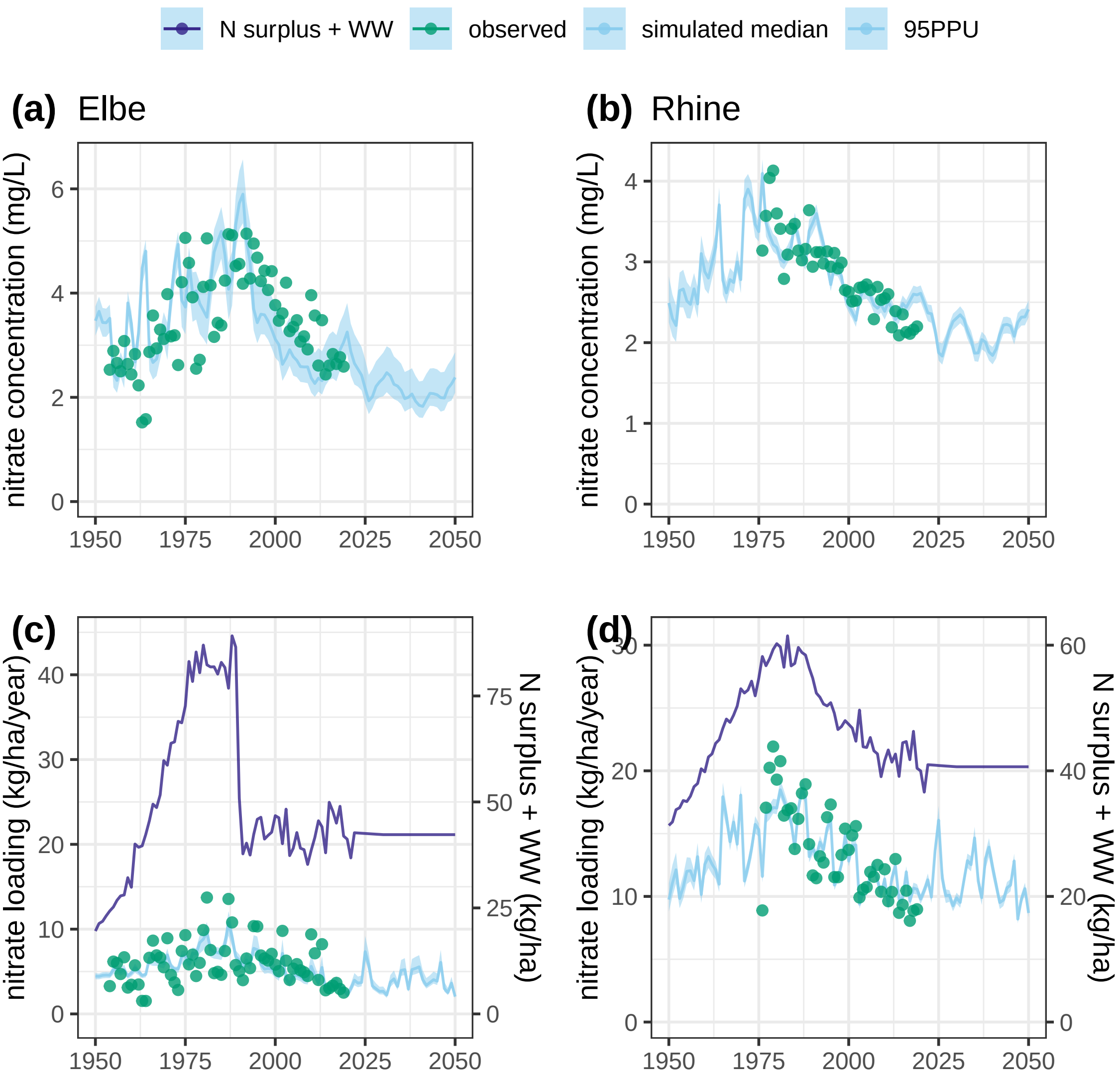
Scenario 4 2050	N surplus [kg N/ha yr]	N wastewater [kg N/ha yr]	mean concentrations [mg/L]	mean export [kg N/ ha yr]	mean export [t N/yr]	stations > 1.9 mg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	37.8	3.2	2.1	9.3	133950.8	-	-14.2	-11.7
Elbe outlet	41.4	1.4	1.2	2.0	25335.6	-	-50.0	-52.5
Rhine subcatchments	38.5	3.4	3.1	10.9	-	84.0	-2.9	-2.4
Elbe subcatchments	37.5	1.7	2.9	7.6	-	70.1	-8.1	-3.2
Hunze subcatchments	77.0	1.1	3.7	9.7	-	50.0		

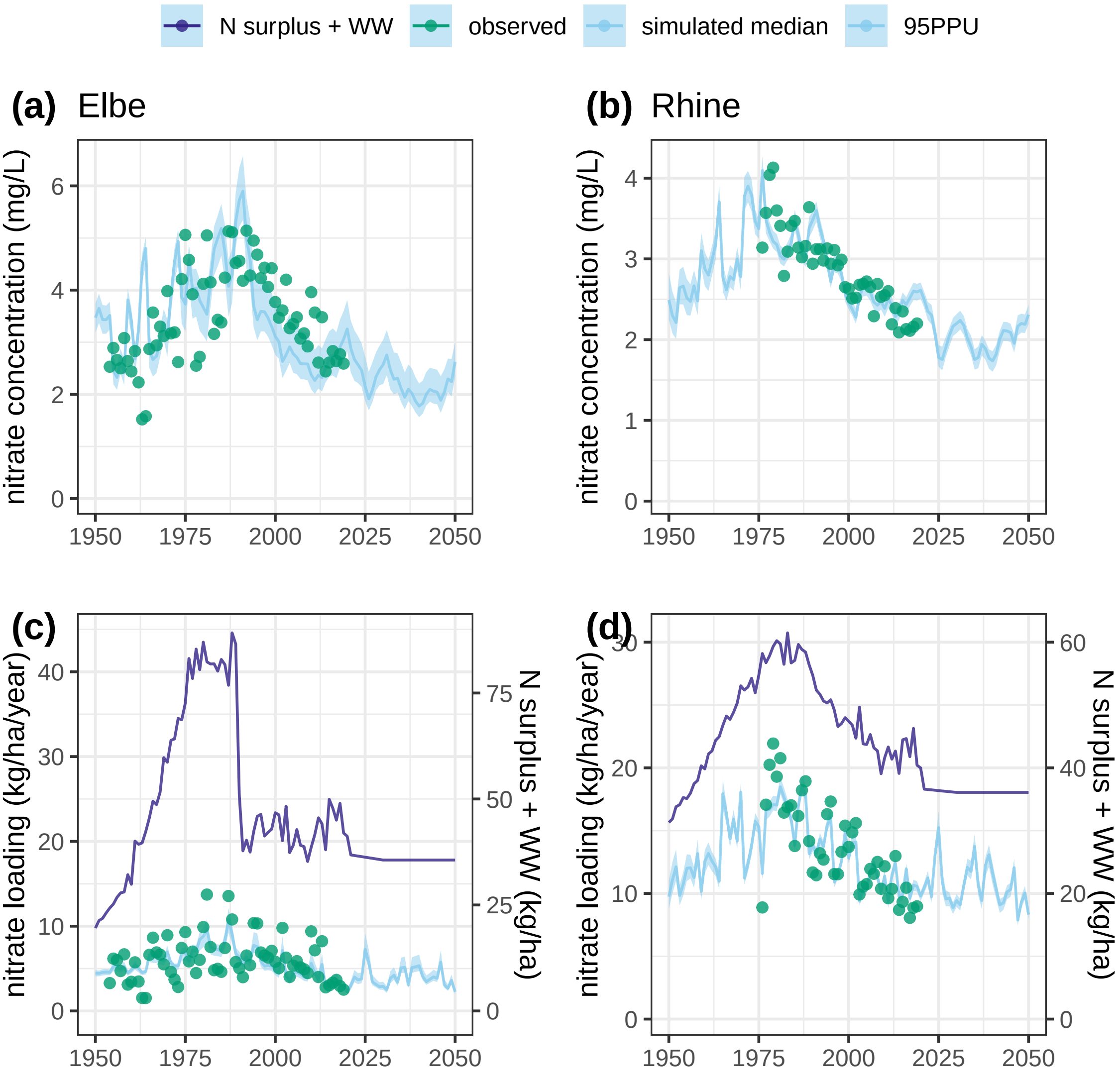
Scenario 5 2030	N surplus [kg N/ha yr]	N wastewater [kg N/ha yr]	mean concentrations [mg/L]	mean export [kg N/ ha yr]	mean export [t N/yr]	stations > 1.9 mg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	32.0	2.9	1.8	8.0	115437.3	-	-26.0	-22.5
Elbe outlet	32.2	0.9	0.5	0.7	8965.3	-	-82.3	-79.0
Rhine subcatchments	31.2	3.1	2.6	10.2	-	75.3	-9.3	-11.5
Elbe subcatchments	27.1	1.4	2.6	5.9	-	67.2	-27.9	-18.2
Hunze subcatchments	66.6	1.3	3.5	9.9	-	50.0		

