



DELIVERABLE 3.5

EFFECTIVENESS OF MEASURES

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Measures & Pathways

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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

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List of abbreviations

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

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. In this updated report results from scenario 4 are improved and results of scenarios 7A to 7C are presented and areas in the Netherlands are added that are part of the Rhine and Maas basin and directly contribute to exports into the North Sea and Wadden Sea (Rijn Noord - NLRNNO, Rijn Oost - NLRNOO, Rijn West - NLRNWE and Maas - NLMS).

2. Methods

2.1 Overview of the implemented scenarios

Table 1 gives an overview of the implemented scenarios, and the narratives connected to these measures. Note that scenarios 7 are intended to close the gap between the reduction quantified for scenario 5 and reduction need for the envisioned safe ecological boundaries of inland waters, estuaries and the Wadden Sea (see D4.2) considering the assessment of the social acceptability of additional measures.

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

Scenario	Target	Narrative
1	Wastewater treatment	UWWTD implemented
2	Agricultural input	ND implemented (in NL and DE)
3	Atmospheric deposition	Current EU and national legislation implemented including e.g. the Dutch regulations to protect Natura 2000 areas
4	Nature-based solutions for nutrient retention	e.g., Biodiversity Strategy 2030 addressed by restoring riparian areas and reactivating floodplains which potentially also fulfils water-related goals of the EU Nature Restoration Law, stopped Dutch ND derogation
5	All	Scenarios 1-4 jointly implemented
6	None	Business as usual. Scenarios 1-4 not implemented. Projected hydrological state represents emission scenario RCP4.5
7	A	All except nature-based solutions
	B	Nature-based solutions (floodplains)
	C	Scenario 7B + more drastic measures in scenarios 2-3

2.2 Implementation of scenarios and measures

Here an overview is given, how the different scenarios and connected measures have been implemented in the two different models in the different case studies. 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 revised 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 in Germany as estimated by the DüngEval project (cf. report D3.4, Gericke & Leujak 2024) 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 Dutch sub-regions and the Hunze subcatchments we used the projected N surplus reduction due to the measures implemented in the 7th Nitrate action program, the effects of stopped derogation of the Nitrate Directive (e.g. widening fertilizer-free buffer strips, restricting fertilization in N polluted areas), and having no overfertilization above the legal application limit (Groenendijk et al. 2023). The reduction was implemented relative to the reference surplus in 2020 linearly to 2030 and left constant between 2030 and 2050. For the Hunze subcatchments we used the improvement of the Ems sub-region the Hunze is located in.

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, the 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 is 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, adapted in 02/2025

We modelled the implemented the EU Nature Restoration Law with 20% more active floodplains in Germany until 2030. The inventory of German floodplains (BMU and BfN 2021) comprises the recent (active) and former floodplains along (large) rivers. We assumed an increase of 20% of the recent floodplain area in all catchments. For the entire Elbe basin this sums up to 303 km² reactivated floodplain (73.7 km² in subcatchments). For the Rhine basin this sums up to 231 km² of additional floodplain (144 km² in subcatchments). For the Netherlands, we assumed that the polders reserved for reconnection according to the Besluit Kwaliteit Leefomgeving are reactivated (Bkl, cf. Asselman et al. 2025) which sums up to 36.4 km² more floodplains in the Rhine basin (and 15.3 km² in the Meuse basin, S. Juch pers. comm.)

The current nitrate retention within the German Rhine and Elbe basins was estimated by Kaden et al. (2023). For the Dutch parts of the Rhine basin, we relied on total estimations summarized by van der Lee et al. (2004) as well as the recent cycle 6 dataset on ecotopes along river Rhine which were found to be identical to the German active floodplain (RIVM 2023).¹ By excluding the retention in rivers, we estimated an average area-specific retention of 10 t N km⁻² for the Elbe basin and 15 t N km⁻² for the Rhine basin. The differences of Elbe and Rhine basins are a function of soil pH suppressing effective denitrification in the more acidic Elbe floodplain soils (Kaden et al. 2023). We assumed the same area-specific retention for the reactivated floodplains in scenario 4. Based on these assumptions, we derived 3026 t N/yr (0.23 k N/ha yr relative to the entire area) additional retention for the Elbe and 3696 t N/yr (0.26 kg/ha yr relative to the entire area) for the Rhine. Note that we derived the activated area for each catchment separately and by that not accounting for a spatial consistency of nested catchments. This does not affect the load reduction at the outlet. This calculated additional retention was subtracted from the areal export flux quantified in scenario 6.

For P, Scholz et al. (2014) provides estimates for retained P of 120 t/yr in the Rhine and 123 t/yr in the Elbe basin. Taking recent floodplain areas into account this translates to an average annual area-specific retention of 104 kg P km⁻² for the Rhine basin and 81 kg P km⁻² for the Elbe basin. These values are well comparable to estimates for the buffering capacity for SRP described in Preiner et al. (2020). In the CⁿANDY model the 20% increase in recent floodplain area adds up to an additional retention of 24 t P per yr in the Rhine and 24.6 t P per yr in the Elbe catchment.

For riparian buffers, we estimated the effect of implementing §38a of the German Federal Water Act (Wasserhaushaltsgesetz), i.e. establishing riparian buffers with a permanent plant cover of 5 m width on arable land with an average slope of at least 5% within 20 m from surface waters. 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, a

¹ Ecotopes with the attribute veg_strut = "Zomerbed" were excluded as rivers.

linear increase 2022-2030 and a constant retention afterwards was assumed. For the Dutch subregions the N retention by buffer strips on agricultural fields were implemented. The change in N retention was calculated from the percentage area of buffer strips, provided for the year 2024 (Gerard Ros, NMI, pers. comm.) multiplied with the retention coefficient values described in Gericke & Leujak (2024). The Dutch buffer strips applied here are in compliance with the regulations related to the stopped derogation of Nitrates Directive, which took effect since January 1st 2024.

For the CⁿANDY model, we considered the additional riparian buffers that affect SRP fluxes to the river network by halving the diffuse agricultural SRP input in the model that flows through additional created riparian buffer 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 subcatchments from the model mHM as provided within the Helmholtz Climate initiative HICAM (<https://www.helmholtz-klima.de/en/about-us/helmholtz-climate-initiative>). The methodology of implementation in mHM is similar to Racovec et al. (2022). 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.

Scenario 7A: Strengthening policies

For this scenario policies affecting inputs from wastewater, agriculture and atmospheric deposition were strengthened while the effects of nature-based solutions were similar to scenarios 4 and 5.

For wastewater inputs to the river networks we assumed that the rules of the UWWTP (optimizing median retention and exported concentrations) are applied to WWTP for larger than 2000 population equivalent. Similar to scenario 1 we applied the projected new N loads from individual WWTP in mQM assuming a linear improvement between 2022 and 2030 and a constant annual load after 2030. In CⁿANDY we computed the impact of the improved P loads for 2030 and 2050. For the Hunze catchments, models were run as described before (D3.2). For the Rhine and Elbe basin for computational and time reasons we established a more efficient surrogate model approach. More specifically, we fitted a linear regression for each basin and each time (2030 and 2050) between P inputs (sum of diffuse and wastewater sources reduced by reductions through nature-based solutions) and the P output metrics (TP loads, TP concentrations, SRP concentrations) from scenarios 1, 4, 5 and 6. These linear response function ($R^2 > 0.98$) were forward applied to the reduced P inputs for this scenario 7A.

For agricultural inputs, we used the scenario C09 of the DüngEval project in German parts of the Rhine and Elbe (cf. Gericke and Leujak 2024). This scenario describes reduced N inputs due to site-specific fertilization beyond the current regulation. For the Dutch subregions and the Hunze subcatchments we implemented results of a scenario study using the INITIATOR model (de Vries et al. 2023). More specifically, we used the N surplus data of scenario S1F in 2050 (full implementation of all measures) relative to that of the reference year 2015 and implemented this reduction linearly between 2015 and the maximum reached in 2050. Note that 2015 was a year with an especially high N surplus compared to the other years of the reference period 2010-2020. Therefore, the absolute surplus was initially higher but finally lower than in scenario 2.

Note that the projected percentage reduction from the INITIATOR model applies to agricultural N surplus and atmospheric reduction at the same time. Outside the Netherlands, we relied on the projected atmospheric deposition assuming maximum technically feasible reductions ("MFR" scenario in Denby et al. 2022). The projections for 2030 and 2050 were based on the reference year 2015.

Scenario 7B: Exploring synergies

In this scenario, inputs by wastewater, agriculture, atmospheric deposition were similar to scenario 7A. From the modelled N exports, we subtracted nitrogen that is retained by enhanced buffer strips according to scenarios 4 and 5. We further accounted for an enhanced retention by floodplains.

More specifically, we assumed a reactivation of 30% of the former, non-active floodplain area in all German subcatchments of Elbe and Rhine. In case that number was smaller than the 20% increase of active floodplain according to scenario 4, we took the value from that scenario. For the entire Elbe basin this sums up to 1128 km²

reactivated floodplain (169 km² in subcatchments). For the Rhine basin this sums up to 650 km² of additional floodplain (469 km² in subcatchments). Using the area-specific retention calculated for scenario 4, we obtained 11282 t N/yr (0.88 k N/ha yr relative to the entire area) additional retention for the Elbe and 10414 t N/yr (0.72 k N/ha yr relative to the entire area) for the Rhine. In the CⁿANDY model the 30% reactivation of former floodplain area adds up to an additional retention of 67.6 t P per yr in the Rhine and 91.7 t P per yr in the Elbe catchment. Note that there was not additional P retention in the case of the Hunze.

For the Dutch sub-regions, we assumed that Dutch policy targets to increase the area-specific retention (i.e. the retention efficiency) by turning “green rivers” to “blue rivers”. We applied the average enhancement of floodplain retention of N in the German Rhine catchments between scenarios 4/5 and 7B (26.6%) to these areas. Note that for the Dutch subcatchments there is a lack of spatially resolved data that would allow to enhance nature-based nutrient reduction.

Scenario 7C: Drastic societal changes, new in 02/2025

In this scenario, more drastic societal changes were applied to diffuse N inputs from agriculture and atmospheric deposition. At the same time, wastewater inputs and nature-based solutions were taken from scenario 7B.

For agricultural inputs in Germany, we took results of the scenario C08 of the DüngEval project which extends the current legal requirements for hot-spot areas that the amount of N fertilizer is to be reduced to 80% of the plant demand to all agricultural land (cf. Gericke and Leujak). In the Dutch subregions, we relied on scenario S3F in de Vries et al. (2023) which adds 50% livestock reduction to scenario 7A.

Similar to scenario 7A, the reductions in the Dutch subregions and Hunze subcatchments were applied to agricultural and atmospheric inputs at the same time. For atmospheric deposition on the Elbe and Rhine subcatchments outside the Netherlands, we relied on EMEP scenarios beyond purely technological solutions (“Low” scenario in Denby et al. 2022). This scenario assumes a climate policy towards the Paris goals and includes lower livestock densities due to dietary changes. The implementation was similar to scenario 7A but interpolated between 2015 and 2050 (no values for 2030 provided).

Since scenario 7C does not apply for P reductions due to the lack of knowledge on the effect for diffuse P fluxes to the stream network (see also D3.5). Therefore no CⁿANDY model runs have been implemented and the results reported are similar to scenario 7B.

3. Results for N

3.1 Overview for N for scenarios 1-5

The table in Annex I gives a full overview of the concentrations and loads of NO₃-N within the demonstrator catchments and subcatchments 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). In the Dutch subregions discharge is projected to decrease by 12.3% (2028-2032) and by 28.3% (2046-2050). Given that the exported loads are tightly connected to discharge, part of the efficiency of measures may be caused 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, by 15.8% at the Elbe outlet and by 1.5% in the Dutch subregions (sum) 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%. From the Dutch subregions summed exports decreased by 12.2% in 2050. The effect on the outlet concentration is rather small for Elbe and Rhine (Figure 1 and 2) but larger for the Dutch subregions where lower dilution potential due to the climate change led to higher concentrations (Fig. 3).

For scenario 5, combining climate change and all measures, strongest reductions in loads and concentrations are reached (Fig. 1-8). Compared to the climate change scenario, exports from the Elbe are reduced by 20.9% for the time horizon 2030 (33.4% compared to the reference period) and 24.6% for the time horizon 2050 (20.6% compared to the reference). The reduction is not as strong in the subcatchments of the Elbe (average 25.6% reduction of exported loads in 2030 compared to reference, 2050: 26.2%). Compared to the climate change scenario, exports from the Rhine are reduced by 13.8% for the time horizon 2030 (17.8% compared to the reference period) and 16.5% for the time horizon 2050 (18.9% compared to the reference period). The reduction is not as strong in the subcatchments of the Rhine (2030: 8.0% reduction of exported loads compared to the reference, 2050: 14.7%). Compared to the climate change scenario, exports from the Dutch subregions are reduced in sum by 18.9% for the time horizon 2030 (20.1% compared to the reference period) and 23.1% for the time horizon 2050 (32.5% compared to the reference period). Concentrations in the Elbe for scenario 5 improve at the outlet from 2.7 mg N/L (reference) to 2.2 mg N/L (2030) and 2.0 mg N/L and in the subcatchments from 3.6 mg N/L to 2.7 mg N/L (2030) and 2.3 mg/L (2050). Concentrations in the Rhine for scenario 5 improve at the outlet from 2.5 mg N/L (reference) to 2.0 mg N/L (2030 and 2050) and in the subcatchments from 3.7 mg N/L to 2.7 mg N/L (2030 and 2050). Concentrations in the Dutch subregions for scenario 5 improve mildly at the outlet from 1.8 mg N/L in the reference to 1.7 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% relative to climate change scenario) and for scenario 2 at the Elbe outlet (2030: 3% reduction, 2050: 7% relative to climate change scenario). For the Dutch subregions weakest effects on the exported loads were found for scenario 3 (2030: 0.5% reduction, 11.9% reduction compared to reference). While nutrient reduction measures clearly 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, 79% of all subcatchments in the Rhine basin and 57% of all subcatchments in the Elbe basin are above the concentration threshold in 2050. 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. The same applies to the Dutch subregions where 1 out of 4 regions is above the threshold in reference as well as in the scenario 5 (2030 and 2050).

We further note that scenario 4 on nature-based solutions has some notable uncertainty. More specifically, we assume a spatially constant denitrification per area in Rhine and in Elbe basins based on Kaden et al. (2023) on the reactivated floodplain areas can be discussed. The Elbe basin has an area of 0.24% of reactivated floodplain, while the Rhine has 0.15%. Within the sub catchments this fraction is much smaller (mean Elbe sub catchment reactivated floodplain area 0.03%, mean Rhine sub catchments 0.01%) as the large part of floodplain in the downstream Elbe and Rhine is not part of the selected subcatchments. The uncertainty for this scenario and consequently for scenario 5, including the same nature-based solutions needs further evaluation and discussion. Further note that this uncertainty is not captured by the model's confidence intervals presented in Figs. 1, 2, 5, and 6 since N removal by floodplains is removed after the modelling.

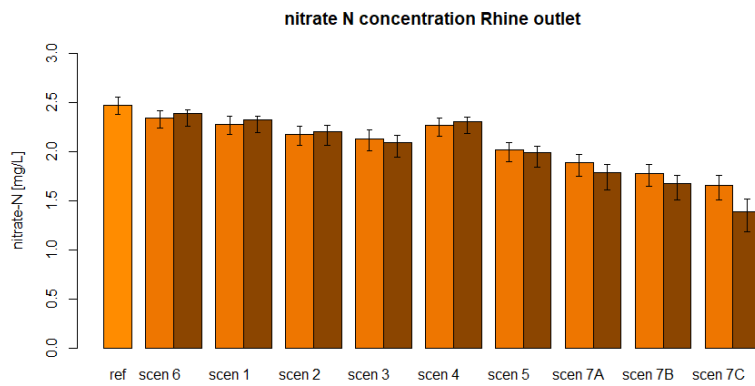


Figure 1. N concentrations the Rhine outlet considering the different scenarios and the reference (ref, 2010-2020). The whiskers refer to the 5-95 percentile confidence interval of the best 100 modelled solutions. Lighter colors – 2030, darker colors 2050.

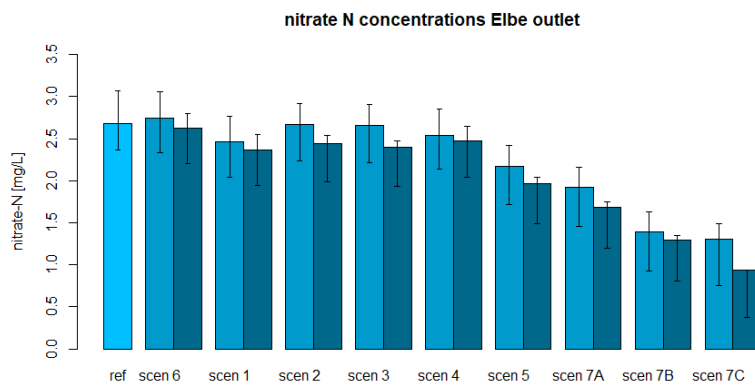


Figure 2. N concentrations the Elbe outlet considering the different scenarios and the reference (ref, 2010-2020). The whiskers refer to the 5-95 percentile confidence interval of the best 100 modelled solutions. Lighter colors – 2030, darker colors 2050.

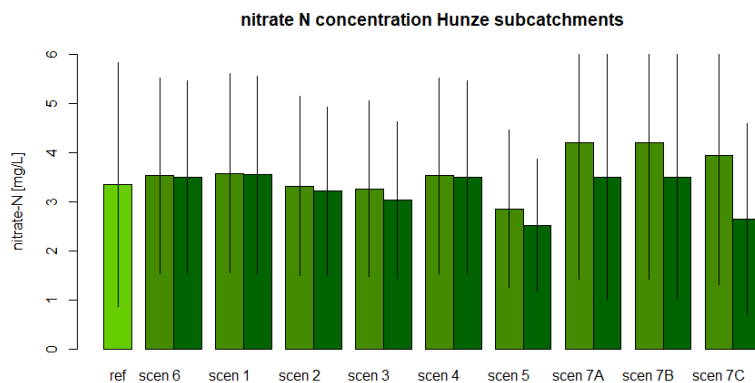


Figure 3. Average N concentrations in the four Hunze catchments considering the different scenarios and the reference (2010-2020). Whisker quantifies the standard deviation of the subcatchments.

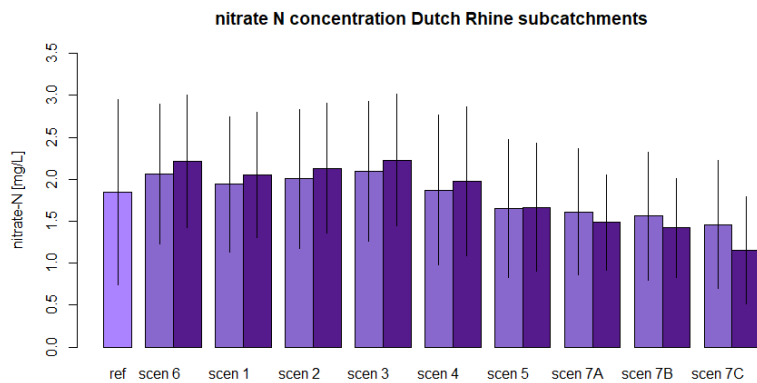


Figure 4. Average N concentrations in the four Dutch subregions considering the different scenarios and the reference (2010-2020). Whisker quantifies the standard deviation of the subregions.

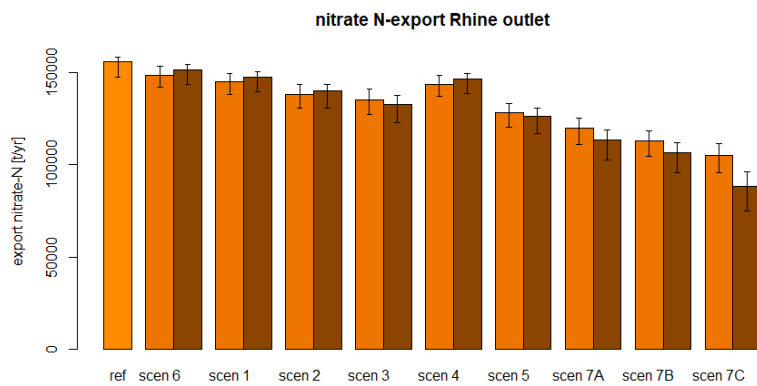


Figure 5. N export at the Rhine outlet considering the different scenarios and the reference (ref, 2010-2020). The whiskers refer to the 5-95 percentile confidence interval of the best 100 modelled solutions. Lighter colors – 2030, darker colors 2050.

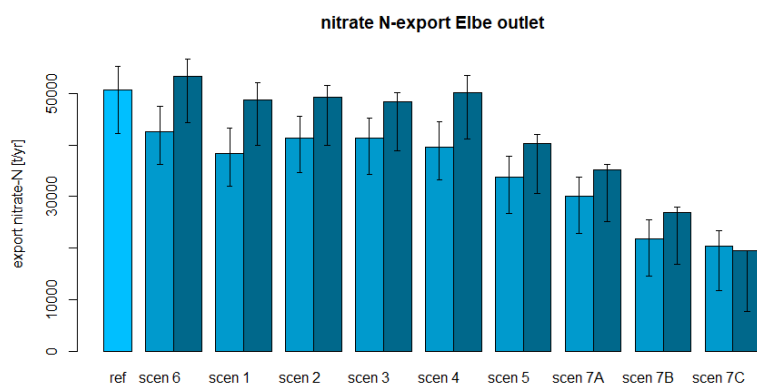


Figure 6. N export at the Elbe outlet considering the different scenarios and the reference (ref, 2010-2020). The whiskers refer to the 5-95 percentile confidence interval of the best 100 modelled solutions. Lighter colors – 2030, darker colors 2050.