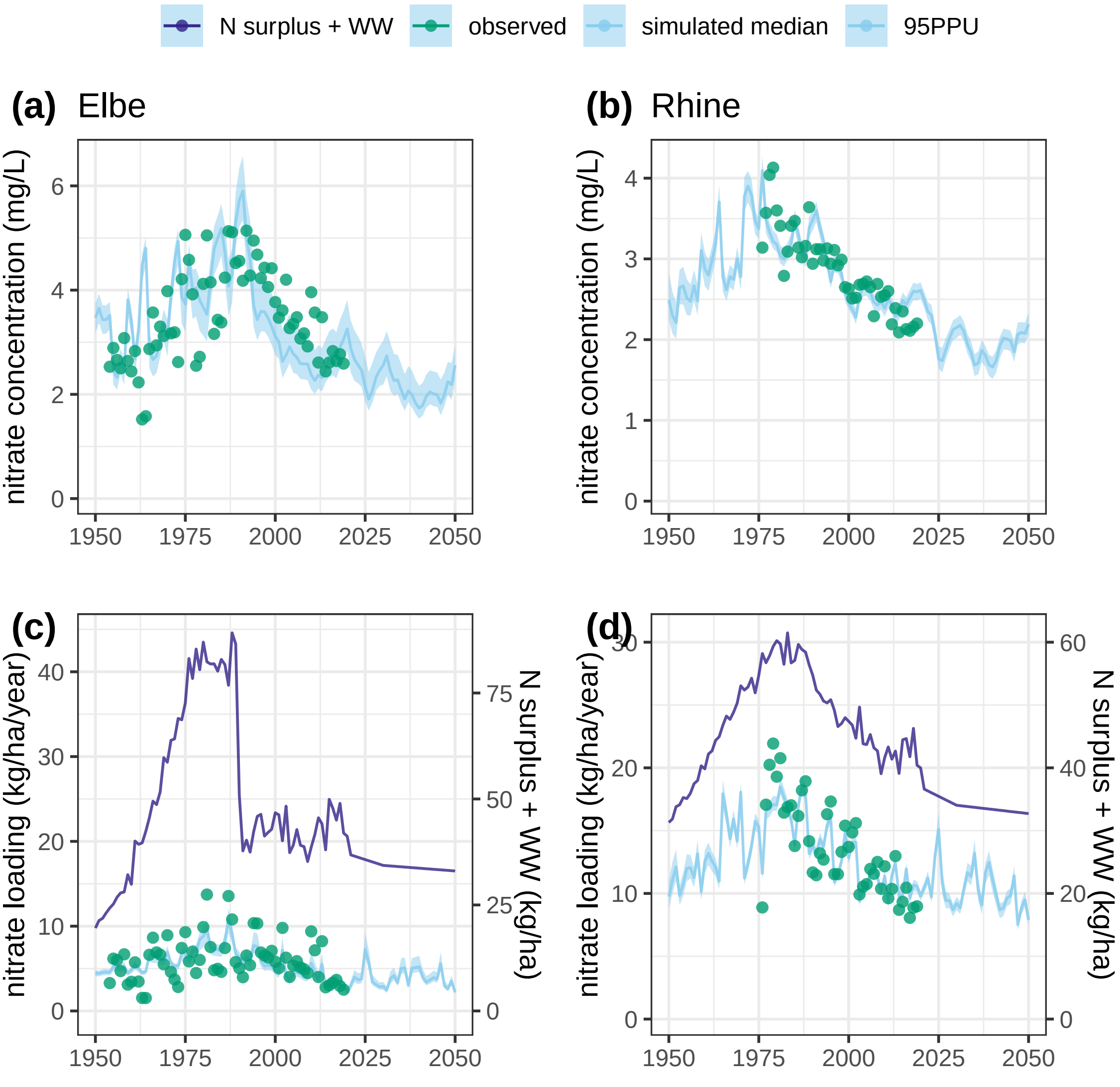
Scenario 5 2050	N surplus [kg N/ha yr]	N wastewater [kg N/ha yr]	mean concentrations [mg/L]	mean export [kg N/ ha yr]	mean export [t N/yr]	stations > 1.9 mg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	30.7	2.8	1.8	7.9	113725.4	-	-27.1	-25.0
Elbe outlet	30.9	0.9	0.7	1.2	15432.2	-	-69.6	-71.0
Rhine subcatchments	29.9	3.0	2.6	9.5	-	72.8	-16.1	-15.6
Elbe subcatchments	25.9	1.4	2.2	5.9	-	56.7	-28.4	-24.6
Hunze subcatchments	64.7	1.3	3.2	8.4	-	50.0		

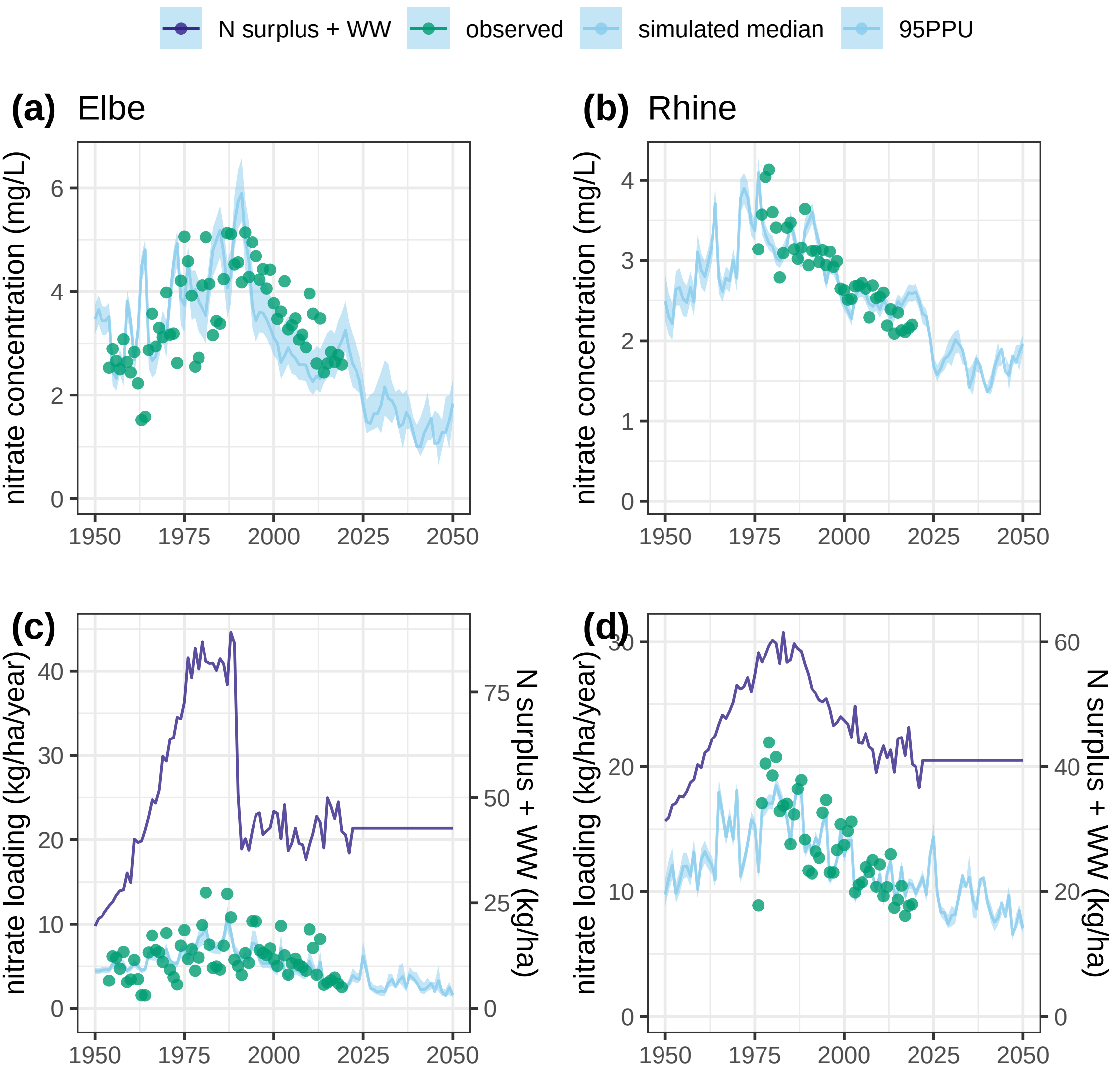
ANNEX II

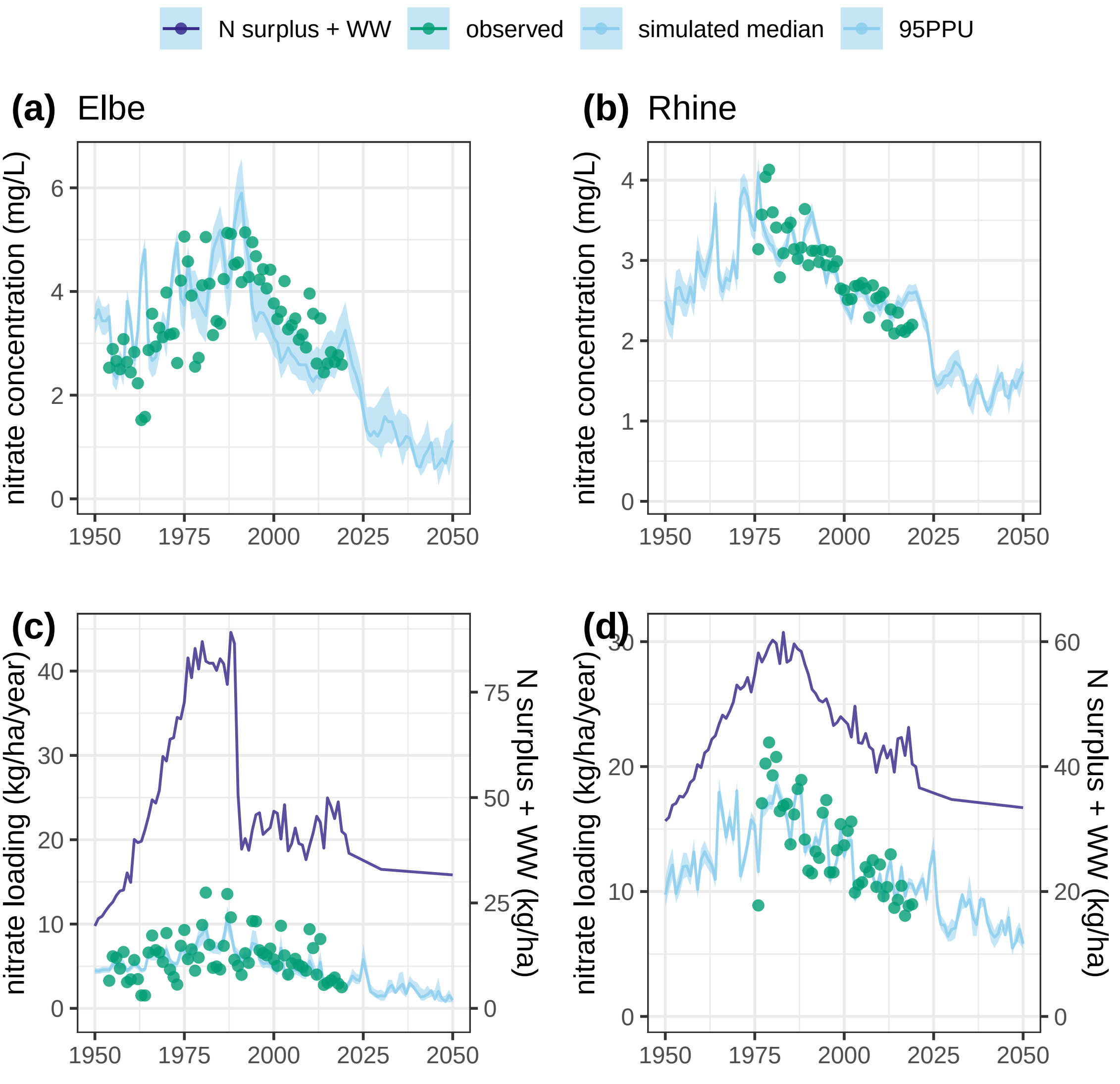
Figures for all scenarios (sim_N_c_loading_Elbe_Rhine_scen_x) on nitrate concentration and nitrage loading for the Elbe and Rhine over time.


N surplus + WW
observed
simulated median
95PPU
(a) Elbe
(b) Rhine
(c)
(d)
nitrate concentration (mg/L)
nitrate loading (kg/ha/year)
N surplus + WW (kg/ha)
0
2
4
6
1
3
10
20
30
40
25
50
75
60
1950
1975
2000
2025
2050

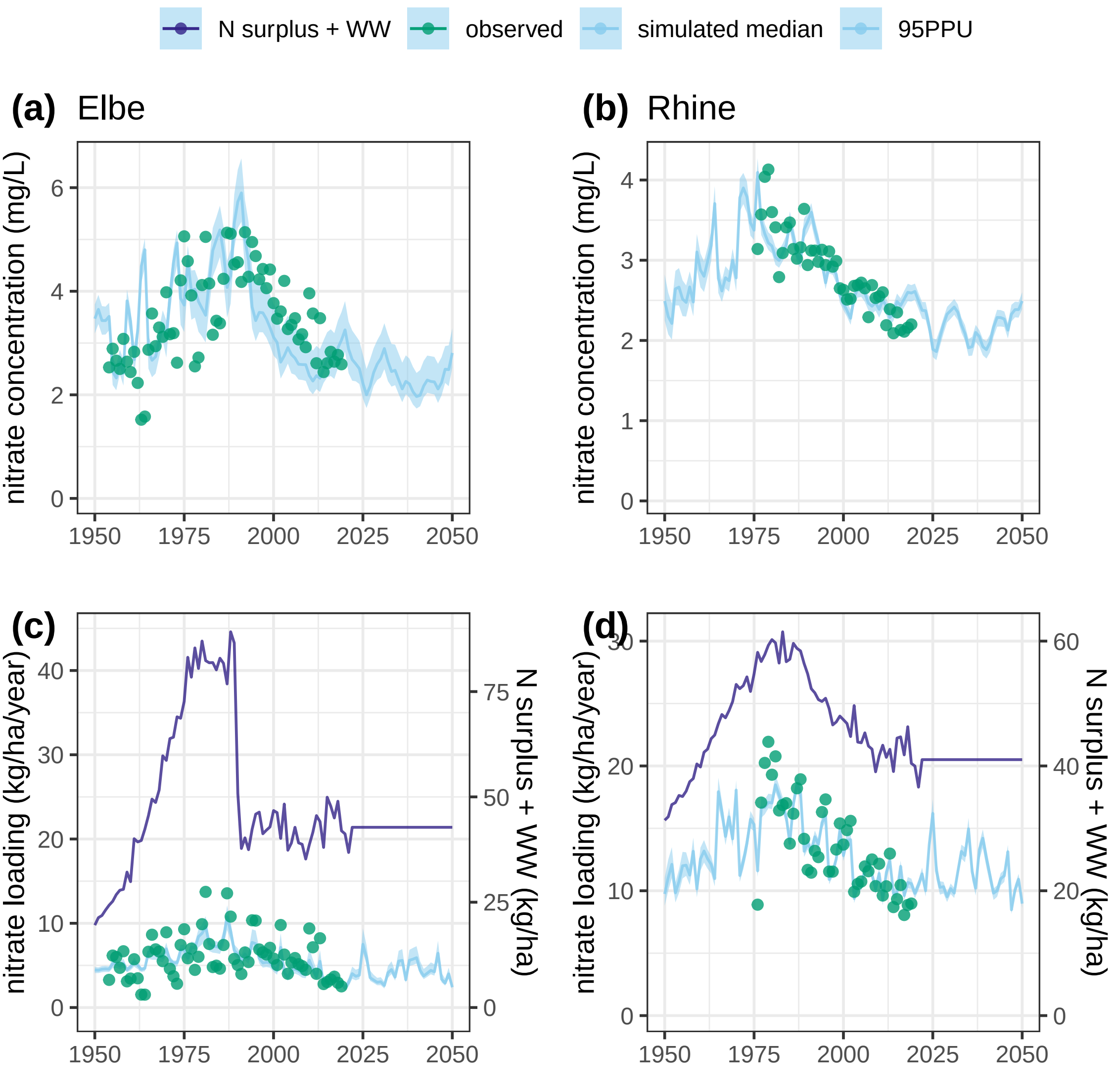

N surplus + WW
observed
simulated median
95PPU
(a) Elbe
(b) Rhine
(c)
(d)
nitrate concentration (mg/L)
nitrate loading (kg/ha/year)
N surplus + WW (kg/ha)
0
2
4
6
1
3
10
20
30
40
25
50
75
60
1950
1975
2000
2025
2050