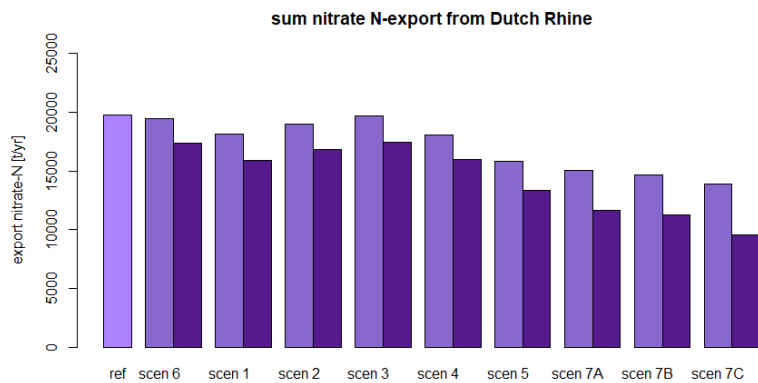


Figure 7. Summed N export from the Dutch subregions considering the different scenarios and the reference (ref, 2010-2020). Lighter colors – 2030, darker colors 2050. As confidence intervals of the four subregions are not additive, they are not reported here but can be seen in chapter 3.2

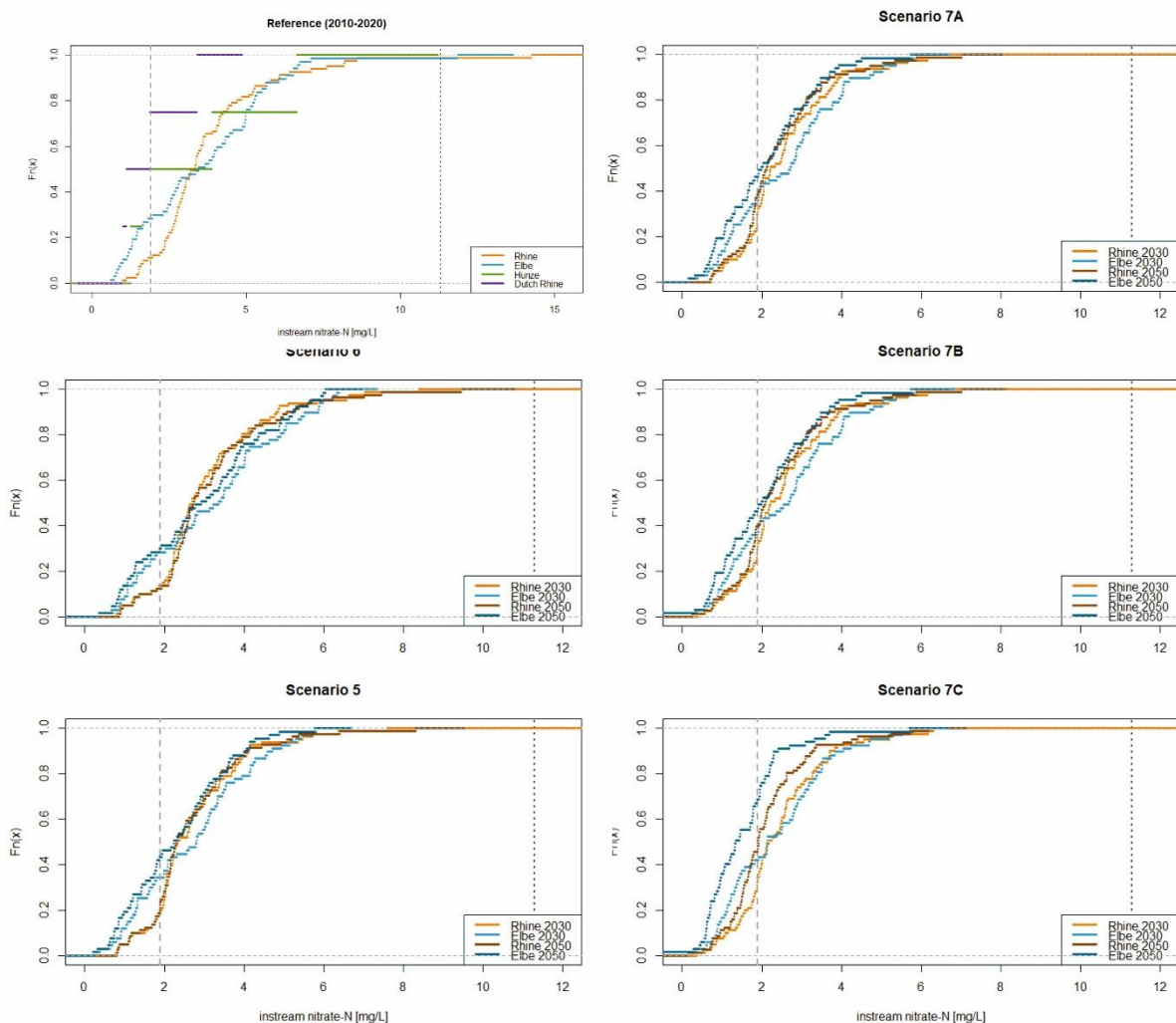


Figure 8. Cumulative density of mean surface water concentrations in the subcatchments of Rhine and Elbe under different scenarios (6, 5, 7A, 7B, 7C). Vertical dashed lines show the threshold of 1.9 mg N/L and 11.3 mg N/L. Upper left plot shows reference conditions (2010-2020, including Hunze and Dutch subregions). The fractions of catchments above and below the concentration thresholds can be read from the intersection of the vertical dashed lines and the cumulative density lines.

3.2 Evaluation of scenario 7A-7C

Within the scenarios 7A to 7C we explored more ambitious nutrient reduction measures that go beyond the planned measures implemented in scenario 5 but also accounting for the effects of climate change.

Nutrients inputs are significantly reduced and natural attenuation is further enhanced in these scenarios. More specifically, in scenario 7A-7C wastewater N inputs are reduced in the Rhine basin by 22.9% until 2050 compared to the reference time and by 65% in the Elbe basin. For the Dutch subregions this reduction is 35.9%. Diffuse N inputs by agriculture and atmospheric deposition are substantially reduced until 2050 in the Rhine basin by 31% (7A, 7B) and 53% (7C). At the same time diffuse inputs into the Elbe basin are reduced by 35% (7A, 7B) and 73% (7C). In the Hunze subcatchments diffuse inputs are reduced by 18% (7A, 7B) and by 67% (7C) in 2050 compared to 2015. Note that 2015 was a year of rather high N surplus in the Hunze basin (34% above the 2010-2020 period average). Consequently, the reduction relative to this reference year is hard to compare to the reduction in scenario 5 (with a reference year 2020). In the four Dutch subregions diffuse inputs are reduced by 12% (7A, 7B) and by 56% (7C) in 2050 compared to 2015.

Moreover, floodplain areas that are reactivated in scenarios 7B and 7C are 0.45% of the entire catchment in the Rhine basin (average in sub catchments 0.08%) and 0.88% in the Elbe basin (average in sub catchments 0.06%). This is substantially higher than the assumptions in scenario 5 and 7B (2.8 times higher in Rhine basin, 3.7 times higher in Elbe basin).

As a result, exported fluxes under scenario 7A from the Rhine reduce by 23.2% and 27.3% (2030, 2050, compared to reference) and from the Elbe by 40.8% and 30.7% resp. From the Dutch subregions exported summed fluxes reduce by 24.0% and 41.3 (2030, 2050). Under scenario 7B exported fluxes from the Rhine reduce by 27.5% to 31.6% (2030, 2050, compared to reference) and from the Elbe by 57.1% to 46.9% resp. From the Dutch subregions exported summed fluxes reduce by 25.9% to 43.2% (2030, 2050). Under scenario 7C exported fluxes from the Rhine reduce by 32.7% to 43.5% (2030, 2050, compared to reference) and from the Elbe by 59.8% to 61.6% resp. From the Dutch subregions summed exported fluxes reduce by 29.9% to 51.8% (2030, 2050). At the same time nitrate-N concentrations at the basin outlet reduced in Rhine to 1.8 mg/L (2050, 7A), 1.7 mg/L (2050, 7B), 1.4 mg/L (2050, 7C), and in Elbe to 1.7 mg/L (2050, 7A), 1.3 mg/L (2050, 7B), 0.9 mg/L (2050, 7C). In the Dutch subregions mean concentrations decrease to 1.6 mg/L (2050, 7A), 1.4 mg/L (2050, 7B) and 1.2 mg/L (2050, 7C). Mean concentration in the Hunze catchments are modelled to be 3.5 mg/L (2050, 7A and 7B), and 2.6 mg/L (2050, 7C). We note that even under the highest reduction scenario 7C sub catchment nitrate-N concentration are still high in the Rhine basin (2050, mean 2.1 mg/L, 54.3% above 1.9 mg/L) and to a lesser extent in the Elbe basin (2050, mean 1.5, 31.3% above 1.9 mg/L) (see Fig. 8).

3.3 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. In the same way the four modelled Dutch subregions are displayed in Figure 11-14. All other scenario figures are provided as supplements in Annex II. Figures 9 and 14 also show that the uncertainty introduced by the model calibration is mostly in an acceptable range compared to the temporal variability introduced by the projected discharge and the nutrient reduction measures. Note a rather high uncertainty for the Dutch NLRNNO subregion likely as a result of limited number of observations that the model is calibrated to.

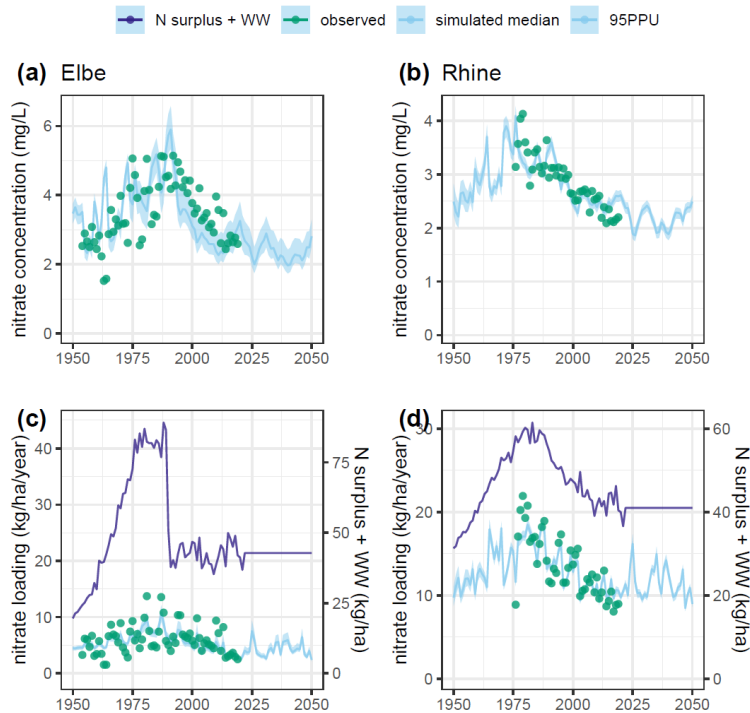


Figure 9. Scenario 6, depicting climate change effects without changes of the nutrient inputs and retention. (a): Elbe outlet concentrations, (b) Rhine outlet concentrations, (c) N loading at the Elbe outlet and N inputs by diffuse and wastewater point sources, (d) N loading at the Rhine outlet and N 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).

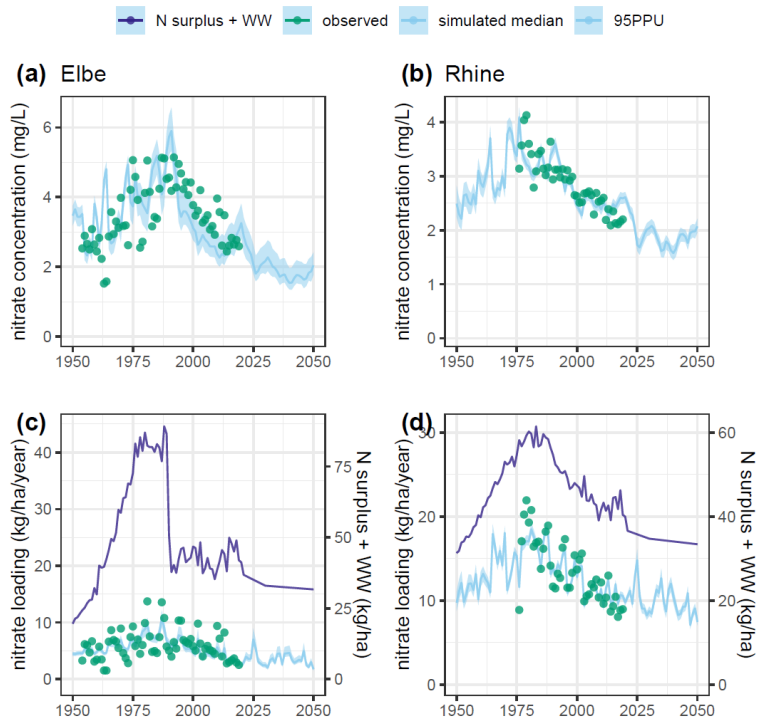


Figure 10. Scenario 5, depicting combined nutrient reduction and climate change effects. (a): Elbe outlet concentrations, (b) Rhine outlet concentrations, (c) N loading at the Elbe outlet and N inputs by diffuse and wastewater point sources, (d) N loading at the Rhine outlet and N inputs by diffuse and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

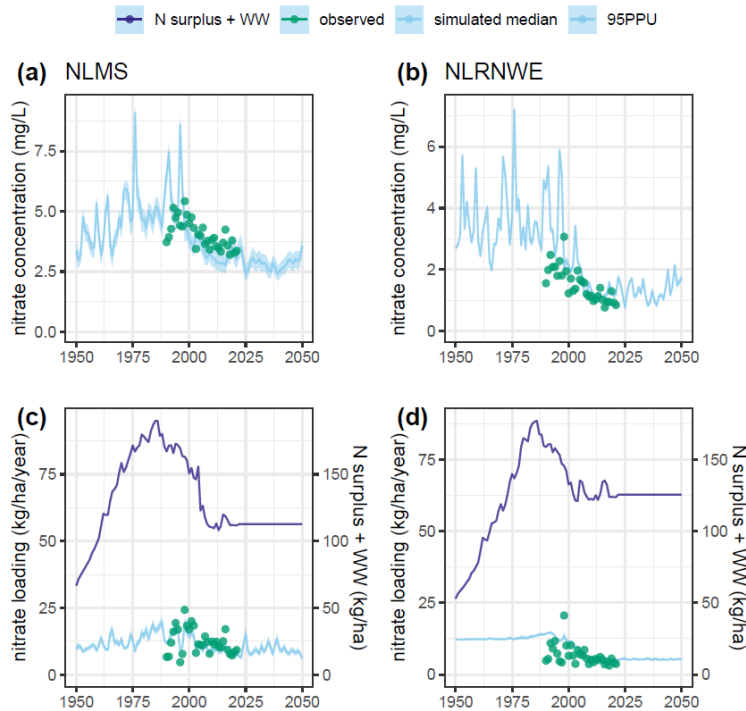


Figure 11. Scenario 6, depicting climate change effects without changes of the nutrient inputs and retention. (a): NLMS concentrations, (b) NLRNWE concentrations, (c) N loading at the NLMS subregion and N inputs by diffuse and wastewater point sources, (d) N loading at the NLRNWE subregion and N inputs 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).

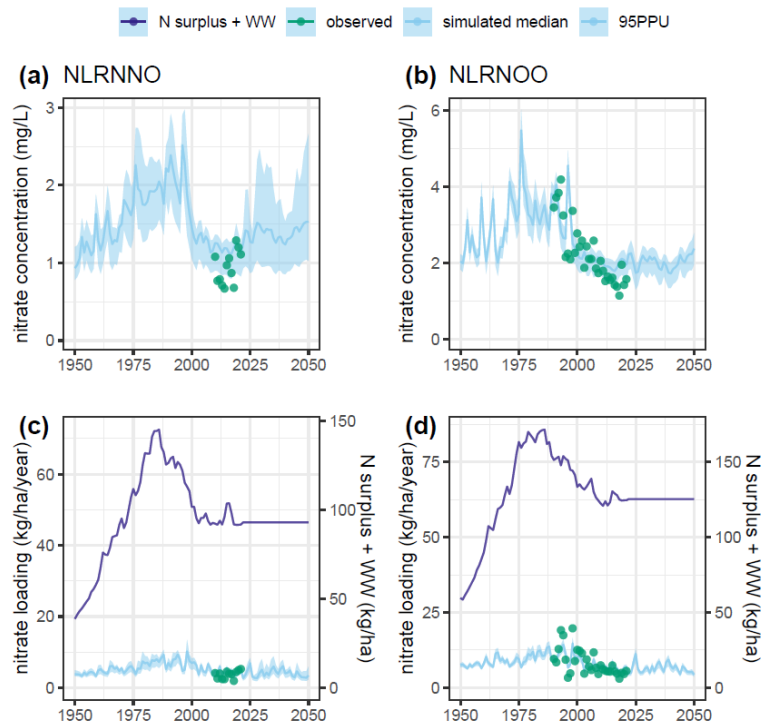


Figure 12. Scenario 6, depicting climate change effects without changes of the nutrient inputs and retention. (a): NLRNNO concentrations, (b) NLRNOO concentrations, (c) N loading at the NLMS subregion and N inputs by diffuse and wastewater point sources, (d) N loading at the NLRNWE subregion and N inputs 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).

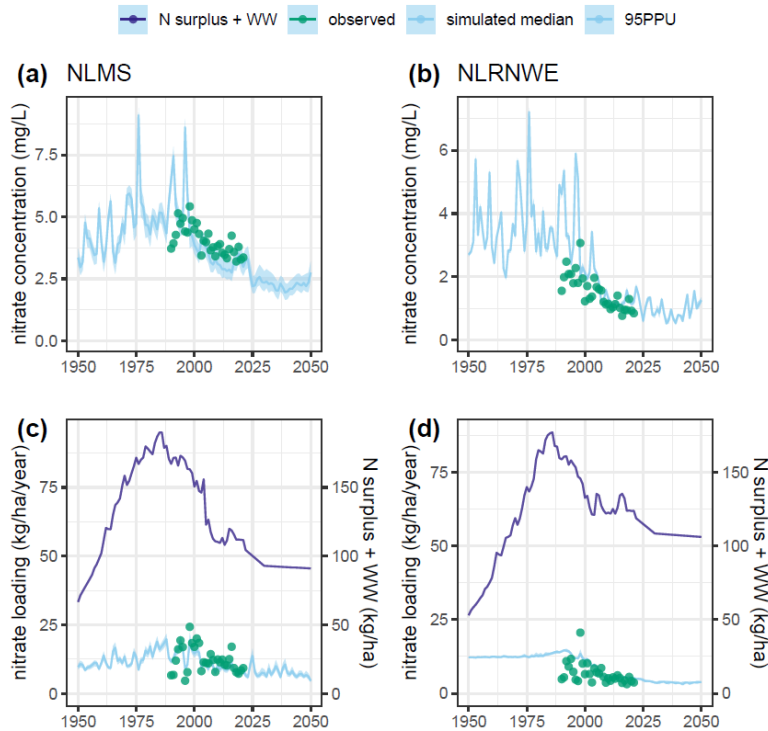


Figure 13. Scenario 5, depicting climate change effects without changes of the nutrient inputs and retention. (a): NLMS concentrations, (b) NLRNWE concentrations, (c) N loading at the NLMS subregion and N inputs by diffuse and wastewater point sources, (d) N loading at the NLRNWE subregion and N inputs 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).

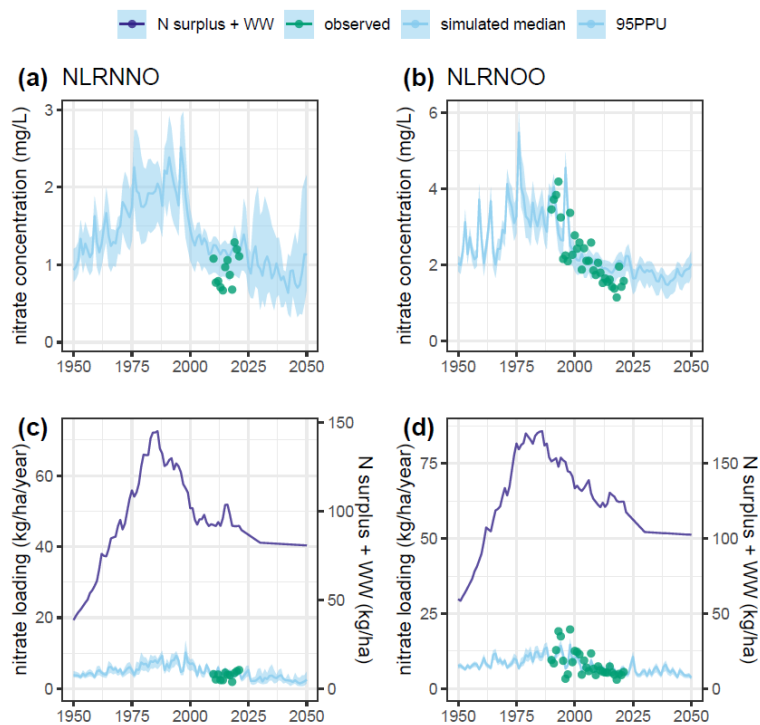


Figure 14. Scenario 5, depicting climate change effects without changes of the nutrient inputs and retention. (a): NLRNNO concentrations, (b) NLRNOO concentrations, (c) N loading at the NLMS subregion and N inputs by diffuse and wastewater point sources, (d) N loading at the NLRNWE subregion and N inputs 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).