N surplus + WW
observed
simulated median
95PPU
(a) Elbe
(b) Rhine
(c)
(d)
nitrate concentration (mg/L)
nitrate loading (kg/ha/year)
N surplus + WW (kg/ha)
0
2
4
6
1
3
10
20
25
30
40
50
60
75
1950
1975
2000
2025
2050


N surplus + WW
observed
simulated median
95PPU
(a) Elbe
(b) Rhine
(c)
(d)
nitrate concentration (mg/L)
nitrate loading (kg/ha/year)
N surplus + WW (kg/ha)
0
2
4
6
1
3
10
20
30
40
25
50
75
60
1950
1975
2000
2025
2050



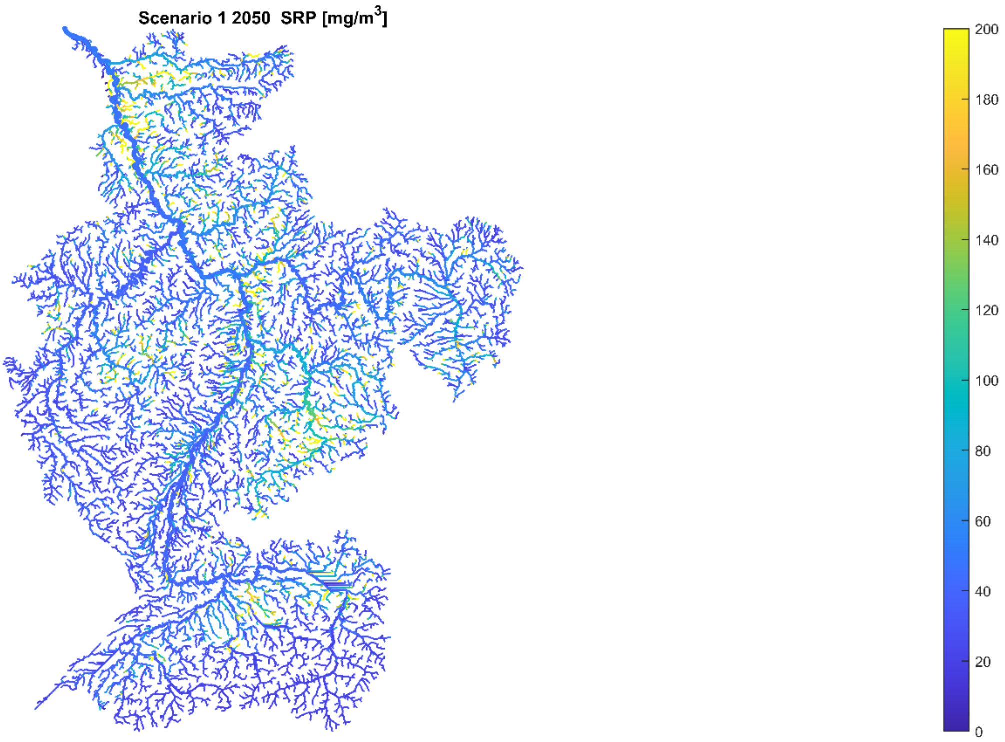
N surplus + WW
observed
simulated median
95PPU
(a) Elbe
(b) Rhine
(c)
(d)
nitrate concentration (mg/L)
nitrate loading (kg/ha/year)
N surplus + WW (kg/ha)
0
2
4
6
1
3
10
20
30
40
25
50
75
60
1950
1975
2000
2025
2050

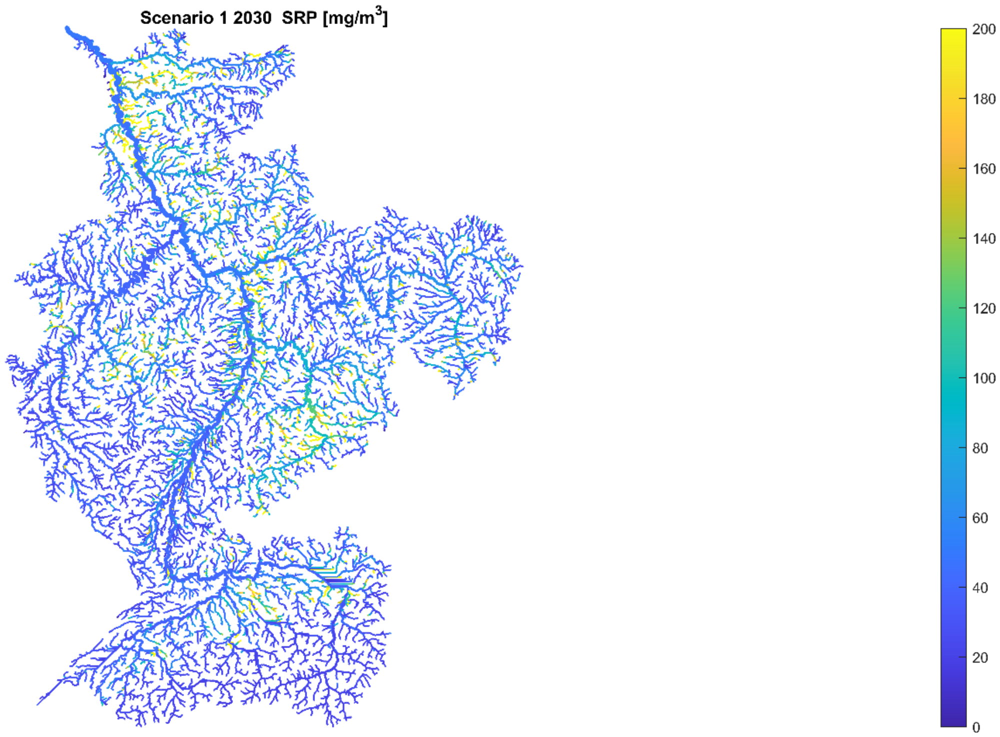


N surplus + WW
observed
simulated median
95PPU
(a) Elbe
(b) Rhine
(c)
(d)
nitrate concentration (mg/L)
nitrate loading (kg/ha/year)
N surplus + WW (kg/ha)
0
2
4
6
0
1
2
3
4
0
10
20
30
40
25
50
75
60
1950
1975
2000
2025
2050

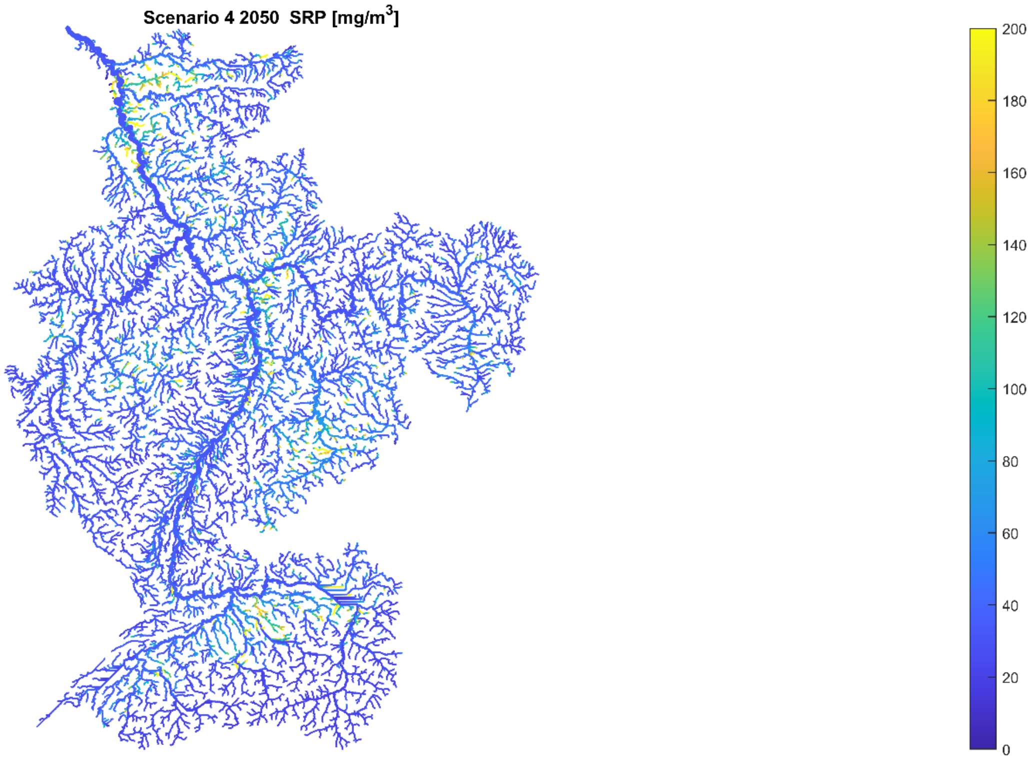
ANNEX III

Figures for remaining scenarios (scenario 1, 4, 5 and 6) for the Rhine and Elbe.

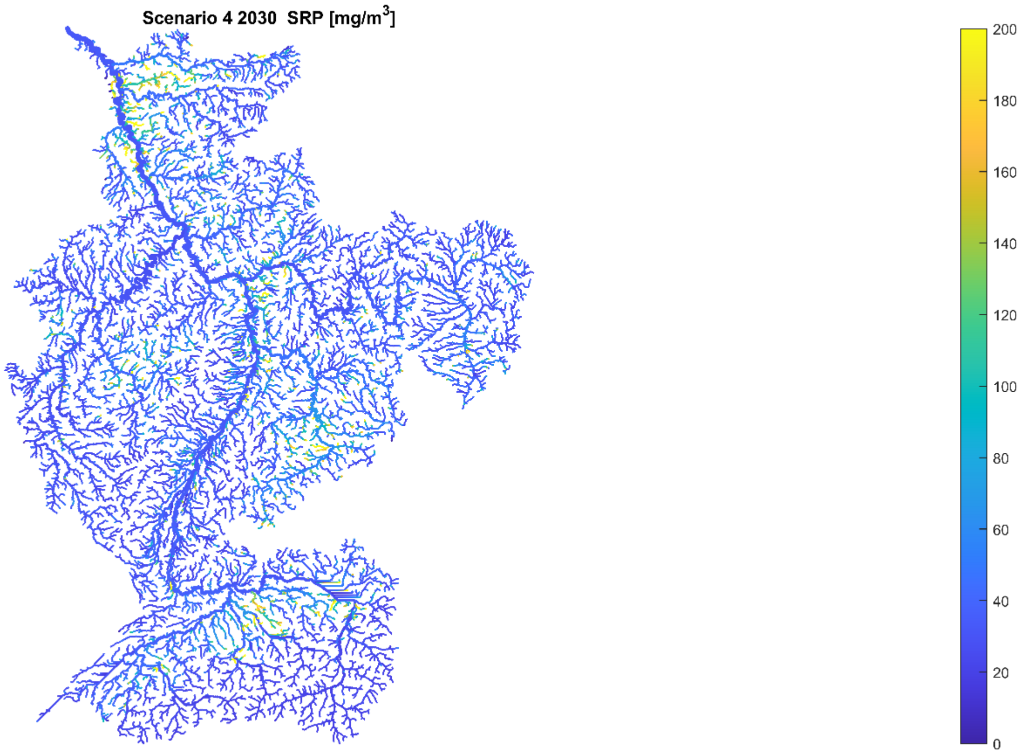

Scenario 1 2050 SRP [mg/m3]
200
180
160
140
120
100
80
60
40
20
0


Scenario 1 2030 SRP [mg/m3]
200
180
160
140
120
100
80
60
40
20
0

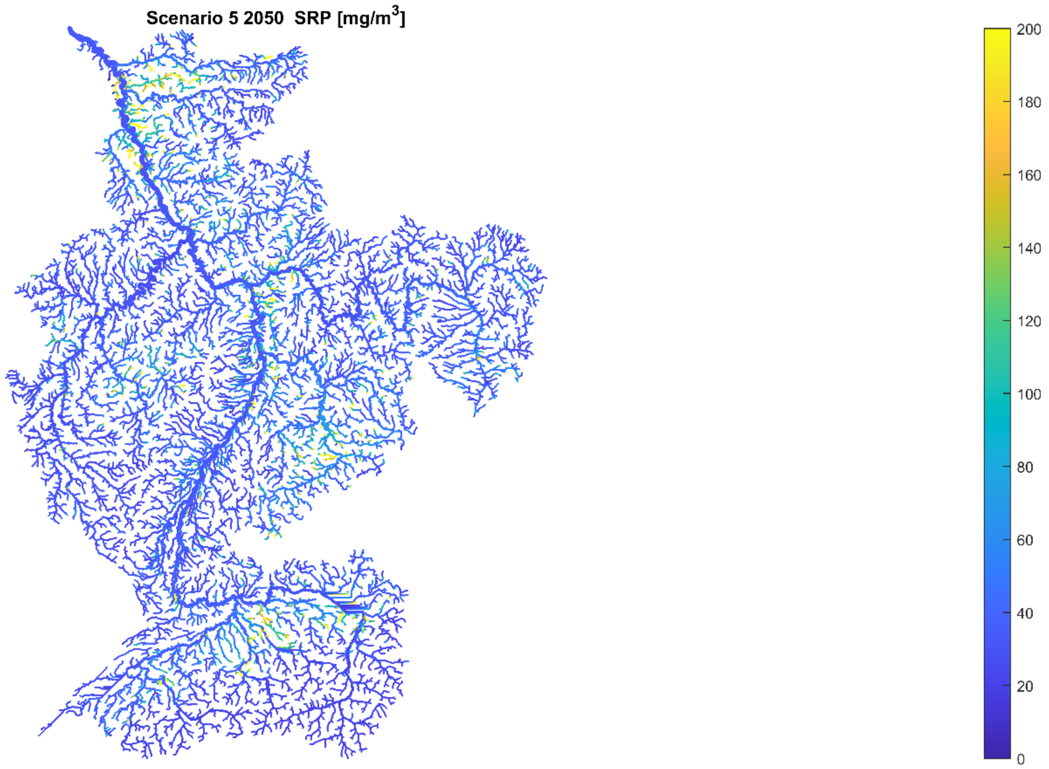
Scenario 4 2050 SRP [mg/m^3]