3.3.1 N evolution at the catchment outlet for scenarios 7

Here we added Figures 15-18 showing the temporal evolution of nitrogen inputs and outputs in Elbe and Rhine basin and the Dutch sub-regions under the drastic nutrient reduction scenario 7C. One can see that both nitrogen loading into the basins as well as nitrate export out of the basin reaches condition prior to 1950.

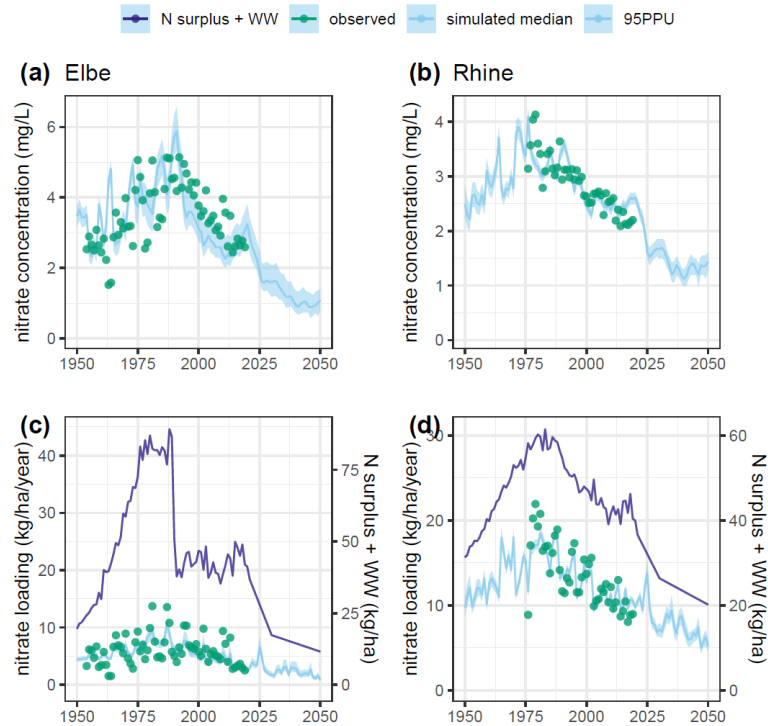


Figure 15. Scenario 7C, depicting combined drastic nutrient reduction and climate change effects. (a): Elbe outlet concentrations, (b) Rhine outlet concentrations, (c) N loading at the Elbe outlet and N inputs by diffuse and wastewater point sources, (d) N loading at the Rhine outlet and N inputs by diffuse and wastewater point sources. Dots display observed values in the past that have been used for model calibration (D3.2; Musolff & Ledesma, 2024).

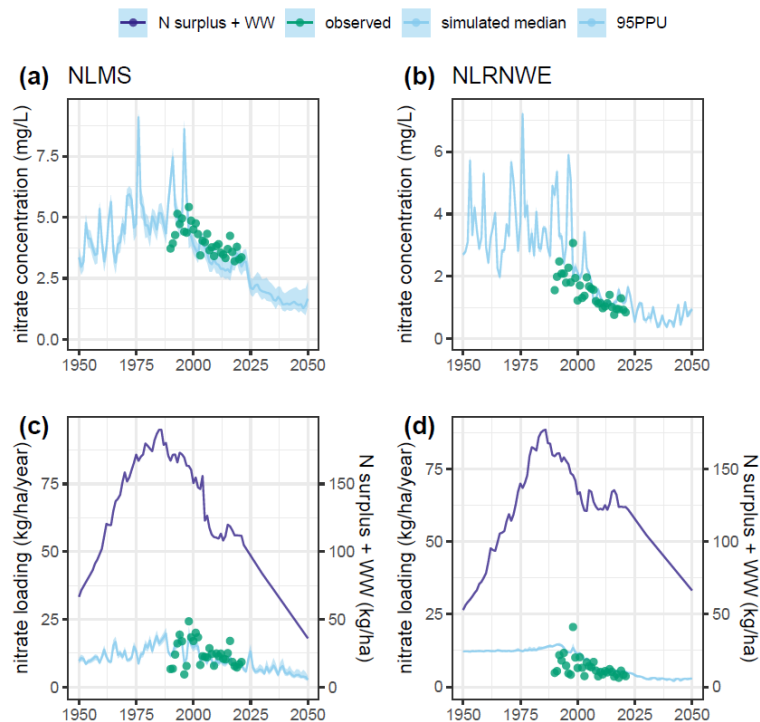


Figure 16. Scenario 7C, depicting climate change effects without changes of the nutrient inputs and retention. (a): NLMS concentrations, (b) NLRNWE concentrations, (c) N loading at the NLMS subregion and N inputs by diffuse and wastewater point sources, (d) N loading at the NLRNWE subregion and N inputs 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).

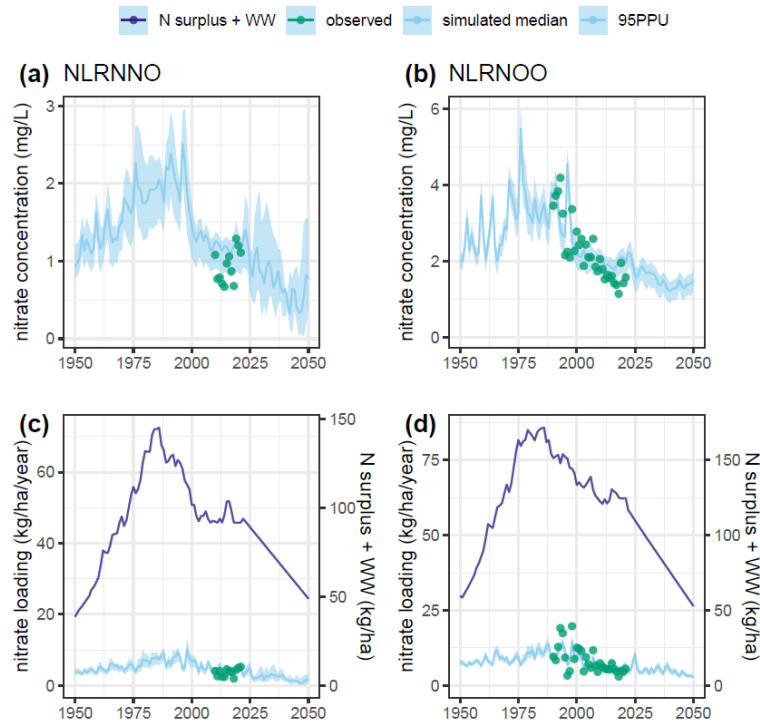


Figure 17. Scenario 7C, depicting climate change effects without changes of the nutrient inputs and retention. (a): NLRNNO concentrations, (b) NLRNWE concentrations, (c) N loading at the NLMS subregion and N inputs by diffuse and wastewater point sources, (d) N loading at the NLRNWE subregion and N inputs 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).

3.4 Spatial distribution of nitrate concentration

In Figures 18 to 20, maps of all modelled subcatchments and subregions show the spatial distribution of nitrate concentrations. Figure 18 shows the reference state as an average of 2010-2020. Figures 19 and 20 show scenarios 5 and 7B in the year 2050. In the reference state a spatial pattern is evident with low concentrations in the northeastern part of the Elbe and southeastern part of Rhine. Elevated concentrations can be found in the southwestern part of Elbe and central part of Rhine. This pattern is persistent in the scenarios as well. Under highest reduction in scenario 7C subcatchments still being above the threshold of 1.9 mg N/L can be found in the central Rhine basin and in southwestern Elbe basin.

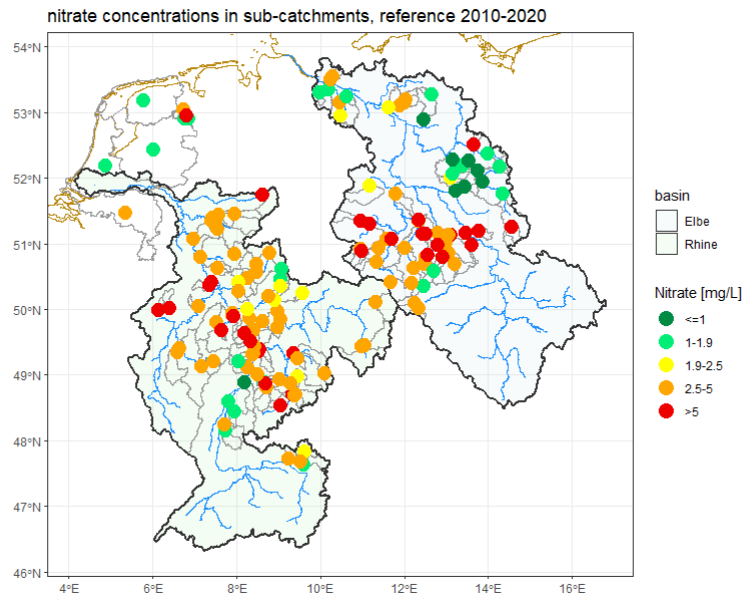


Figure 18. Spatial distribution of mean nitrate concentrations in Elbe, Rhine and Hunze subcatchments and the Dutch subregions for the reference state. Color coding uses the threshold concentration of 1.9 mg N/L (yellow).

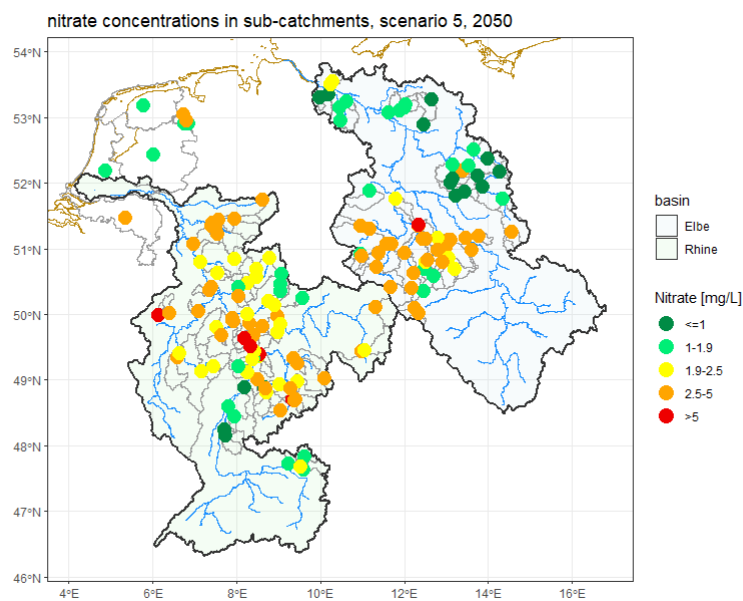


Figure 19. Spatial distribution of mean nitrate concentrations in Elbe, Rhine and Hunze subcatchments and the Dutch subregions for the scenario 5. Color coding uses the threshold concentration of 1.9 mg N/L (yellow).

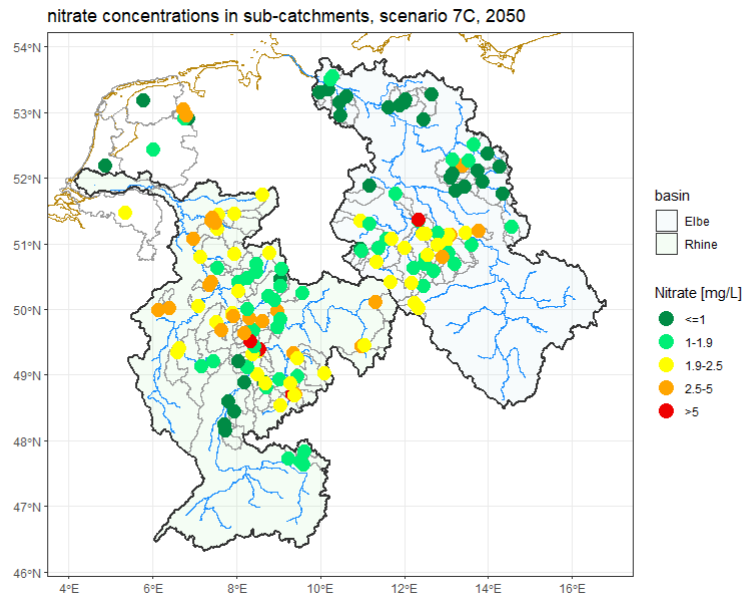


Figure 20. Spatial distribution of mean nitrate concentrations in Elbe, Rhine and Hunze subcatchments and the Dutch subregions for the scenario 7C. Color coding uses the threshold concentration of 1.9 mg N/L (yellow).

4. Results for P

4.1 Overview for P, scenarios 1-5

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. 24-25) to a smaller extent to the concentrations at the outlet (Fig. 23-24). Exported TP fluxes are partly (Elbe) 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. The reason for that is the stronger difference in discharge between the time-horizons for Elbe (34% difference between 2030 and 2050) compared to the Rhine (<1% difference). Discharge is the main control on the time for algal growth, decay and sedimentation in the river network.

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. 21-22, 24-25). Compared to the climate change scenario, exports from the Elbe reduced by 9% for the time horizon 2030 (22% compared to the reference period) and by 26% for the time horizon 2050 (45% compared to the reference period). Exports from the Rhine reduced by 39% for the time horizon 2030 and 2050 (24% 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 and by additional floodplain retention reduced exported loads from the Elbe and Rhine by around 1% relative to the climate change scenario. 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. 26) and more than 34% of all river sections in the Elbe basin (Fig. 27) 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 sub-catchments was projected to be not in line with the threshold in all the scenarios.

We note that the inability of the C^NANDY 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 is a scientific challenge that, to the best of our knowledge, remains insufficiently solved for modelling at the scale of river basins and networks.

4.2 Evaluation of scenarios 7A-7C

Within the scenarios 7A to 7C we explored more ambitious nutrient reduction measures that go beyond the planned measures implemented in scenario 5 but also accounting for the effects of climate change projected until 2050.

Nutrients inputs are significantly reduced, and natural attenuation is further enhanced in these scenarios. More specifically, in scenario 7A-7C wastewater P inputs are reduced in the Rhine basin by 65.1% until 2050 compared to the reference time and by 68.5% in the Elbe basin. For the Hunze catchment this reduction is 33.5% (for the one considered WWTP).

Moreover, floodplain areas that are reactivated in scenarios 7B and 7C are 0.45% of the entire catchment in the Rhine basin (average in sub catchments 0.08%) and 0.88% in the Elbe basin (average in sub catchments 0.06%). This is substantially higher than the assumptions in scenario 5 and 7B (2.8 times higher in Rhine basin, 3.7 times higher in Elbe basin).

As a result, exported TP fluxes under scenario 7A from the Rhine reduce by 29.7% and 30.4% (2030, 2050, compared to reference) and from the Elbe by 20.0% and 46.6% resp. Under scenario 7B and 7C (similar here) exported fluxes from the Rhine reduce by 30.4% to 31.0% (2030, 2050, compared to reference) and from the Elbe by 21.9% to 48.1% resp. At the same time SRP concentrations at the basin outlet reduced from 47.2 µg/L in Rhine to 29 µg/L (2050, 7A, 7B, 7C), and in Elbe from 61.7 µg/L to 33.5 µg/L (2050, 7A), 32.1 µg/L (2050, 7B, 7C). Mean SRP concentrations in the Hunze catchments are modelled to be 36.6 µg/L (2050, 7A, 7B, 7C). We note that under the highest reduction scenario 7B/7C the fraction of the stream network above the threshold of

0.055 mg/L in the Rhine is 12.9% (2050, 7A) and 12.7% (2030, 7B, 7C) and 30.2% (2050, 7A) and 29.5% (2050, 7B, 7C).

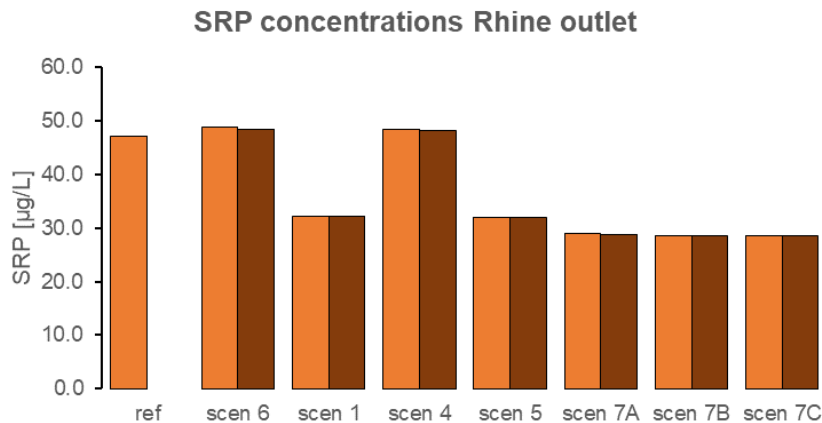


Figure 21. SRP concentrations the Rhine outlet considering the different scenarios and the reference (2010-2020).

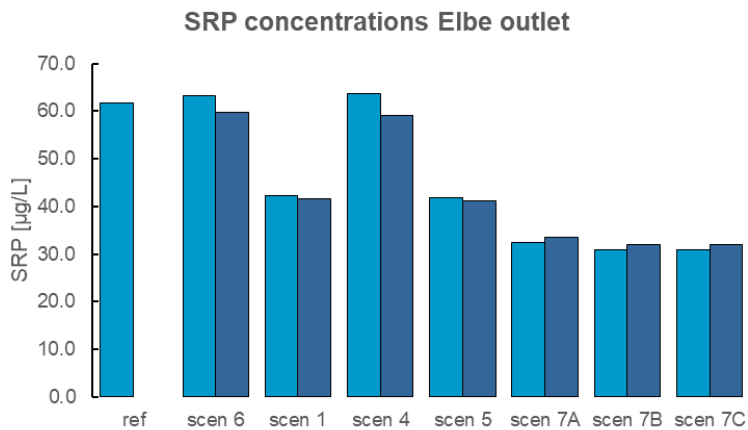


Figure 22. SRP concentrations the Elbe outlet considering the different scenarios and the reference (2010-2020).

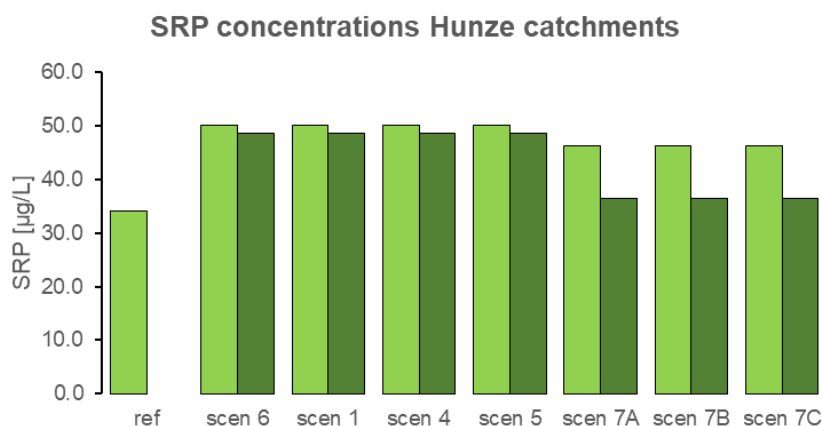


Figure 23. Average SRP concentrations in the Hunze catchments considering the different scenarios and the reference (2010-2020).

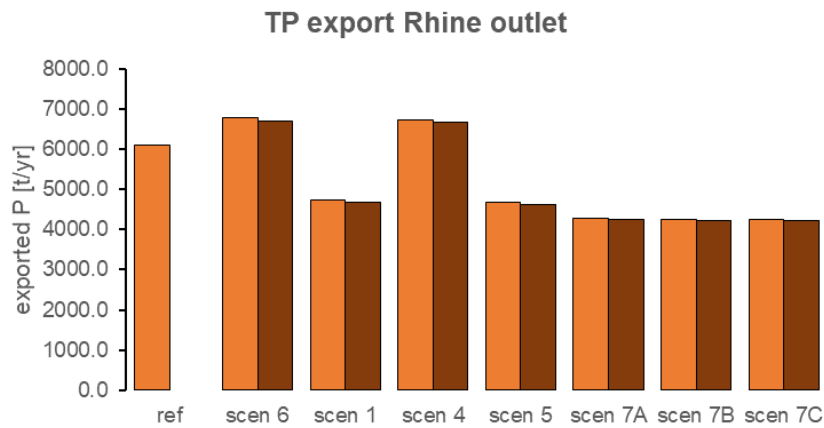


Figure 24. TP export at the Rhine outlet considering the different scenarios and the reference (2010-2020).

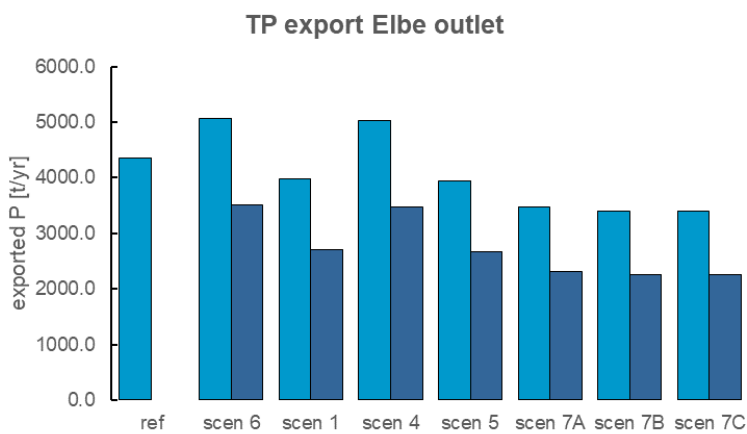


Figure 25. TP export at the Elbe outlet considering the different scenarios and the reference (2010-2020).