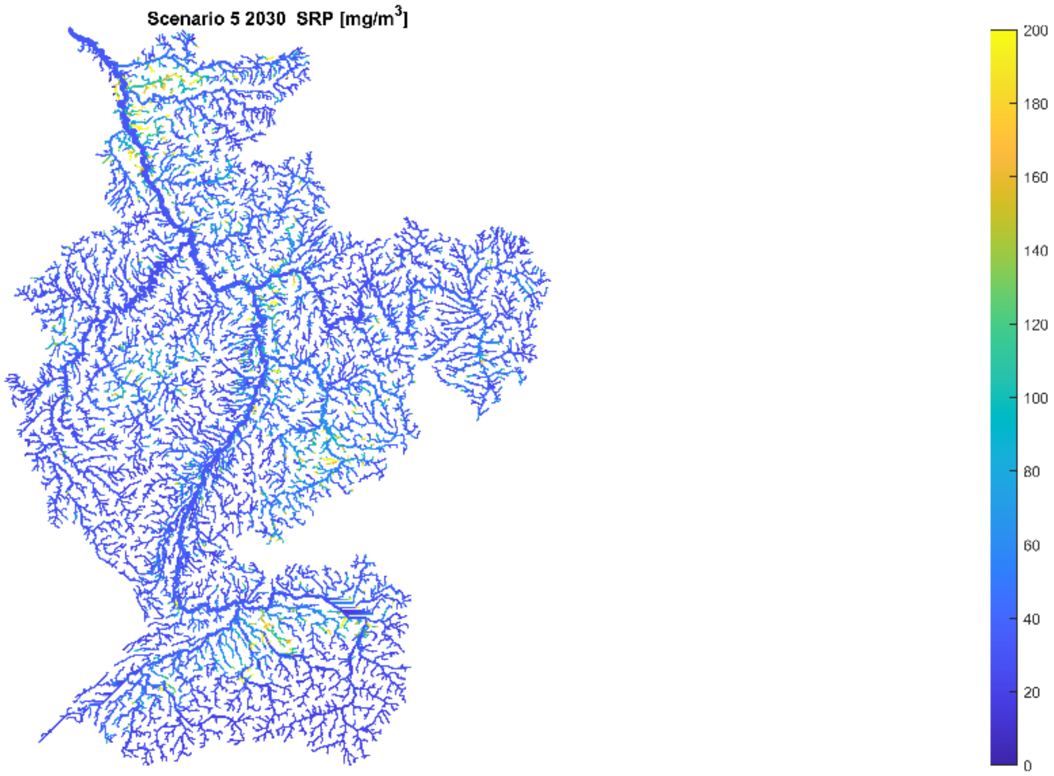
Scenario 4 2030 SRP [mg/m^3]

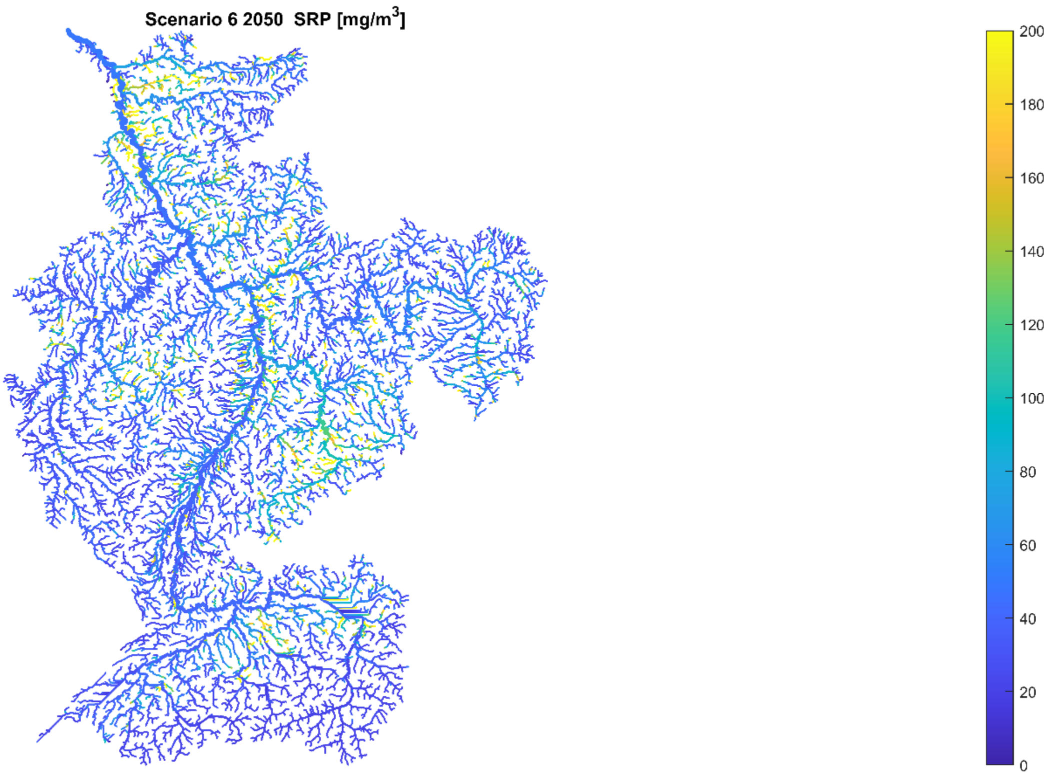


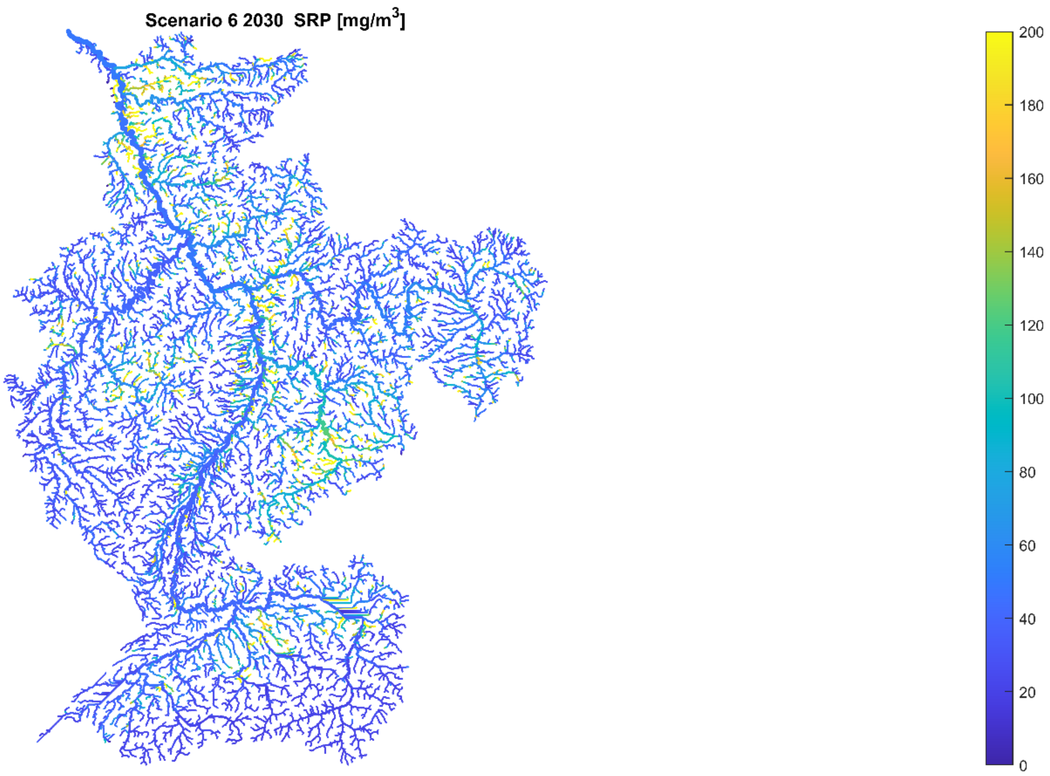
Scenario 5 2050 SRP [mg/m^3]

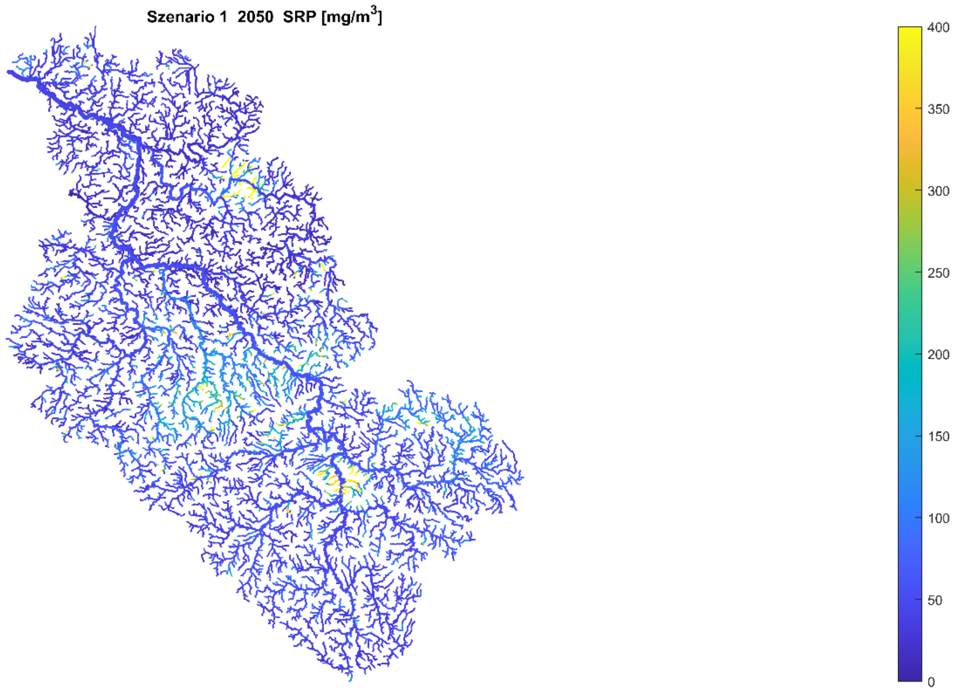


Scenario 5 2030 SRP [mg/m^3]

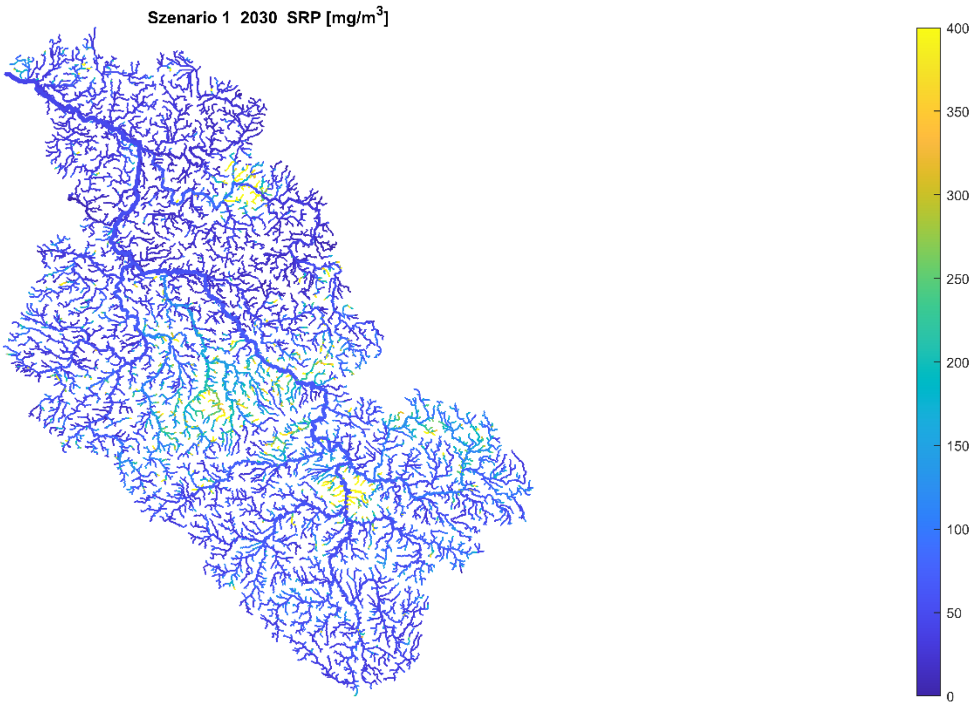



Scenario 6 2050 SRP [mg/m^3]
200
180
160
140
120
100
80
60
40
20
0


Scenario 6 2030 SRP [mg/m^3]
200
180
160
140
120
100
80
60
40
20
0

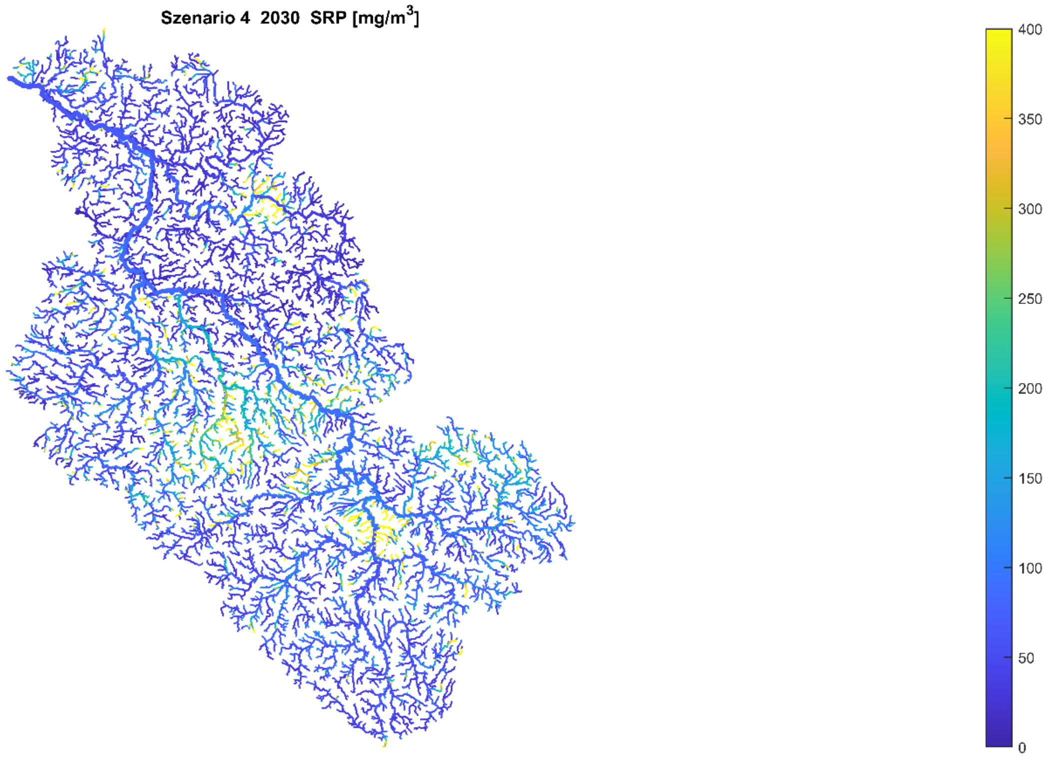


Szenario 1 2050 SRP [mg/m^3]
400
350
300
250
200
150
100
50
0

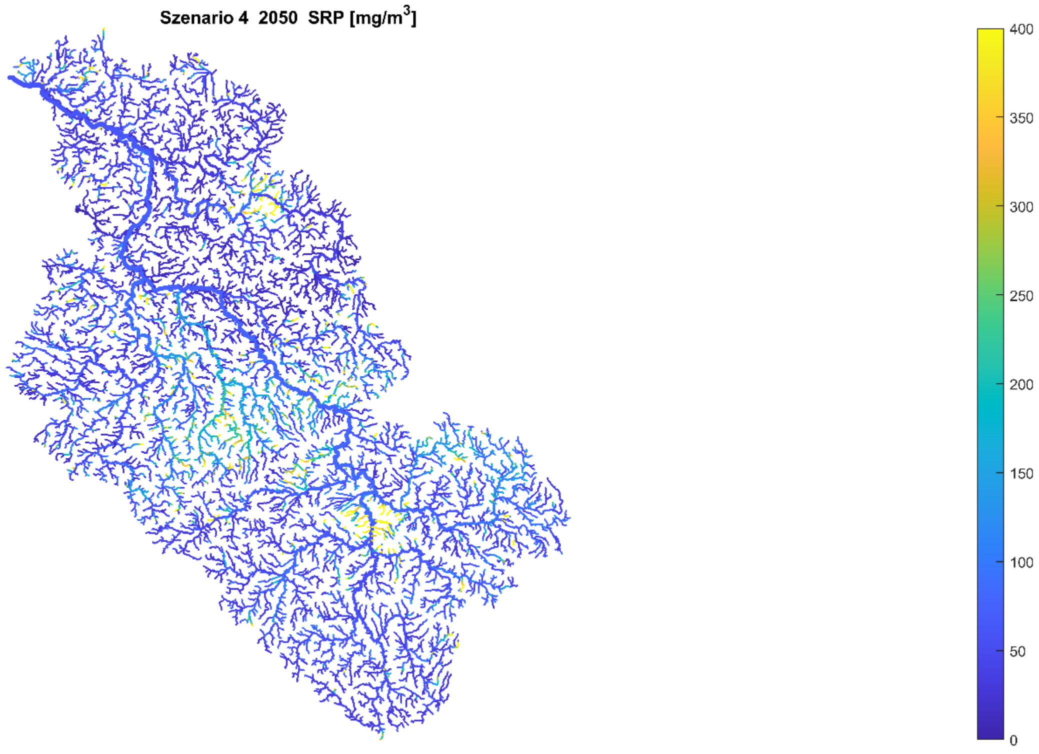


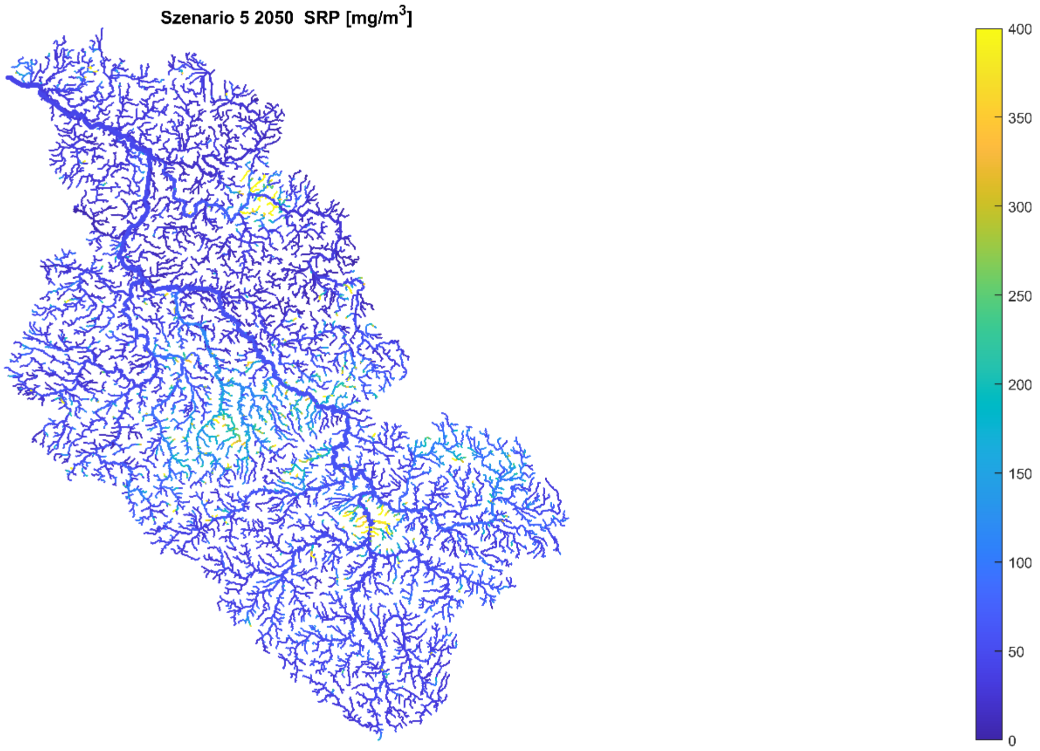