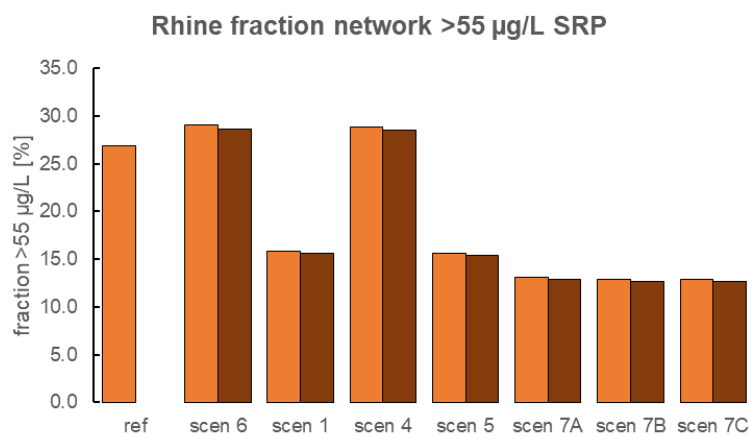


Figure 26. Fraction of river network in the Rhine above the threshold of 0.055 µg/L SRP considering the different scenarios and the reference (2010-2020).

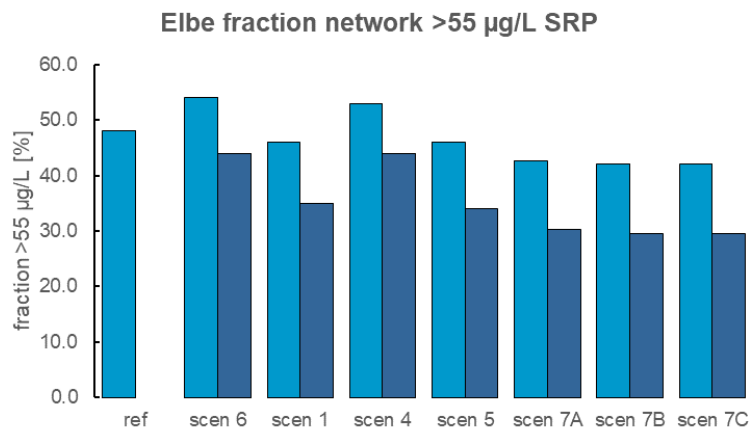


Figure 27. Fraction of river network in the Elbe above the threshold of 0.055 µg/L SRP considering the different scenarios and the reference (2010-2020).

4.3 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 D4.2).

All other figures for Elbe and Rhine SRP distribution are enclosed in Annex III. Note that the surrogate modelling approach for P in scenarios 7A-7C does not allow for a plot of the spatial distribution but is limited to the metrics reported above only.

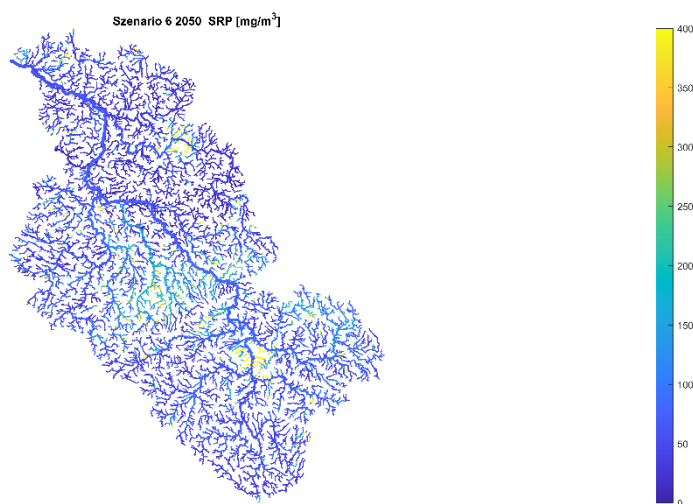


Figure 28. River network SRP concentrations in µg/L (=mg/m³) of the Elbe river under climate change conditions while sources are kept constant (scenario 6, year 2050).

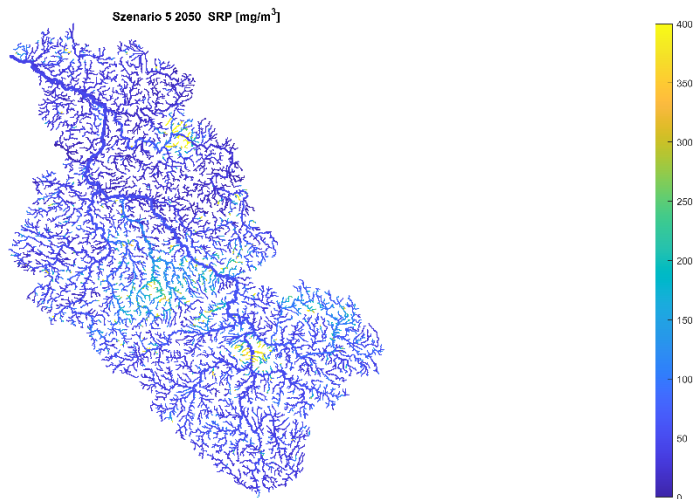


Figure 29. River network SRP concentrations in $\mu\text{g/L}$ ($=\text{mg/m}^3$) of the Elbe river under climate change conditions while wastewater sources are reduced and buffer strips are enhanced (scenario 5, year 2050).

5. Results of N and P for the Hunze basin

5.1 Hunze-case scenario exploration

The Hunze is a ca. 250 km² agricultural catchment in the North of the Netherlands, which drains into lake Zuidlaardermeer and ultimately into the Wadden Sea. Within NAPSEA the Hunze represents a regional case for which future scenarios to reach safe ecological limits can be explored in more detail than for the Rhine and Elbe catchments (mQM and CANDY models) and with bottom-up input from the local Water Authority (Water Board Hunze and Aa's). This will inform and complement the higher-level model explorations of the Rhine wide catchment carried out with the mQM model.

5.2 Area description

The Hunze is a slowly flowing, partly meandering lowland stream in a predominantly sandy, agricultural catchment with a dense artificial drainage network (Waterschap Hunze en Aa's, 2008; Schollemma, 2020). The two southern most upstream Hunze stream branches (Voorste Diep and Achterste Diep) are relatively steep and fast flowing. The area north of their confluence is relatively flat until the mouth into lake Zuidlaardermeer (Fig. 30). The WWTP of Gieten drains into the Hunze just north of the confluence and about 12 km from the mouth. The receiving lake Zuidlaardermeer (area 6.5 km², average depth 1.16 m) and its surrounding wetlands are a Natura 2000 nature reserve and important bird habitat (Klomp, 2021). The drainage from the Zuidlaardermeer flows to the North, via the city of Groningen and lake Lauwersmeer, towards the Wadden Sea. More details about the Hunze catchment are reported in Van Beusekom et al., 2024.

5.3 Safe Ecological Limits for the Hunze – case study

The ecological status of the Hunze and lake Zuidlaardermeer have improved during the last decades. The nutrient concentrations in the Hunze and in lake Zuidlaardermeer have also decreased and are currently stabilizing around the WFD targets for summer average total nitrogen (TN) and total phosphorus (TP) concentrations (2.3 mg/l N and 0.11 mg/l P for Hunze; 1.3 mg/l N and 0.09 mg/l P for Zuidlaardermeer). Despite these improvements, blooms of blue-green algae (cyanobacteria) still compromise local bathing water quality and the development of submersed vegetation.

Additional safe ecological limits were deduced by Van Beusekom et al. (2024) based on the nutrient input reductions needed to restore the ecology of the receiving downstream water systems. For the Hunze catchment, these additional targets were based on the reduction needs to restore the ecology of lake Zuidlaardermeer and the Wadden Sea.

Regarding TP, to change lake Zuidlaardermeer from an algae-dominated state into a clear state (dominated by submersed vegetation), a critical P-load threshold of 2.75 mg P/m²/d is suggested based on PC-lake meta-model calculations (Van Beusekom et al., 2024). Presently (2003-2016), an average TP-load of 4.5 mg P/m²/d prevails, implying a load reduction need of almost 40%. This can be translated into a 40% reduction of the TP concentrations within the Hunze catchment. The annual average TP concentration for 2012-2016 was 0.12 mg/l, so a 40% reduction would translate to an average TP concentration target of 0.072 mg/l.

Note that the critical P-load threshold of 2.75 mg P/m²/d is stricter than reported by Klomp (2021) based on the full PC-lake model, which may be partly explained by recent wetland extensions. This reflects that the ecology of the Zuidlaardermeer can also be restored by making the lake system itself more robust (and increasing the critical P-loads), e.g. by extending shallow wetlands and/or by reducing the wave impact. In addition, the development of submerged vegetation is already possible in shallow parts while exceeding the defined threshold based on the average depth.

Regarding TN, additional targets to restore the ecology of the receiving Wadden Sea (seagrass recovery and prevention of harmful algae blooms) were defined (Van Beusekom et al., 2024). The required 34-39% load reduction

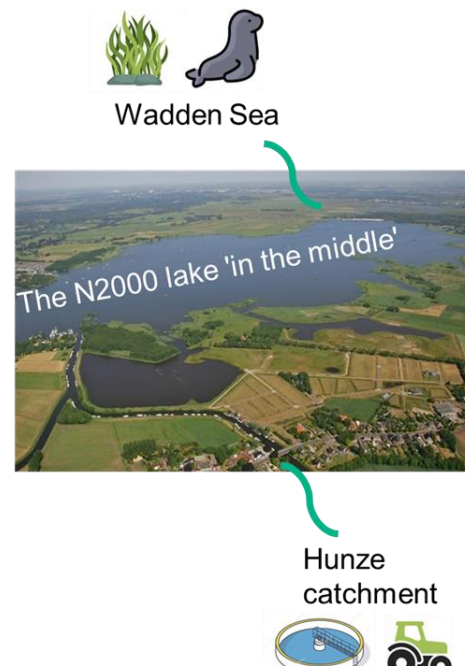


Figure 30. Zuidlaardermeer from South to North with Hunze mouth on the forefront and outflow in the direction of the Wadden Sea in the background (photo source: www.haren-haren.nl/zuidlaardermeer/)

(relative to 2010-2017 levels) would correspond to a reduction in average winter (October to March) TN concentrations from 3.9 mg/l to 2.4-2.6 mg/l and a reduction of average summer (April to September) TN concentrations from 2.4 mg/l to 1.4-1.6 mg/l. A separate winter target was defined in order to highlight the relevance of also reducing winter concentrations in order to reduce the total TN loads.

More details about the safe ecological limits are provided by Van Beusekom et al. (2024).

5.4 Model setup

For exploring mitigation strategies towards reaching the existing WFD targets and the additional safe ecological limits, a water and nutrient transport model was developed. For this modeling, an already existing model of the Hunze catchment (Gevaert and Waterloo, 2019) was updated and improved. The model was made using the Soil and Water Assessment Tool (SWAT; Neitsch et al., 2011). Within SWAT, water and nutrients are routed through hydrological response units (HRU's with unique combinations of soil type and land use) via sub-catchments towards the main surface water streams. The Hunze model consists of 33 subbasins and 1962 HRU's. Details about the implementation of land use and landscape characteristics are given by Gevaert and Waterloo (2019). The meteorological inputs were inherited from the original model set up.

The model covers the period 2007-2016. The years 2007-2011 are used for spin up. For comparisons with the scenario results the years 2012-2016 were used as the reference period. After comparing model results for NO_3 (as the dominant TN fraction) and TP against measured concentrations, the SWAT model was updated to better represent the seasonal fluctuations in discharge and in concentrations. The most significant modification was refining the tile drainage system to more accurately simulate the shallow lateral discharge via the artificial network of ditches and tube drains in agricultural areas by setting the tile drainage depth to 0.6 m. This shallow lateral drainage is a dominant flow route for water and dissolved nutrients, bypassing the hydrological and geochemical attenuation in the deeper groundwater system (see Fig. 31). Surface runoff represents a relatively small proportion of the discharge but is a relevant transport route for particulate nutrients (especially P). The updated model was recalibrated, and the updated SWAT model adequately captures the measured NO_3 and TP concentration dynamics (Figures 32 and 33). To take into account parameter uncertainty, the model was run with over 200 parameters settings using the available workflow within SWAT. The best fit was selected based on 23 calibration parameters.

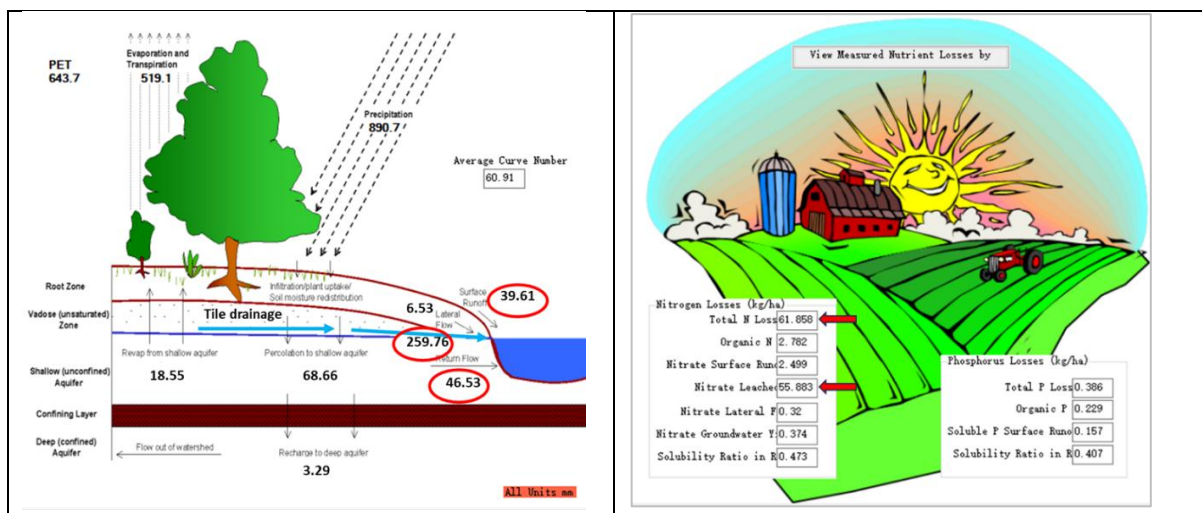


Figure 31. Visualisation of the SWAT water balance and flow route contributions (left), average N and P losses in the Hunze catchment (right). Note that Tile drainage in our model represents both tube drains and small agricultural ditches.

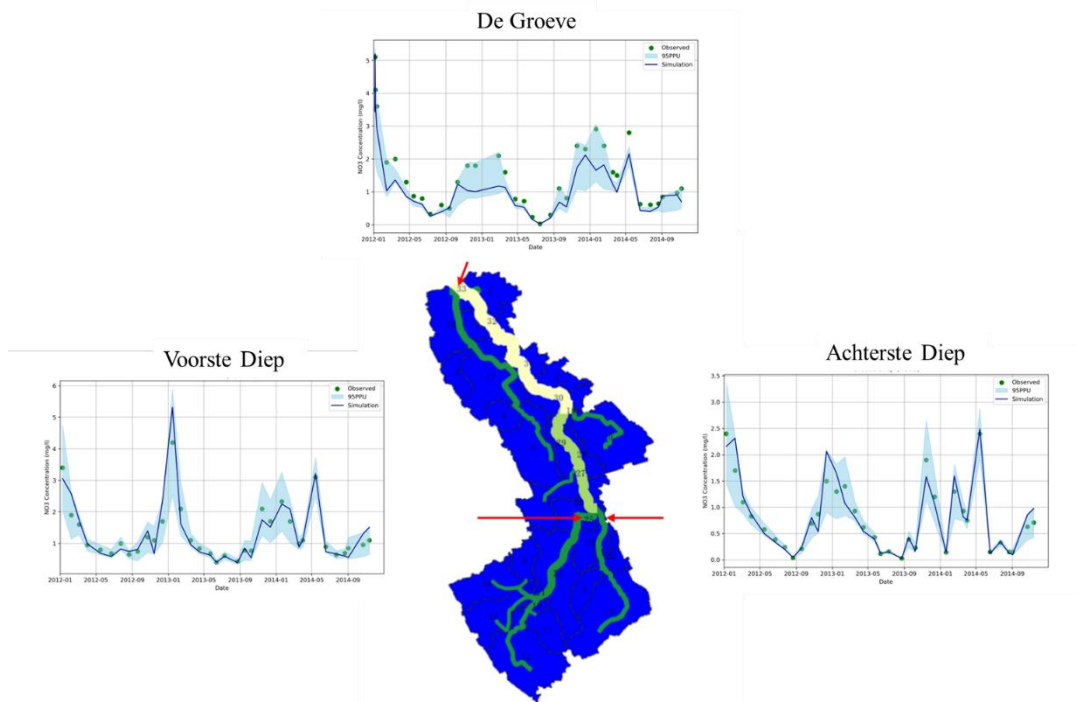


Figure 32. SWAT model setup for the Hunze catchment and calibration results for nitrate at the mouth (De Groeve) and at the two upstream tributaries Voorste Diep (left) and Achterste Diep (right). The blue range in the plots (95PPU) represents the parameter uncertainty range, the line represents the best fit.

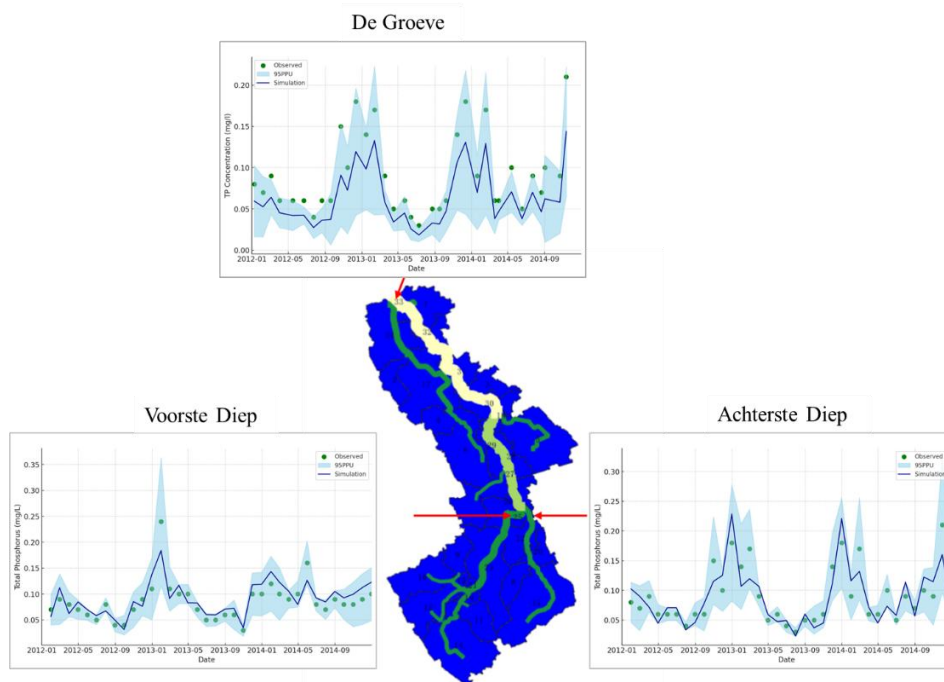


Figure 33. SWAT model setup for the Hunze catchment and calibration results for TP at the mouth (De Groeve) and at the two upstream tributaries Voorste Diep (left) and Achterste Diep (right). The blue range in the plots (95PPU) represents the parameter uncertainty range and the line represents the best fit.

5.5 Scenario description

The implemented scenarios and connected measures in the Hunze case study are more detailed and tailored to local stakeholder's questions and needs compared to the Elbe and Rhine cases above. Therefore, narratives and numberings are different and are explained in detail below.

Two IPCC climate change scenarios (RCP 4.5 (intermediate) and 8.5 (worst-case) in 2050) were implemented to explore the consequences of the changes in hydrology (more evapotranspiration, more extremes) on nutrient transport. For these climate change scenarios we used the monthly averaged precipitation and evaporation for the Netherlands over the years 2050-2055 (Fig. 34). The other scenarios (Fig. 35 and Table 2) explore the effects of land use change, improved wastewater treatment, and nature-based solutions. The land use change scenarios (1-5) reflect quite extreme conversions, such as all agriculture into nature (1), all arable agriculture into dairy farming (3) and vice-versa (4). The conversion of agriculture into mammut grass cultivation (2) is linked to the growing demand for bio-based building materials and the conversion to bean cultivation (5) is linked to the protein transition.

We explored two scenarios for improved wastewater treatment (6-7). Scenario 6 simulates an already planned improvement of the TP purification (with no effect on TN). In addition, we quantify the effect of reduced N and P outflow from the treatment plant which could be realized by larger buffers for peak events or by improved treatment (7).

Scenarios 8 and 9 explore the effects of best agricultural land management practices. A 10% higher nutrient uptake efficiency (8) can be achieved in several ways, e.g. by improving the soil quality and by improving the timing and dosing of fertilizer inputs. Optimizing infiltration (9) reduces N and P losses via overland flow and can be realized e.g. by improving the soil quality or by implementing infiltration trenches, sedimentation ponds and/or dams between crop rows.

Several options for Nature-based Solutions in and around the main streams (Figures 32 and 33) are explored in scenarios 10-13. A 10% higher in-stream retention for N and P (10) can be realized with longer residence times (e.g. through re-meandering) or by creating more space for submerged vegetation. Furthermore, the effects riparian buffer zone with a width of 20 m (11) and 100 m (12) are explored. Scenario 13 quantifies the effects of a planned 90 ha extension of the Tusschenwater wetland in the downstream part of the Hunze catchment.

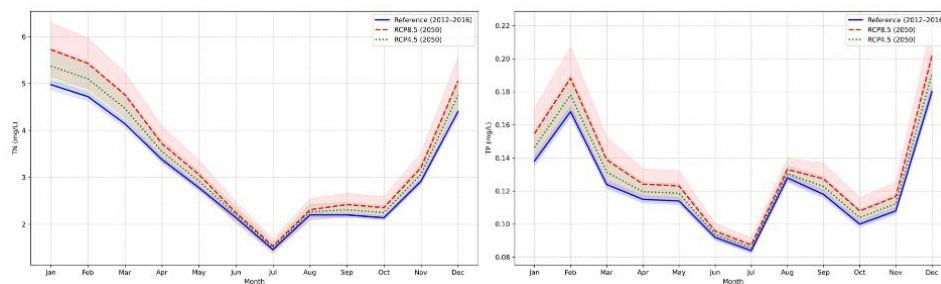


Fig 34. Seasonal variability of TN and TP under different climate change scenarios (RCP4.5 and RCP8.5 in 2050s).

	Scenarios number	Specific measures
Land use change	SC1	Convert agriculture to nature
	SC2	Convert agriculture to mammut grass cultivation
	SC3	Convert arable into dairy
	SC4	Convert dairy into arable
	SC5	Convert to beans
Waste water treatment	SC6	WWTP improved P removal
	SC7	WWTP reduce the summer peak
Agriculture	SC8	Optimize crop nutrient uptake
	SC9	Optimize infiltration in the arable areas
Nature-based solutions	SC10	Optimize in-stream retention
	SC11	Optimize riparian retention 20m
	SC12	Optimize riparian retention 100m
	SC13	Extend purification wetland

Fig 35. Overview of the 13 nutrient mitigation scenarios in the Hunze case study categorized by intervention type: land use change (SC1–SC5), wastewater treatment improvement (SC6–SC7), agricultural management (SC8–SC9), and nature-based solutions (SC10–SC13). See Table 2 for more details.

5.6 Scenario results

Example detailed results scenario 1

As an example, Figure 36 shows the effects of the land use conversion from agriculture to nature on the concentrations of TN and TP. These figures are available for all scenarios in Appendix IV. The upper plots (a and b) show the estimated monthly concentrations 1 year and 10 years after the implementation. Both the current WFD-targets (red) and the additional safe ecological limits (SEL, blue) are plotted for reference. The lower plots give the average winter and summer concentrations and enable a more direct comparison to the targets. All other plots show only the results after 10 years.

For the quite drastic example scenario in Figure 36 (conversion of all agriculture into nature), the results indicate that all targets may already be met 1 year after the implementation. This quick response corresponds with the dominance of short travel time flow routes for nutrient transport towards surface water in the Hunze catchment. After 10 years, the nutrient concentrations are far below the targets, especially for TN.

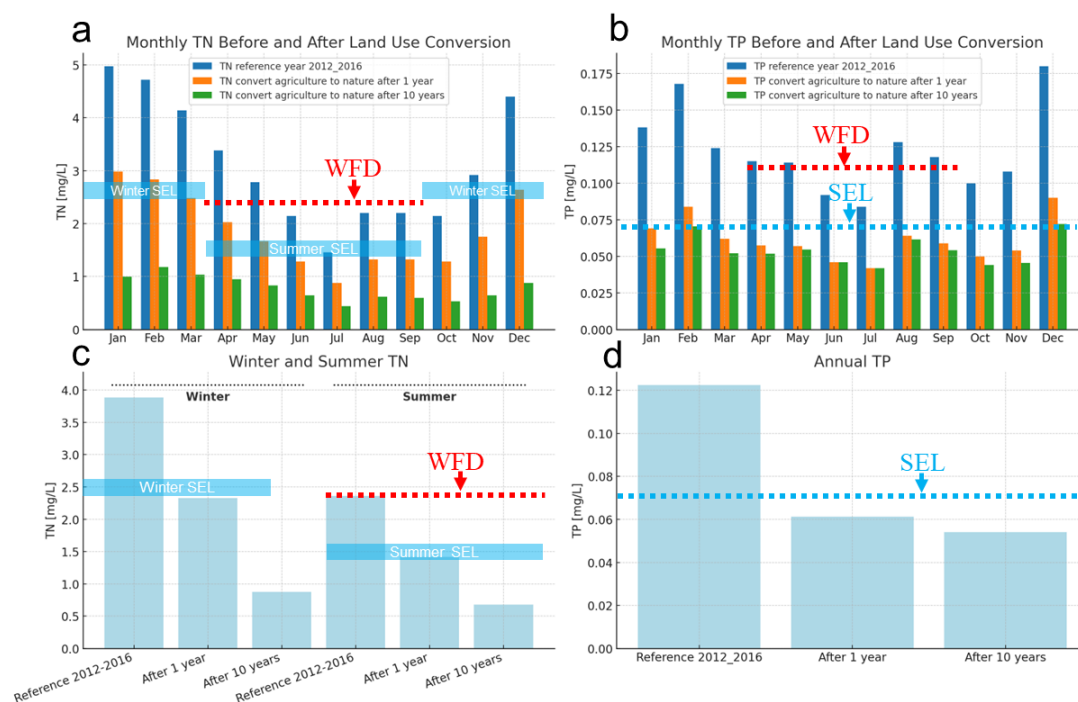


Fig 36. TN and TP concentration under the land use change scenario from agriculture to nature. SEL is the Safe Ecological Limit, WFD refers to the Water Framework Directive target.

Climate change scenario

To explore the potential impact of climate change, Figure 34 presents the average seasonal variation of TN in the current climate (reference) and for 2050s in the ICPP scenarios RCP 4.5 (intermediate) and RCP 8.5 (worst case). For both scenarios higher TN and TP concentrations are predicted for 2050s. The winter TN and TP concentrations are expected to increase with ca. 7% in RCP4.5 and with ca. 13% in RCP8.5. The increases in summer concentrations are expected to be much lower. Note that the uncertainty around these predictions is very large and that only the hydrological effects of climate change are considered. Additionally, substantially greater variability is anticipated during the winter period relative to the summer dry period.

In summary, the results in Figure 34 indicate that climate change may cause higher nutrient concentrations and loads in the Hunze catchment and is a potential risk for reaching the safe ecological limits both for the Hunze itself and the receiving downstream ecosystems.

Overview all mitigation scenarios

The effects of all scenarios on annual TP concentrations, and summer and winter TN concentrations 10 years after implementation are presented in Figure 37. Detailed results with monthly values (like Figure 36) are presented in Appendix IV. The nutrient concentrations reduce in all scenarios except 4 (convert dairy to arable), which causes a significant increase in both TP (+20%), summer TN (+18%), and winter TN concentrations (+52%). The other catchment-scale land use transition scenario's (1, 2, 3, 5) result in substantial reductions and in most cases in compliance with the targets. The effects of other individual measures (wastewater treatment improvement, agricultural measures, nature-based solutions) are smaller. The measures in these scenario's (6-13) however can

be combined into a mitigation package that leads to reaching all targets. There are many potential combinations, and it is not always possible to add up the reduction effects of scenarios. Still, the results in Figure 37 give an indication of what combinations of measures would be sufficient, although combined scenarios have not yet been explored.

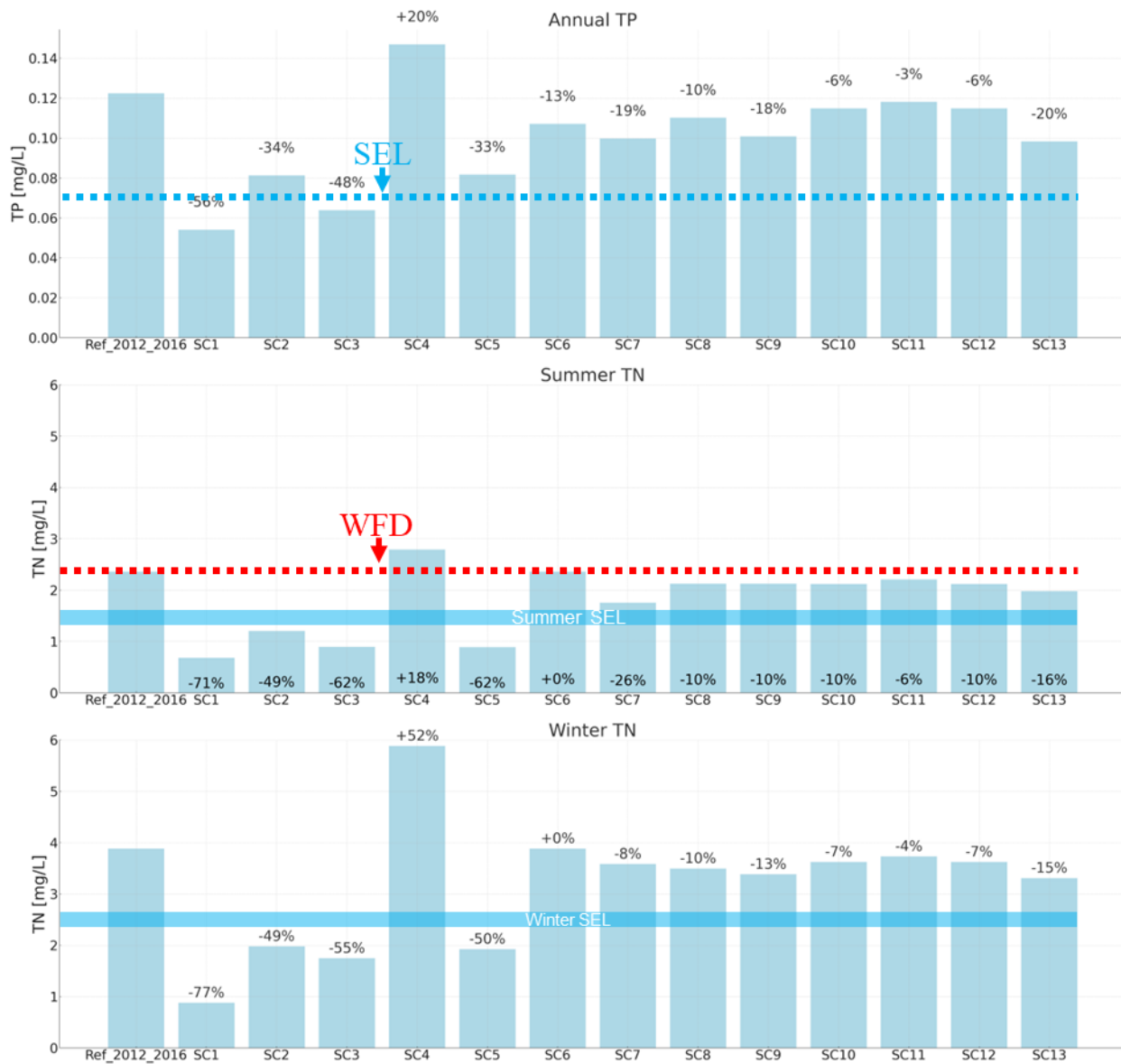


Fig 37. TN and TP concentration results for all scenarios, SEL is the Safe Ecological Limit target. WFD refers to the Water Framework Directive target. Note that the upper (TP) graph gives annual average concentrations; while the middle and lower plots give summer and winter average TN concentrations, respectively.

Table 2. List of model scenarios for the Hunze. More details about the model implementation of scenarios 1-5 are in Appendix IV.

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

5.7 Discussion

Within NAPSEA the Hunze is a regional case study which represents a local example for which future scenarios to reach safe ecological limits have been explored in more detail and with bottom-up input from the local Water Authority (Water Board Hunze and Aa's). The approach and results are in line with the Rhine and Elbe catchment-wide study in NAPSEA, although for the Hunze catchment a SWAT model with a higher spatial and temporal

resolution was used. Its results provide more detailed information on the availability and effectivity of measures in the local situation and their feasibility of achieving both the local and the downstream safe ecological limits.

The considered safe ecological limits for the Hunze catchment include (see also Van Beusekom et al., 2024):

1. The current WFD-targets for summer-average TN and TP concentrations to protect the local ecology.
2. Newly proposed target for annual TP concentrations and loads to protect the ecology of the receiving lake Zuidlaardermeer.
3. Newly proposed target for winter-average TN concentrations to protect the ecology of receiving Wadden Sea.

In the current situation (reference scenario), the Hunze catchment is already close to reaching the current WFD-targets for summer average TN and TP concentrations. However, the newly proposed targets for annual TP and winter TN concentrations are not met and climate change is expected to increase the nutrient concentrations. Additional measures are therefore needed to protect the ecology of downstream receiving water systems like lake Zuidlaardermeer and the Wadden Sea.

The SWAT model scenario-exploration gives insights into the effects of different mitigation strategies. The results suggest that there are several sets of measures that may achieve all safe ecological limits. In addition to drastic measures such as land use change, these could consist of improved agricultural practices (improving infiltration and nutrient uptake efficiency), water management measures (such as improving wastewater treatment), or nature-based solutions (such as the extension of the surface area of the downstream purifying wetland).

The most drastic land use change scenario (1) changing all agriculture into nature brings the nutrient levels far below the safe ecological boundaries. Most other explored land-use change options (convert to mammut grass (2), dairy (3), beans (5)) also reduce the nutrient losses and could lead to achieving the safe ecological limits. However, when the replacement of arable farming by dairy farming also involves higher cattle densities, this may increase the atmospheric N inputs. The option to convert all dairy into arable farming (4) may reduce the atmospheric N loading, but is expected to increase nutrient losses to water.

The local water authority is already planning improvements of the wastewater treatment (6) and enlarging the Tusschenwater wetland (13). When combined, these changes are expected to bring the TP and summer TN levels withing the safe ecological boundaries, although achieving the winter TN levels may remain a challenge.

The effects of agricultural measures like increasing the nutrient uptake efficiency (8) and reducing overland flow by promoting infiltration (9) can help to also bring the winter concentration levels below the safe ecological limits. However, the adoption of agricultural measures largely depends on national and EU regulations, whereas the Water Board can only stimulate farmers to take voluntary measures. The effects of the agricultural measures are in the same range as the effects of the explored nature-based solutions (optimize in-stream retention (10) and retention in riparian buffer strips (11, 12)). The effective extension of the Tusschenwater wetland (13) mentioned above can also be considered a nature-based solution.

From this scenario exploration follows that there are multiple options in the Hunze catchment to reach bot the current WFD targets and the additional safe ecological limits. The already planned wastewater treatment improvement (6) and extension of the Tusschenwater wetland (13) brings all targets into sight. Compliance is realistic also without drastic extra measures. Land use change (1,2,3,5) in only part of the catchment can for example be sufficient. However, the targets can also be met by a further improving the wastewater treatment or by adopting the proposed agricultural measures and/or nature-based solutions.

In catchments with a larger reduction need (also after implementing the already planned mitigation), more drastic combinations of extra measures may be needed compared to the Hunze.

5.8 Conclusions

The Hunze catchment provides a representative Dutch local case, in which options to achieve the safe ecological limits protecting both the local and downstream aquatic ecology were studied in more detail and with input from the local water authority. Since the 1990s, the nutrient concentrations in the Hunze have decreased and are now stabilizing around the WFD targets for summer average TN and TP concentrations. Additional more stringent safe ecological limits (particularly for the winter concentrations and loads) have been proposed to restore the ecology of the receiving downstream water resources, like lake Zuidlaardermeer and the Wadden Sea. Especially the winter nutrient concentrations and loads still need substantial reductions to reach these additional targets.

The scenario explorations in a SWAT model of the Hunze catchment shows that the existing local WFD targets and the additional safe ecological limits are achievable through several complementary measures. The planned wetland extension and upgrades to the wastewater treatment plant, would already bring the targets into sight. The remaining reduction step can be realized through a combination of land use change, further WWTP load reduction, agricultural

management measures and/or nature-based solutions. For measures with impact on agriculture, the local water authority can mainly stimulate voluntary adoption, while large scale implementation would require national or EU-level regulation.

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

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

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Annex I

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

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	37.6	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	-	-
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	37.6	3.2	2.3	10.3	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	37.6	2.9	2.3	10.3	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	37.6	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	-9.2
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	-	-

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	-	-

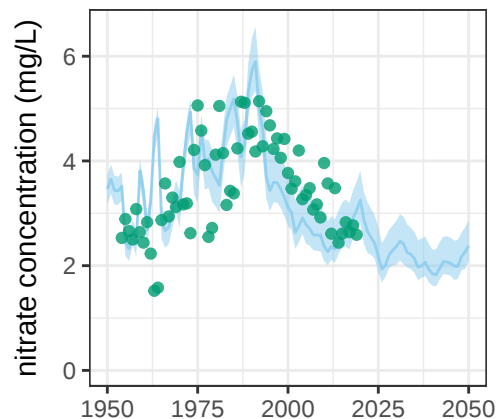
Scenario 5 2050	diffuse P [kg/ha yr]	wastewater P [kg/ha yr]	mean concentrations SRP [µg/L]	mean concentrations TP [µg/L]	mean export TP [t/yr]	network > 55 µg/L	export change to reference [%]	export change to Scenario 6 [%]
Rhine outlet	0.245	0.128	32.1	72.4	5136.8	-	27.8	30.6
Elbe outlet	0.155	0.073	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	-	-

Annex II

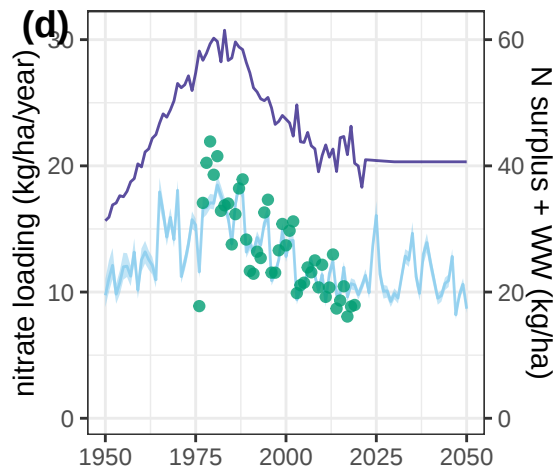
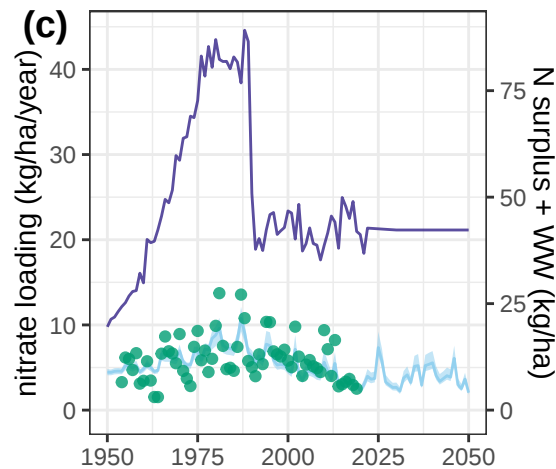
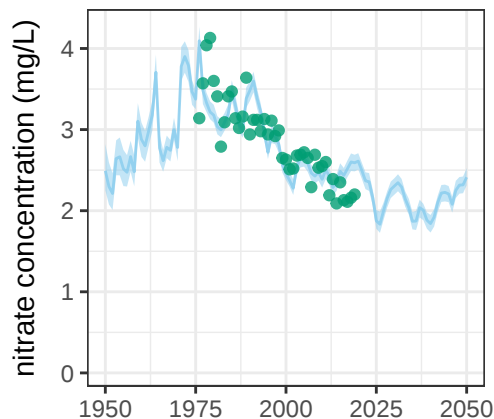
Figures for all scenarios (sim_N_c_loading_Elbe_Rhine_scen_x) on nitrate concentration and nitrate loading for the Elbe and Rhine outlet over time.