Szenario 1 2030 SRP [mg/m^3]
400
350
300
250
200
150
100
50
0

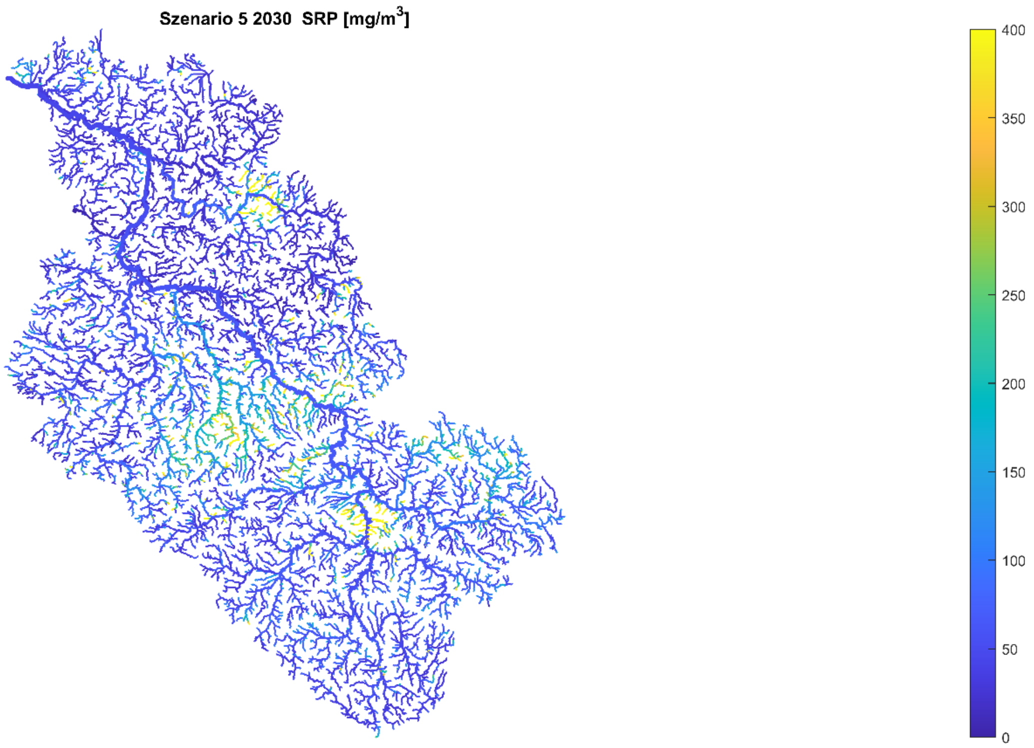
Szenario 4 2030 SRP [mg/m^3]



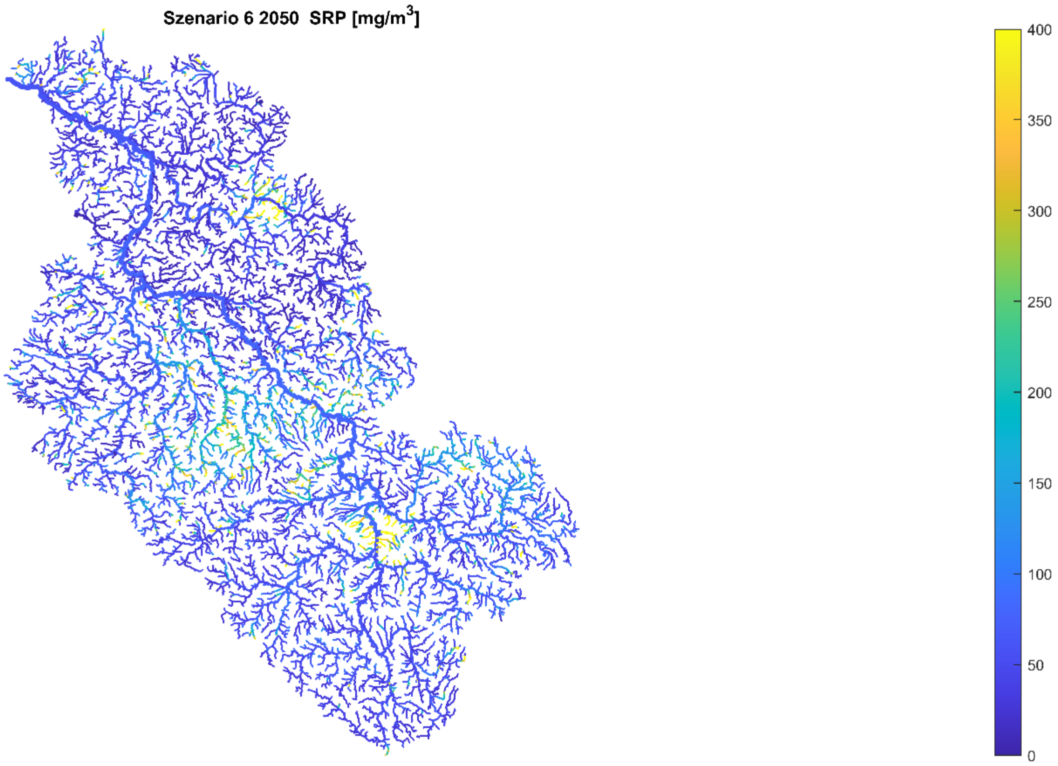
Szenario 4 2050 SRP [mg/m^3]




Szenario 5 2050 SRP [mg/m³]
400
350
300
250
200
150
100
50
0


Szenario 5 2030 SRP [mg/m³]
400
350
300
250
200
150
100
50
0

Szenario 6 2050 SRP [mg/m^3]



Szenario 6 2030 SRP [mg/m^3]