(a) Elbe

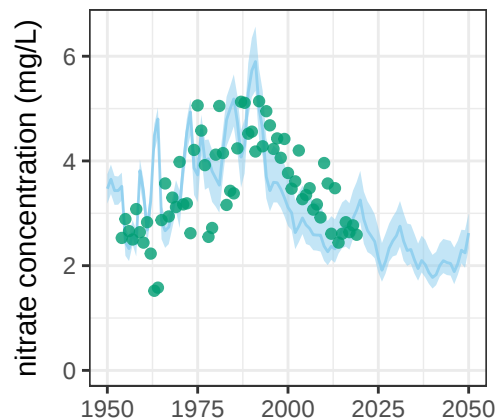


(b) Rhine

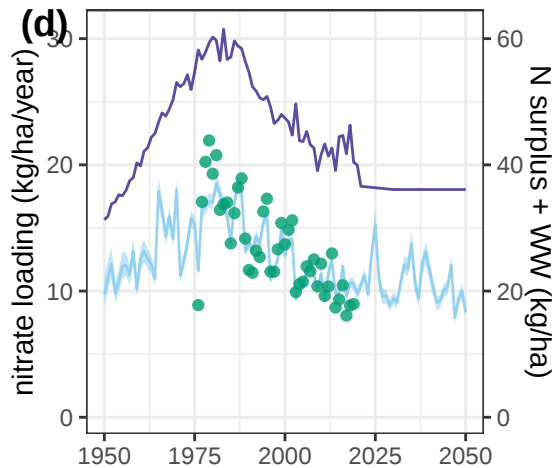
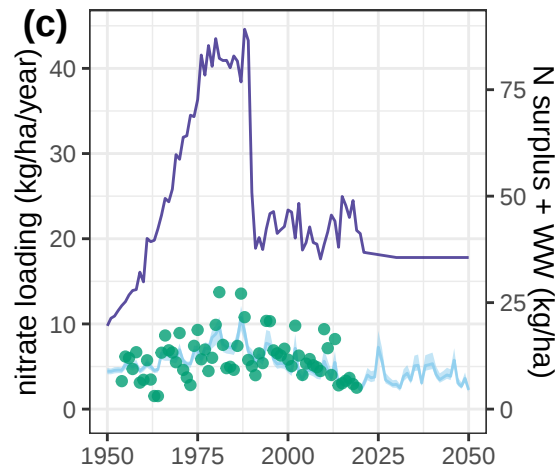
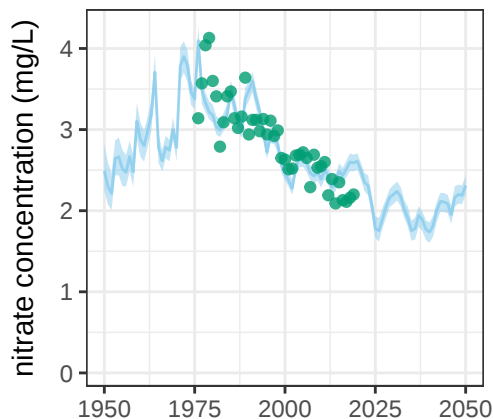




(a) Elbe

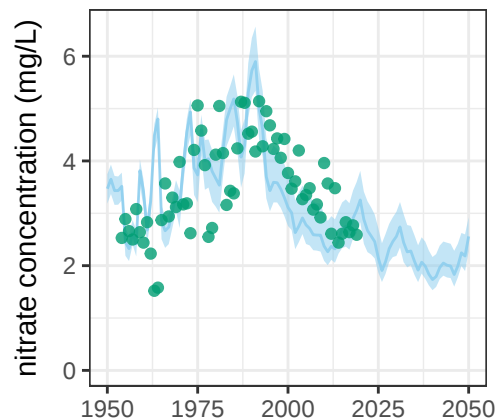


(b) Rhine

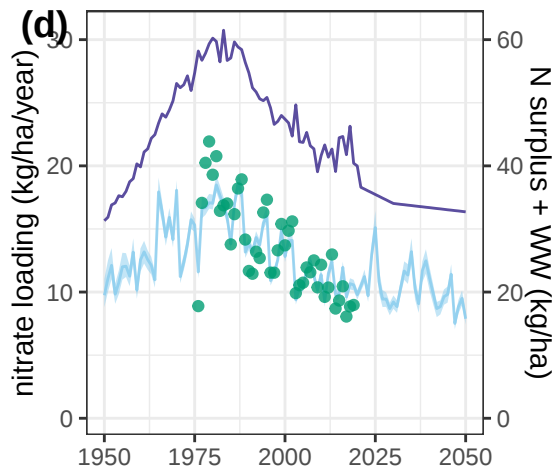
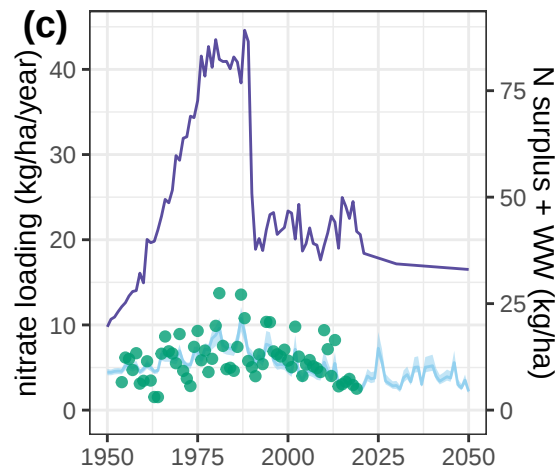
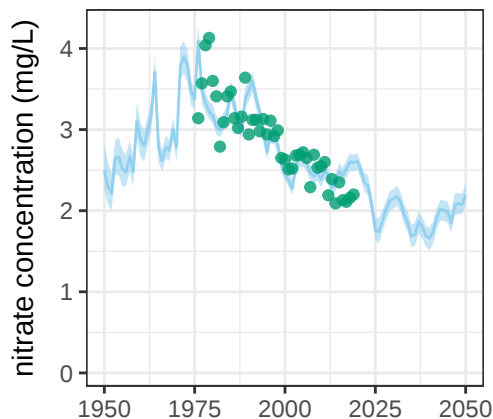




(a) Elbe

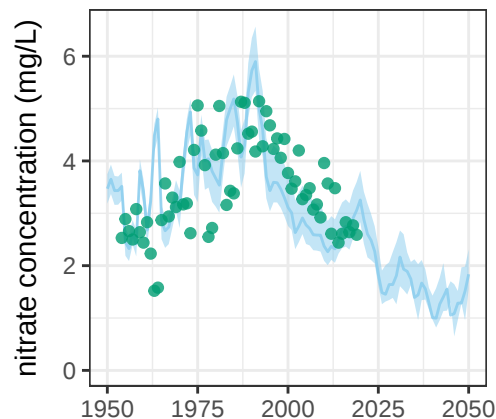


(b) Rhine

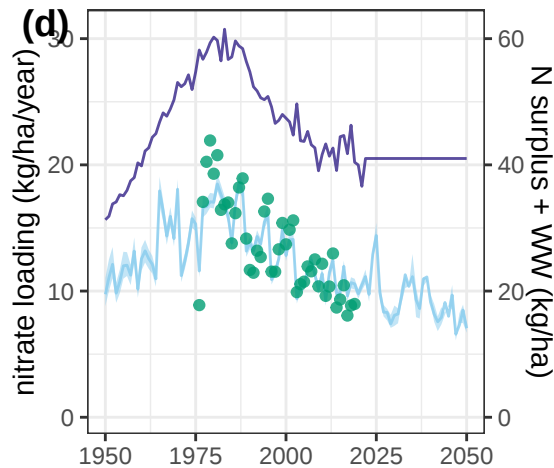
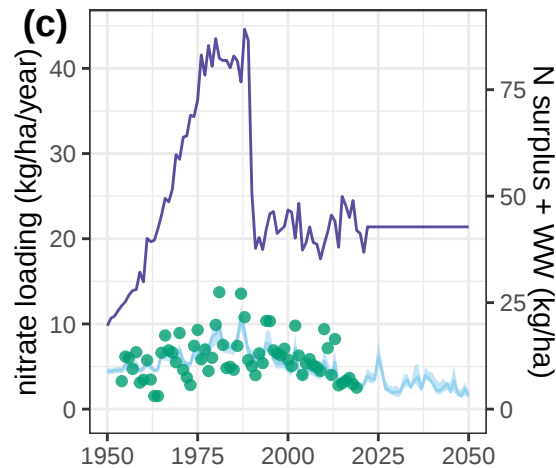
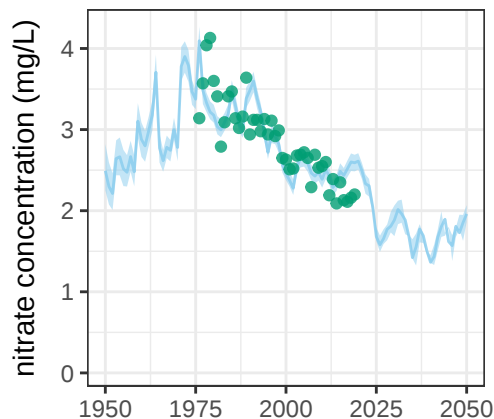




(a) Elbe

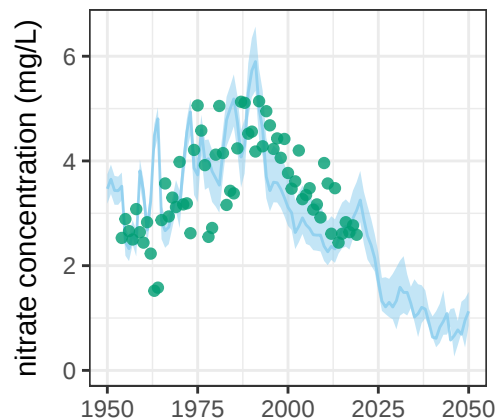


(b) Rhine

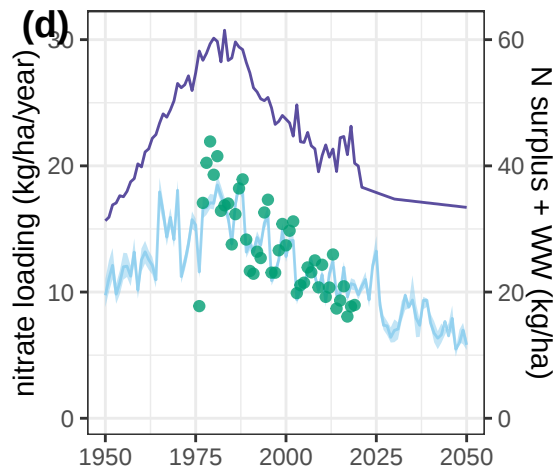
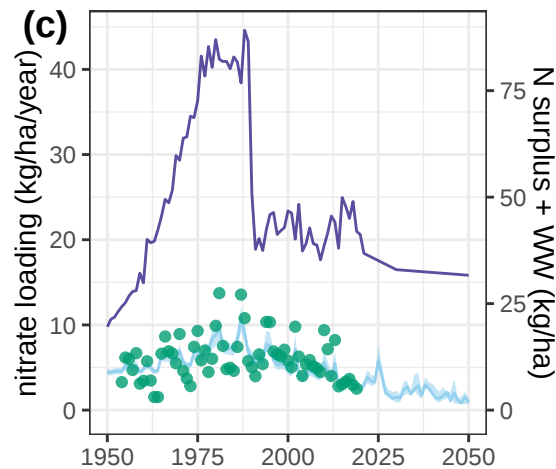
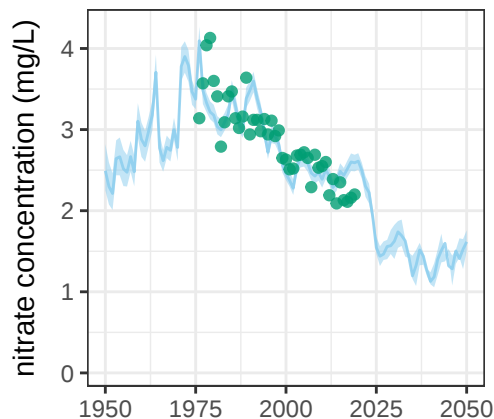




(a) Elbe

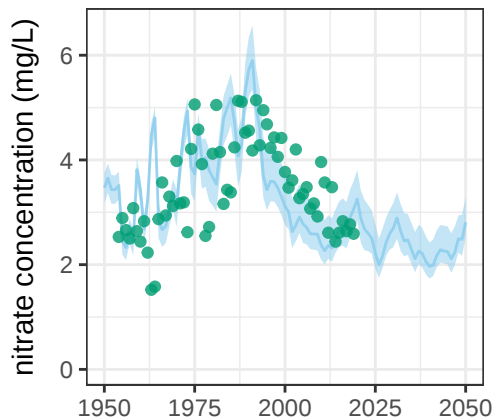


(b) Rhine

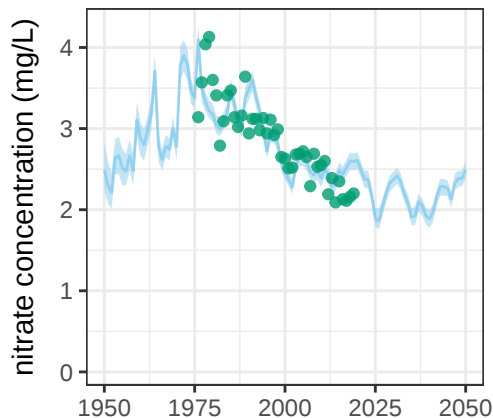




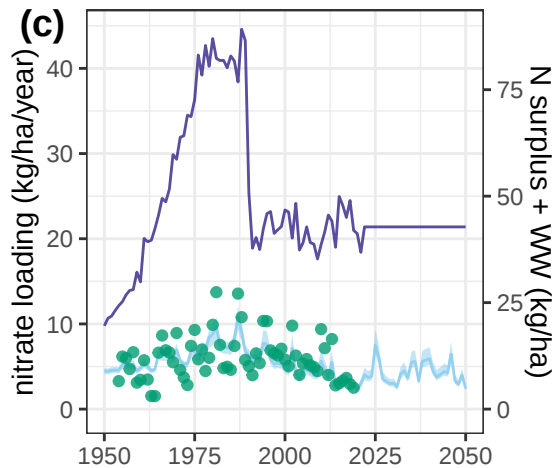
(a) Elbe



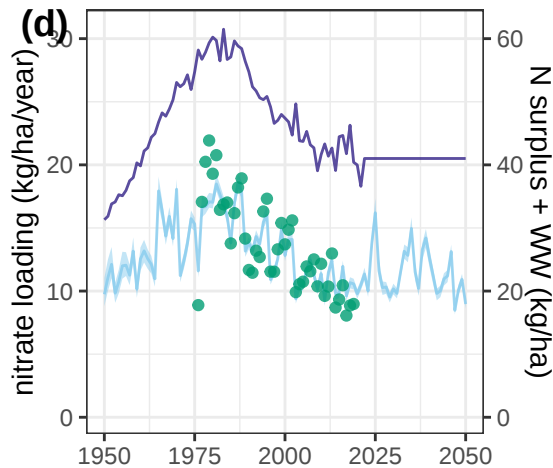
(b) Rhine



(c)

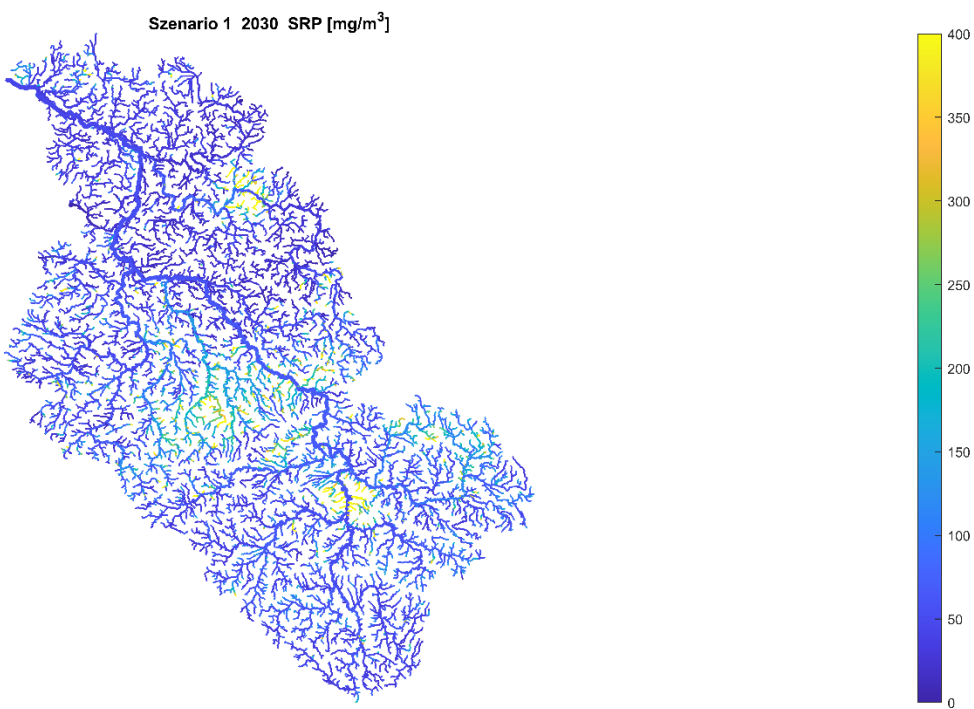
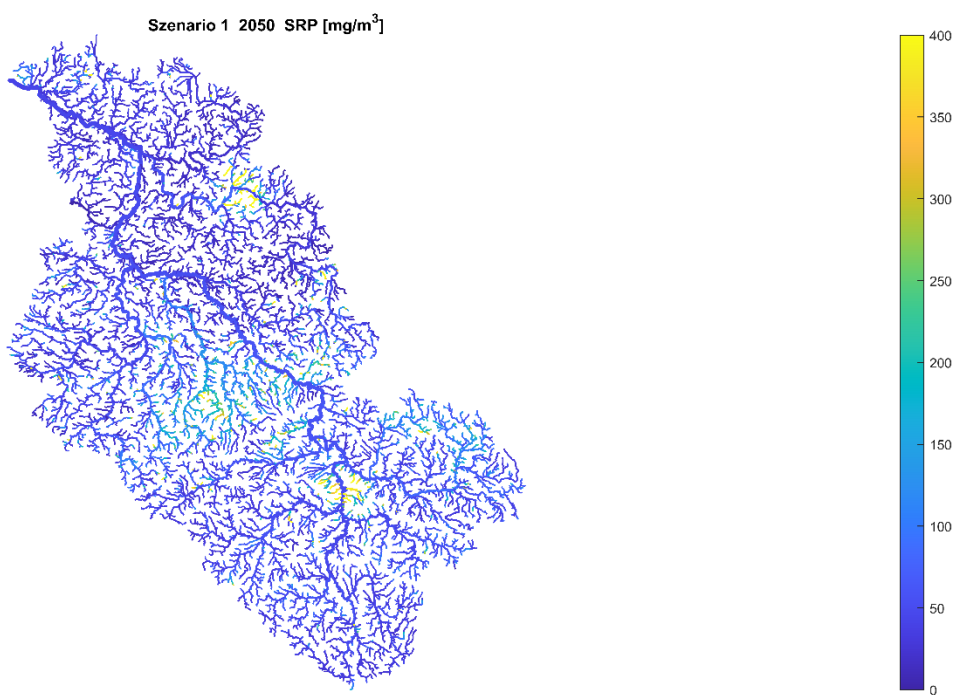


(d)

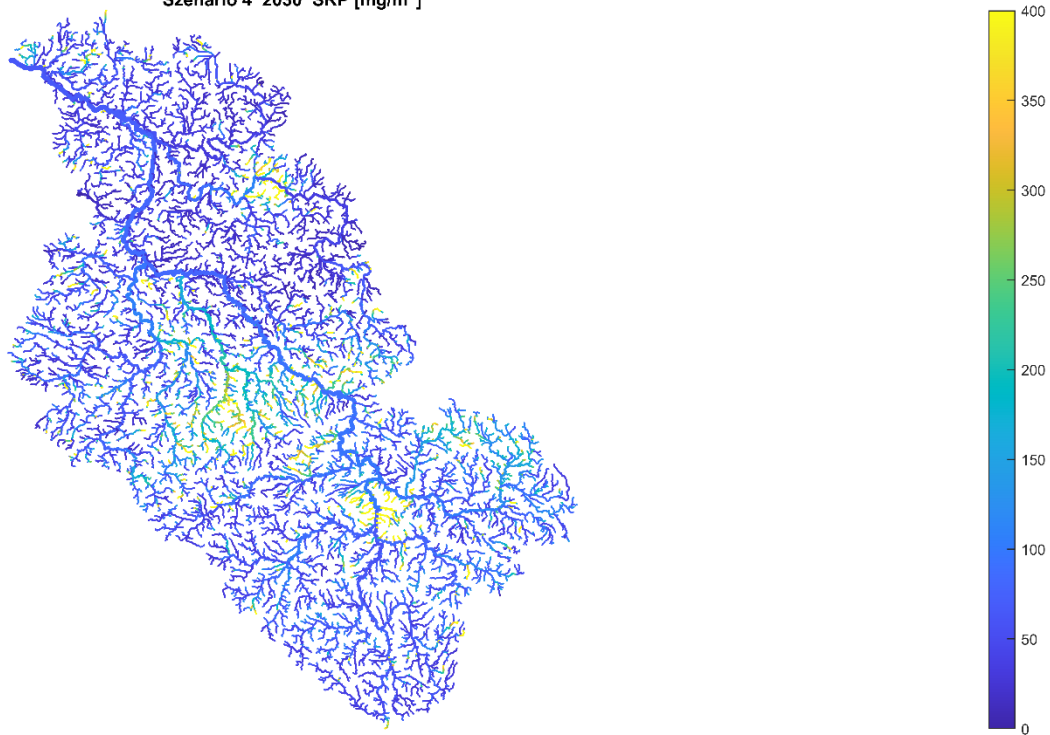


Annex III

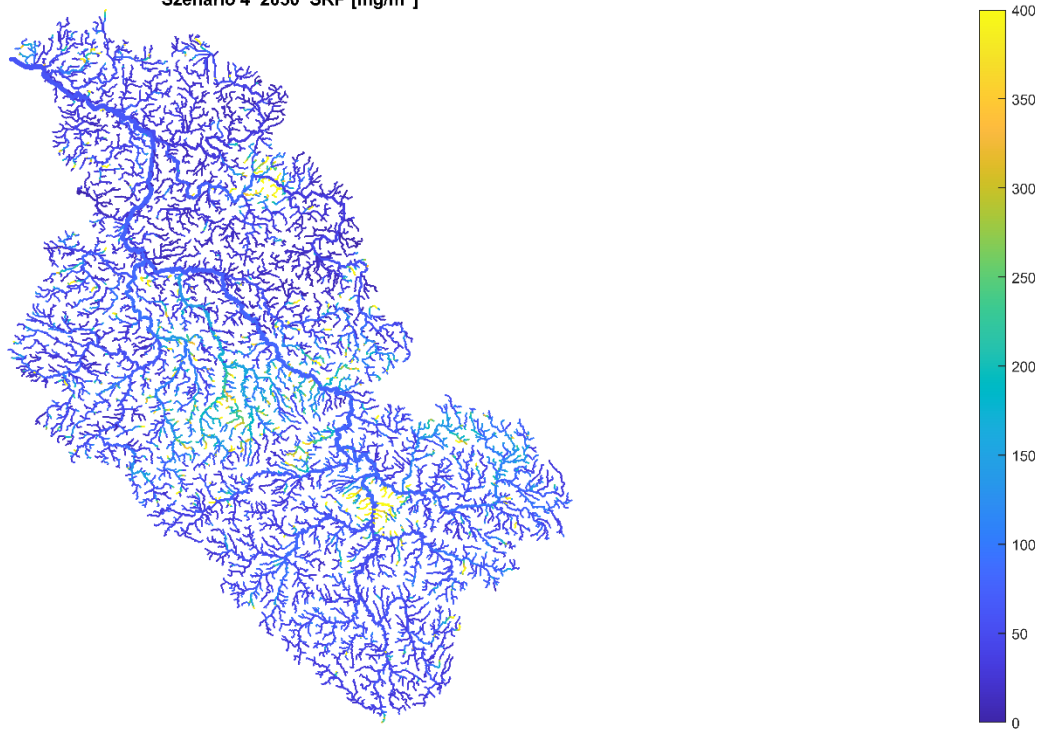
Figures for remaining scenarios for the Rhine and Elbe.



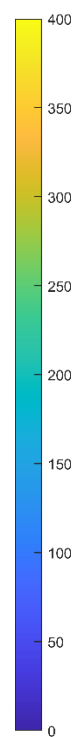
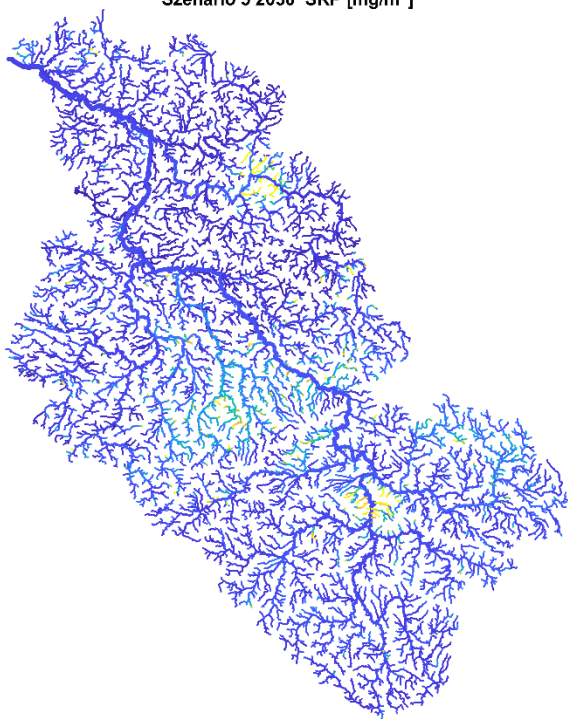
Szenario 4 2030 SRP [mg/m³]



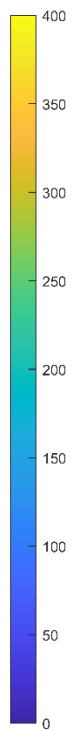
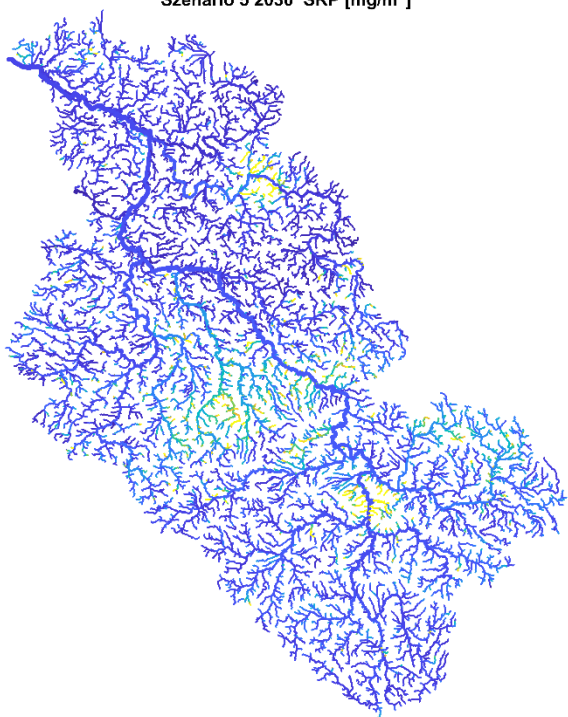
Szenario 4 2050 SRP [mg/m³]



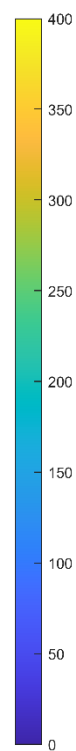
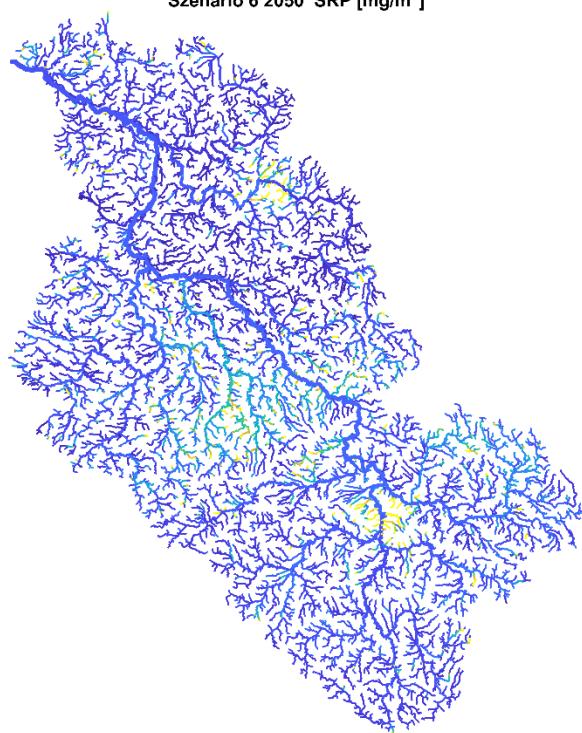
Szenario 5 2050 SRP [mg/m³]



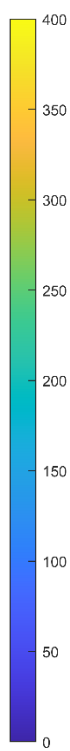
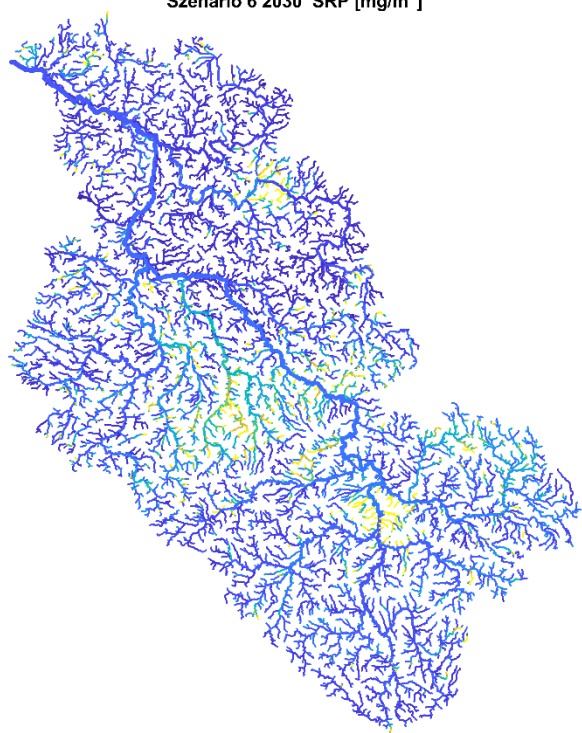
Szenario 5 2030 SRP [mg/m³]

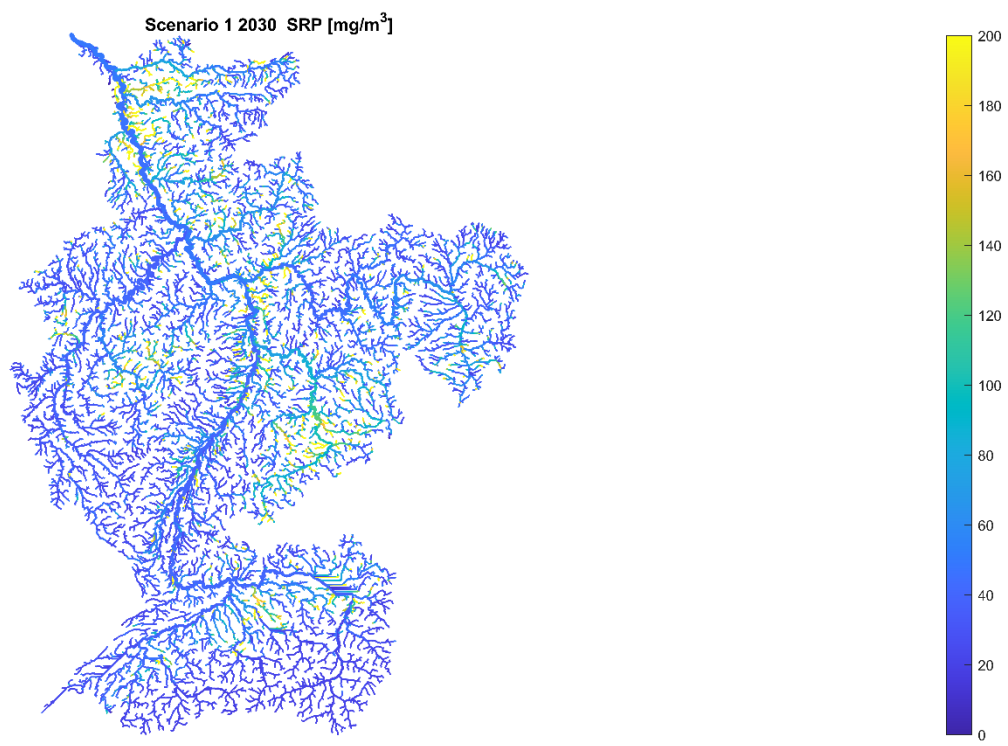
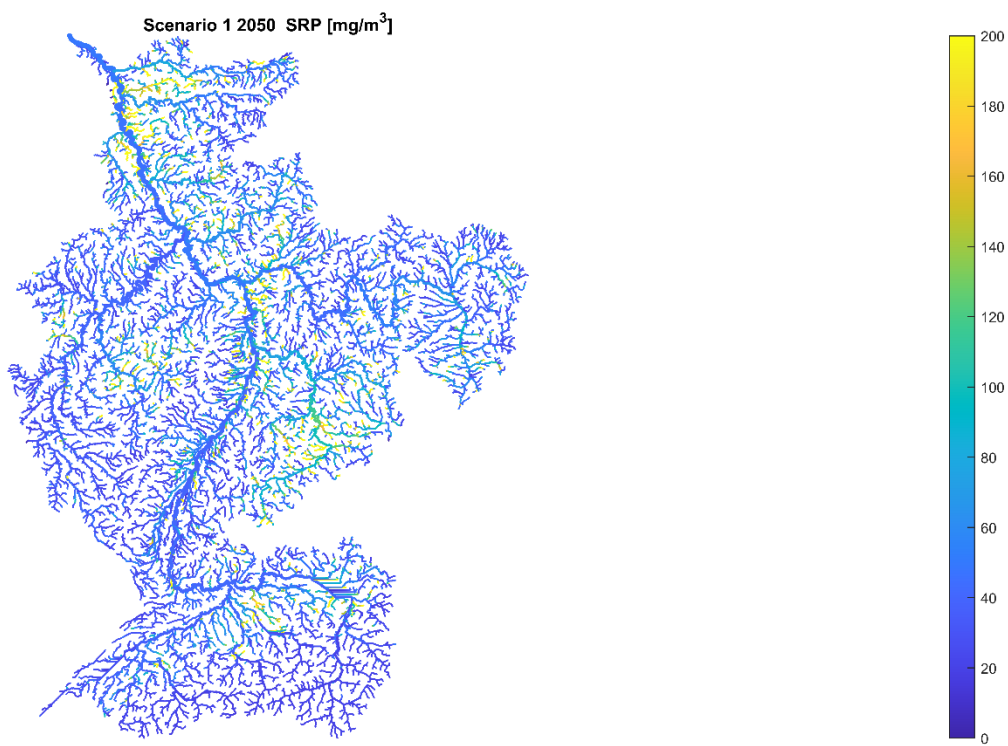


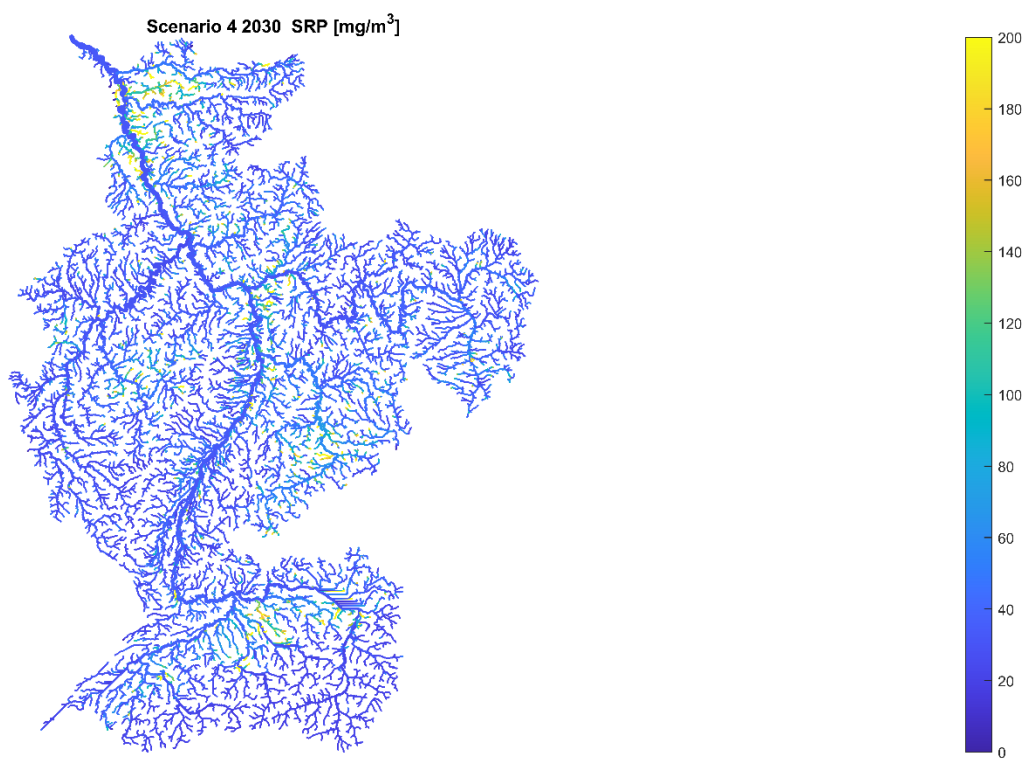
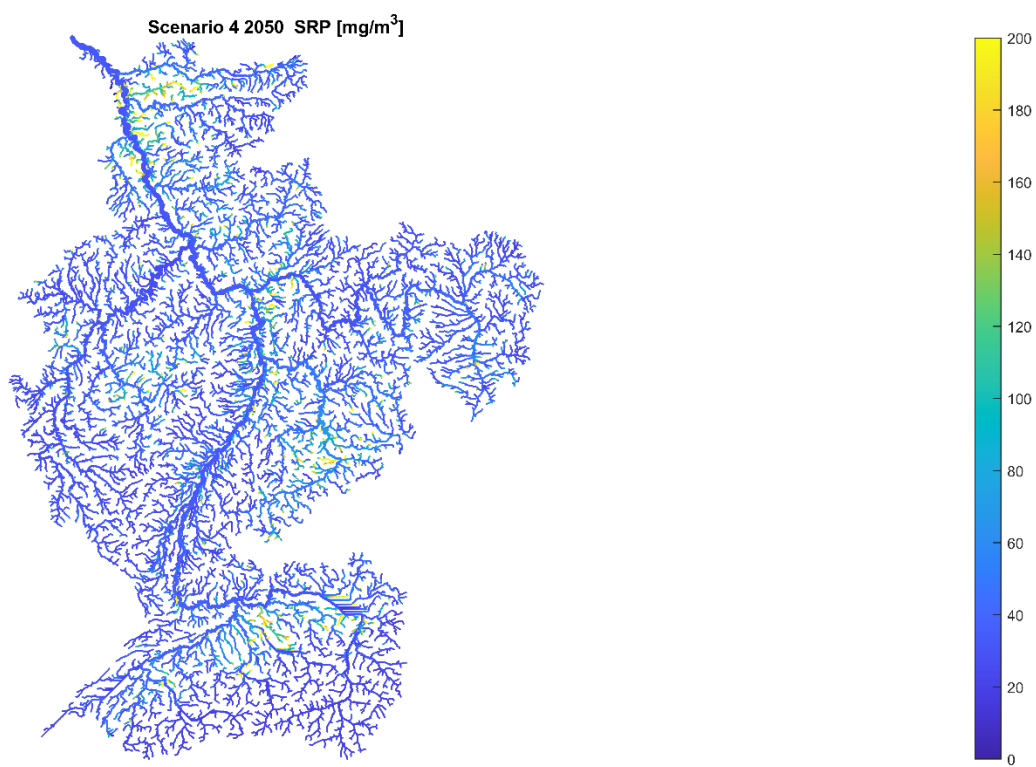
Szenario 6 2050 SRP [mg/m³]

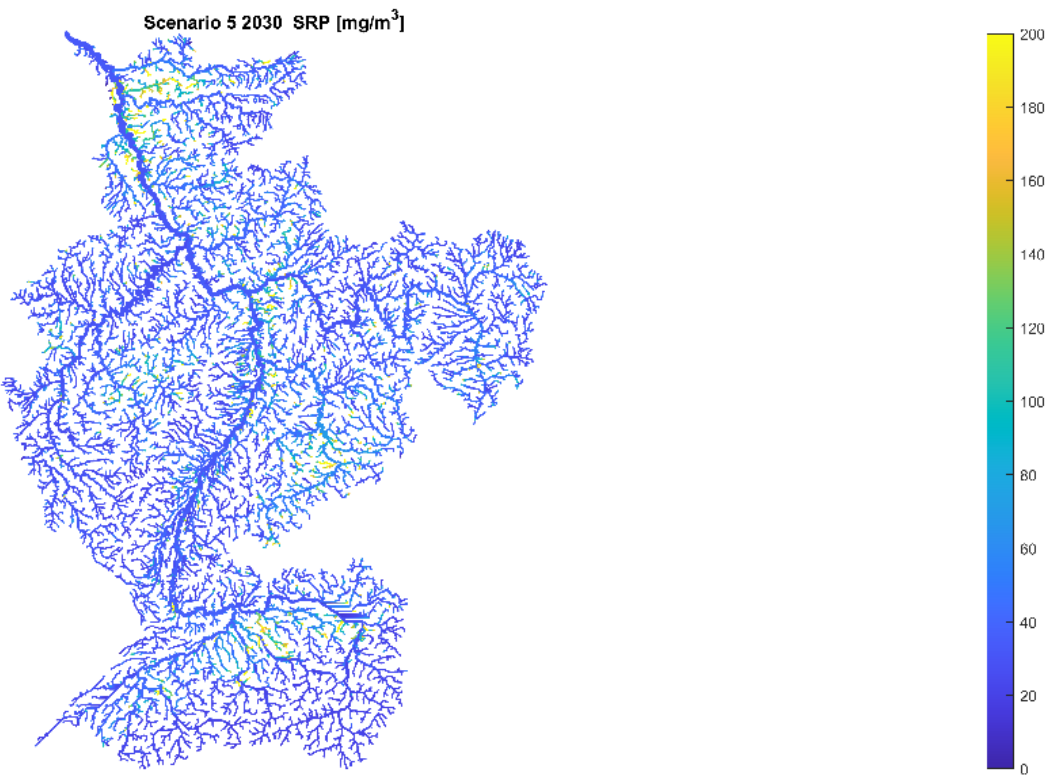
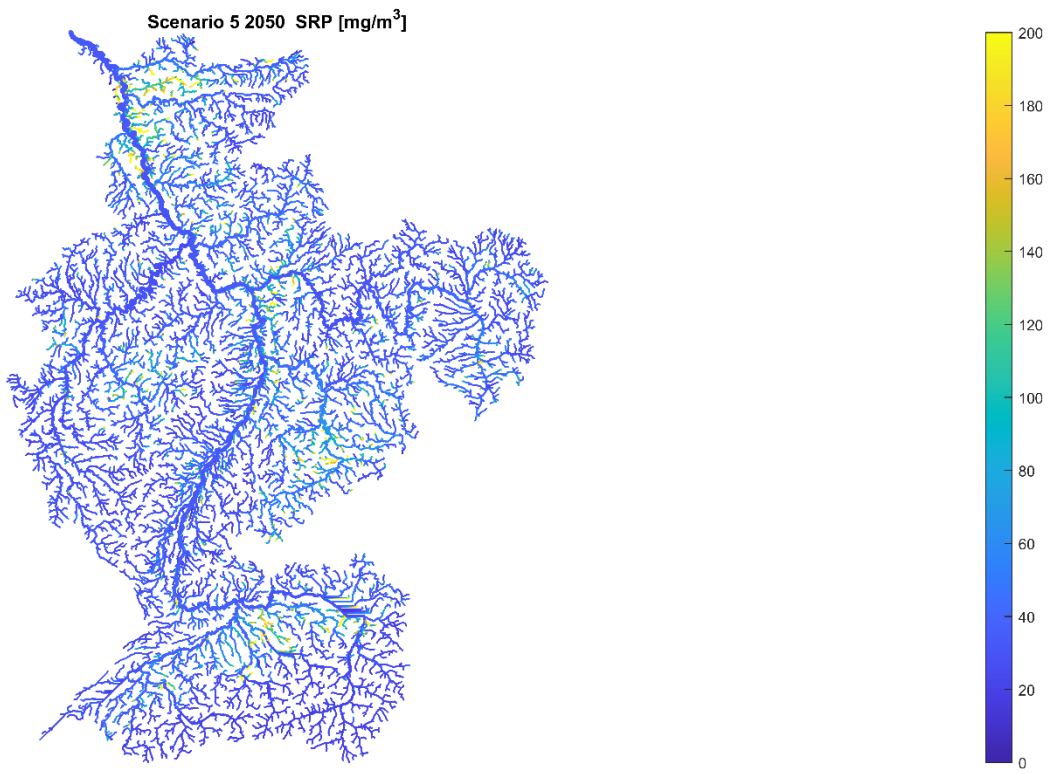


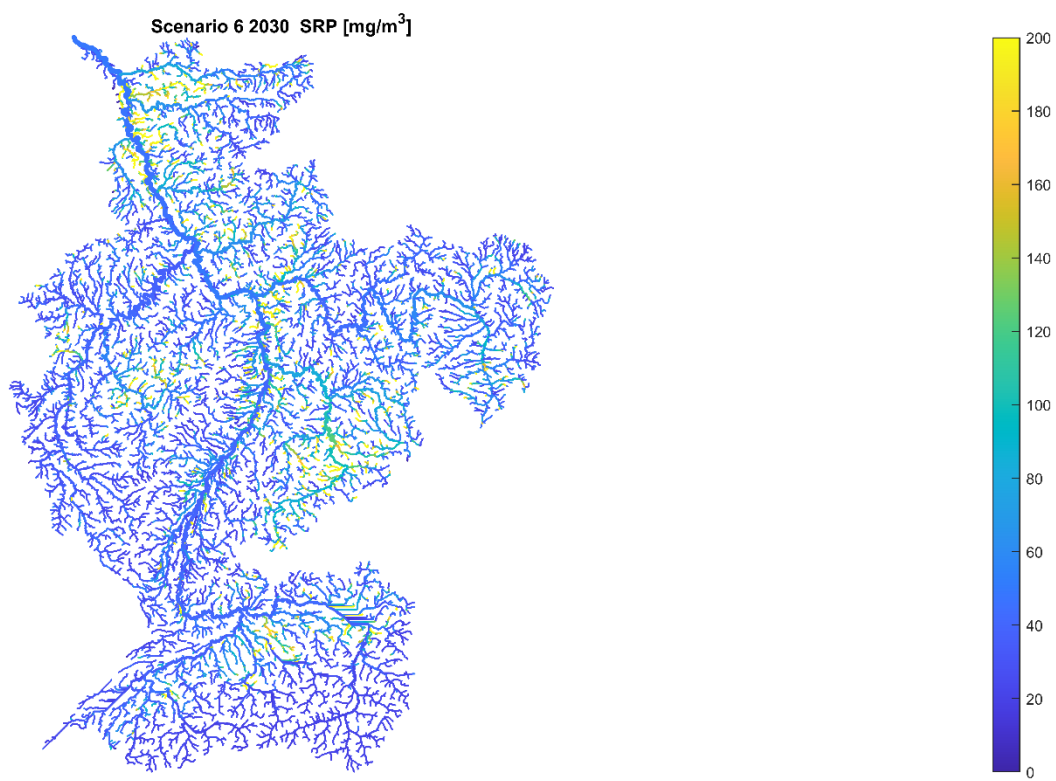
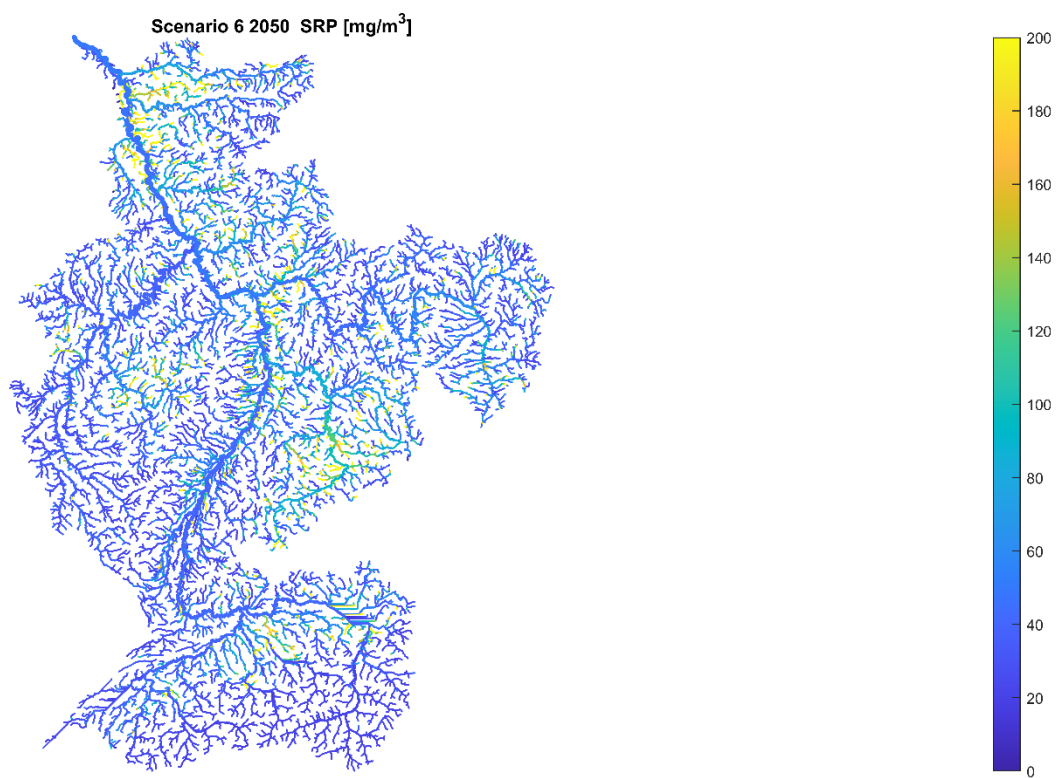
Szenario 6 2030 SRP [mg/m³]











Annex IV

This appendix provides additional details on the individual scenarios for the Hunze catchment. For each scenario, we briefly describe the background, the model implementation and the key results.

SC1 Convert agriculture to nature

Background

SC1 explores an extreme scenario in which all agricultural land is converted to natural land use. This scenario is meant as an ultimate scenario, although the WWTP effluent will remain as major nutrient source. For P, the legacy storage in the soil is expected to continue contributing to surface water loads for decades. For N, the legacy influence is likely to be smaller; however, the removal of artificial drainage systems (e.g., small ditches and tile drains) in this scenario will increase the average hydrological travel time.

Implementation

Implementing this scenario required more than a simple land use changes; several additional model parameters were adjusted to represent natural conditions. Table A.1 provides the complete list of changes. These changes were applied across all agricultural land uses, including both dairy and arable systems.

Table A.1. Convert agriculture to nature.

Parameter	SWAT File	Modification	Impact on Water Quality	Explanation
Land Use Code	.hru, crop.dat	Change from cropland (AGRL) to grassland (PAST)	↓ Runoff, N, P	Permanent vegetation increases infiltration and reduces soil erosion.
SCS Curve Number (CN2)	.mgt	Lower CN (75→60)	↓ Runoff, ↑ Infiltration	Grassland has higher infiltration, reducing surface flow.
USLE_C (Erosion Factor)	crop.dat	Lower value (0.20 → 0.01)	↓ P loss	Grassland minimizes soil erosion.
Manning's n (Surface Roughness)	.hru	Increase (0.1 → 0.2)	↓ Runoff velocity, ↓ Erosion	Vegetation slows runoff, reducing sediment transport.
Fertilizer Input (N, P)	.mgt	Remove fertilizer	↓ N, P runoff/leaching	Eliminates excess nutrients entering water.
Tillage Operations	.mgt	Remove tillage events	↓ Erosion, ↑ Soil structure	No-till maintains soil integrity.
Soil Saturated Hydraulic Conductivity (SOL_K)	.sol	Increase K value *3	↑ Infiltration, ↓ Surface runoff	Improved soil porosity under permanent vegetation.
Tile drainage		Remove tile drainage	↑ Residence time	Increase the N legacy

Results

The predicted concentrations under SC1 are all well below the current WFD targets and the Safe Ecological Limits. For TN, the reduction in concentrations is more pronounced than that of TP. With particularly substantial decreases observed in winter TN concentrations.

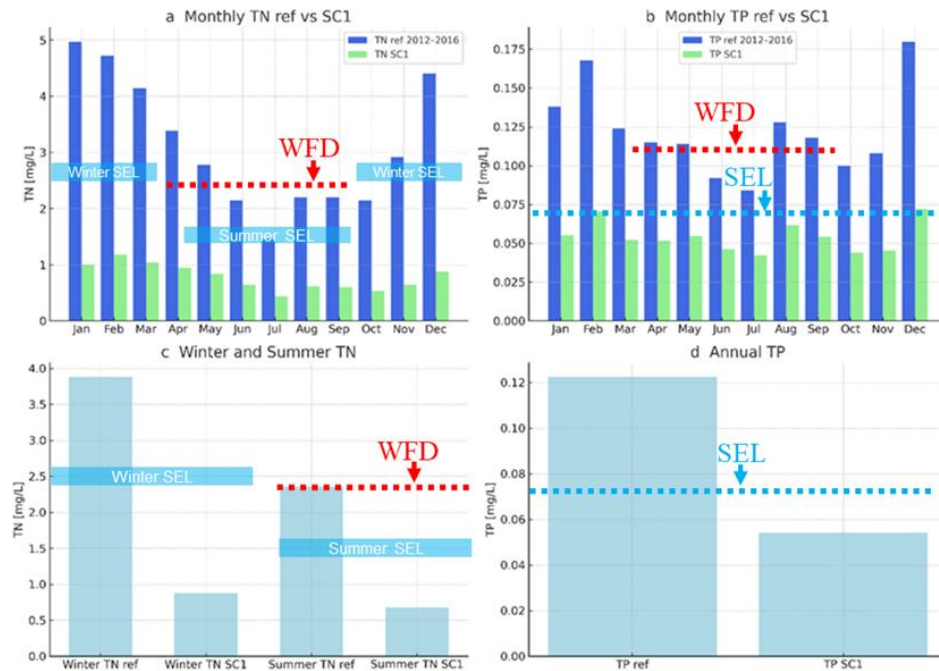


Fig A.1. Monthly TN and TP results ref vs SC1

SC2 Convert agriculture to Mammut grass cultivation

Background

A farmer within the Hunze catchment has initiated the cultivation of Mammut grass. Converting arable land to Mammut grass cultivation offers several environmental benefits; it reduces nutrient losses, improves soil quality, and contributes significantly to carbon sequestration. Mammut grass can be used as a raw material for plant-based building materials, renewable ethanol production, and green cellulose for the paper industry. Therefore, Mammut grass aligns well with the broader transition towards sustainable, plant-based resource use.

In this scenario, we explore the potential impact of large-scale adoption of Mammut grass cultivation in the Hunze catchment. Specifically, all arable land within the catchment was converted into Mammut grass.

Implementation

Implementing this scenario involves more than just changing the land use. Several additional parameters were also adjusted to reflect the specific characteristics of Mammut grass cultivation. Table A.2 gives the complete list of changes in the model. These changes were made for all arable land use.

Table A.2. Convert agriculture to Mammut grass cultivation.

Parameter	SWAT File	Modification	Impact on Water Quality	Explanation
Land Use Code	.hru, crop.dat	Change cropland (AGRL) to mammut grass (MAMG). Use perennial settings.	↓ Runoff, ↓ N, ↓ P	Mammut grass is a perennial crop with deep roots, improving infiltration and reducing erosion.
SCS Curve Number (CN2)	.mgt	Lower CN2 (75 → 60)	↓ Runoff, ↑ Infiltration	Permanent vegetation enhances infiltration, reducing runoff peaks.
USLE_C (Erosion Factor)	crop.dat	Reduce (0.2→0.003)	↓ P loss	Dense cover prevents soil erosion, cutting sediment-bound P export.
Manning's n (Surface Roughness)	.hru	Increase (0.1→0.2)	↓ Runoff velocity, ↓ Erosion	Tall vegetation slows water movement, reducing peak flows.
Soil Saturated Hydraulic Conductivity (SOL_K)	.sol	Increase by 20%	↑ Infiltration, ↓ Surface runoff	Deep roots improve soil structure, increasing permeability.
Management Operations	.mgt	No tillage after planting. Annual harvest with residue left.	↓ Erosion, ↑ Soil stability	Perennial growth eliminates plowing, keeping soil intact.
Fertilizer Input (N, P)	.mgt	Decrease by 20%	↓ N, ↓ P runoff	Lower fertilizer need due to nutrient recycling by

Results

The predicted concentrations in SC2 are substantially lower than the reference concentrations. For both TN and TP, the current summer average standards WFD standards would clearly be met. For TN, both winter and summer concentrations are also just below the safe ecological limits. In the case of TP, the predicted monthly concentrations under SC2 fluctuate around the safe ecological limit, while the annual average remains slightly above this threshold.

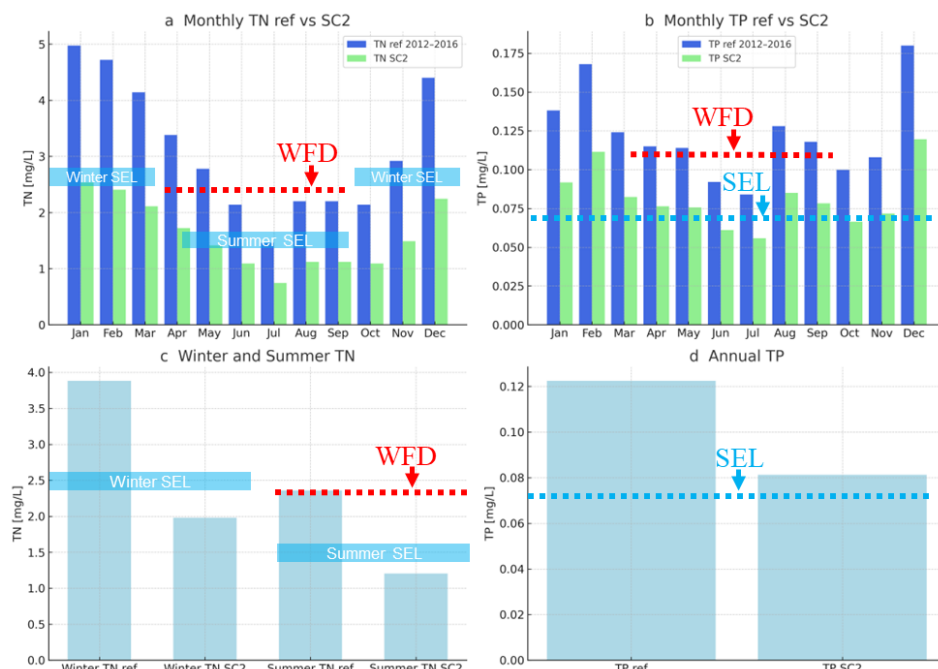


Fig A.2. Monthly TN and TP results ref vs SC2

SC3 Convert arable into dairy

Background

On average, nutrient losses from arable land are higher than those from grassland. In particular, permanent grassland exhibits relatively low nutrient losses and provides additional benefits such as improved soil quality, enhanced hydrological functioning, and increased carbon sequestration. In this scenario, we assess the effect of drastically conversion of all arable land to dairy farming.

Implementation

Implementing this scenario involves more than a simple land use change. Table A.3 gives the complete list of changes in the model. These changes were made for all arable land.

Table A.3. Convert arable into dairy.

Parameter	SWAT File	Modification	Impact on Water Quality	Explanation
Land Use Code	hru_crop.dat	Change cropland (AGRL) to dairy grassland (PASTY). Adjust biomass cycling.	↑ Runoff, ↓ N, ↓ P	Dairy grasslands in the Netherlands provide permanent vegetation cover.
SCS Curve Number (CN2)	.mgt	Lower CN2 (75 → 65).	↑ Runoff, ↓ Infiltration	Pasture reduces runoff, but trampling and compaction limit infiltration.
USLE C (Erosion Factor)	crop.dat	Reduce to (0.2 → 0.02) but higher than undisturbed grassland.	↓ P loss	Perennial cover prevents erosion, but bare patches from overgrazing can still cause issues.
Manning's n (Surface Roughness)	hru	Increase (0.1 → 0.25)	↑ Runoff velocity, ↓ Erosion	Dense grass slows runoff, increasing surface water retention.
Soil Saturated Hydraulic Conductivity (SOL_K)	.sol	Increase by 20%.	↑ Infiltration, ↓ Surface runoff	Manure and roots enhance soil porosity, improving infiltration but increasing nitrate leaching.

Management Operations	.mgt	No annual tillage;	↓ Erosion, ↑ Soil stability	No tillage preserves soil structure, but overgrazing can lead to soil degradation.
Fertilizer Input (N, P)	.mgt	Decrease by 20% and optimize timing to minimize runoff.	↓ N, ↓ P runoff	Manure application requires careful management to prevent excess N and P loss.

Results

The predicted concentrations in SC3 are clearly below the current WFD standards for summer average TN and TP concentrations. In addition, all safe ecological limits are met. For TP, the predicted yearly average concentration falls just below the safe ecological limits.

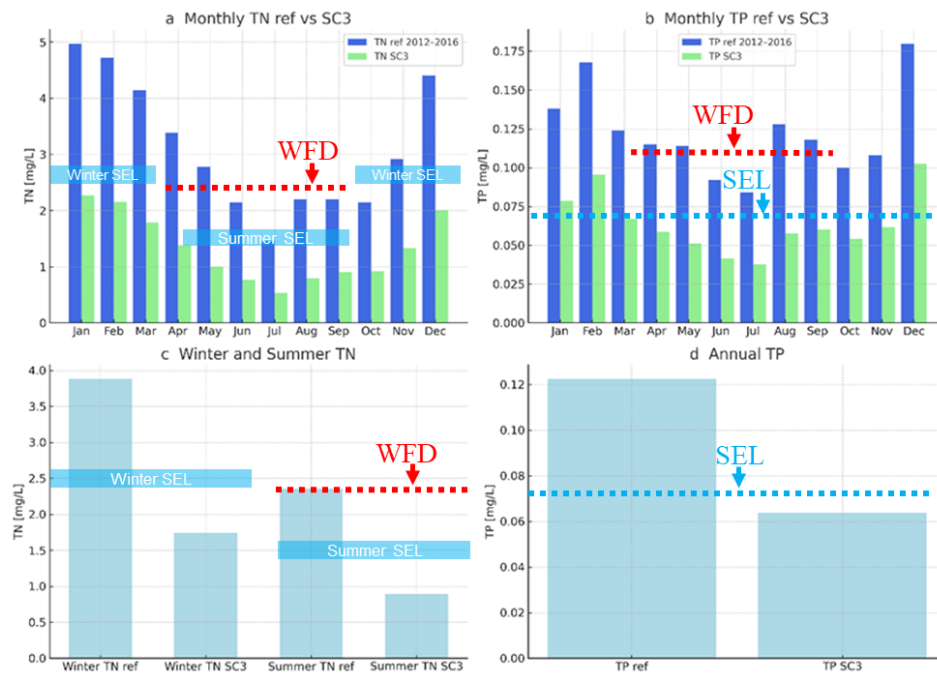


Fig A.3. Monthly TN and TP results ref vs SC3

SC4 Convert dairy into arable

Background

A current trend in Dutch agriculture is that dairy farming converts into arable farming. There are several causes of this trend:

- Recently, the Dutch dairy sector lost its derogation allowing the application of higher quantities of livestock manure. Consequently, dairy farmers now face increased operational costs, as more manure must be transported and processed externally at greater expense.
- Dairy farmers, especially those operating near protected nature reserves, are encouraged to cease farming activities. This policy aims to reduce atmospheric nitrogen emissions and nitrogen deposition within the sensitive nature reserves.
- Land prices in the Netherlands are increasingly high, necessitating relatively high profits per hectare. This economic pressure encourages the cultivation of intensive arable crops.

Conversion of dairy farming and (permanent) grassland into arable farming may reduce atmospheric nitrogen emissions but is expected to have negative impact on groundwater and surface water quality. In this scenario, we explore the effect of the extreme case in which all dairy land is converted into arable land.

Implementation

Implementing this scenario involves more than a mere change in land use. Table A.4 provides the complete overview of all changes in the model. These changes were made for all grassland in the Hunze catchment.

Table A.4. Convert dairy into arable.

Parameter	SWAT File	Modification	Impact on Water Quality	Explanation
Land Use Code	.hru_crop.dat	Change pasture (PAST) to cropland (AGRL). Adjust plant growth parameters.	↑ Runoff, ↑ N, ↑ P	Arable land has seasons of bare soil, increasing runoff and nutrient runoff.
SCS Curve Number (CN2)	.mgt	Increase CN2 (65 → 80) to reflect higher runoff from tilled soil.	↑ Runoff, ↓ Infiltration	Tilled soil has lower infiltration, leading to higher runoff and potential flooding.
USLE C (Erosion Factor)	crop.dat	Increase USLE C (0.02 → 0.2) to account for bare soil erosion risk.	↑ P loss	Exposed soil is more prone to erosion, increasing sediment-bound P transport.
Manning's n (Surface Roughness)	.hru	Decrease Manning's n (0.25 → 0.1) due to smoother tilled surface.	↑ Runoff velocity, ↑ Erosion	Tilled fields have a smoother surface, allowing faster water movement.
Soil Saturated Hydraulic Conductivity (SOL_K)	.sol	Decrease by 20 as soil compaction increases.	↓ Infiltration, ↑ Surface runoff	Compacted soils have lower permeability, leading to more surface runoff.
Management Operations	.mgt	Annual tillage, seasonal planting; no permanent ground cover.	↑ Erosion, ↓ Soil stability	Without permanent vegetation, soil becomes more vulnerable to erosion.
Fertilizer Input (N)	.mgt	Increase fertilizer input 25% to match crop demands.	↑ N not for P runoff	Higher fertilizer needs increase the risk of nutrient leaching and runoff.

Results

The predicted concentrations in SC4 indicate a clear deterioration in water quality within the Hunze catchment. Both TN and TP concentrations are projected to increase significantly after converting dairy to arable farming. As a result, the current WFD targets will be exceeded, and the safe ecological limits will not be met by far.

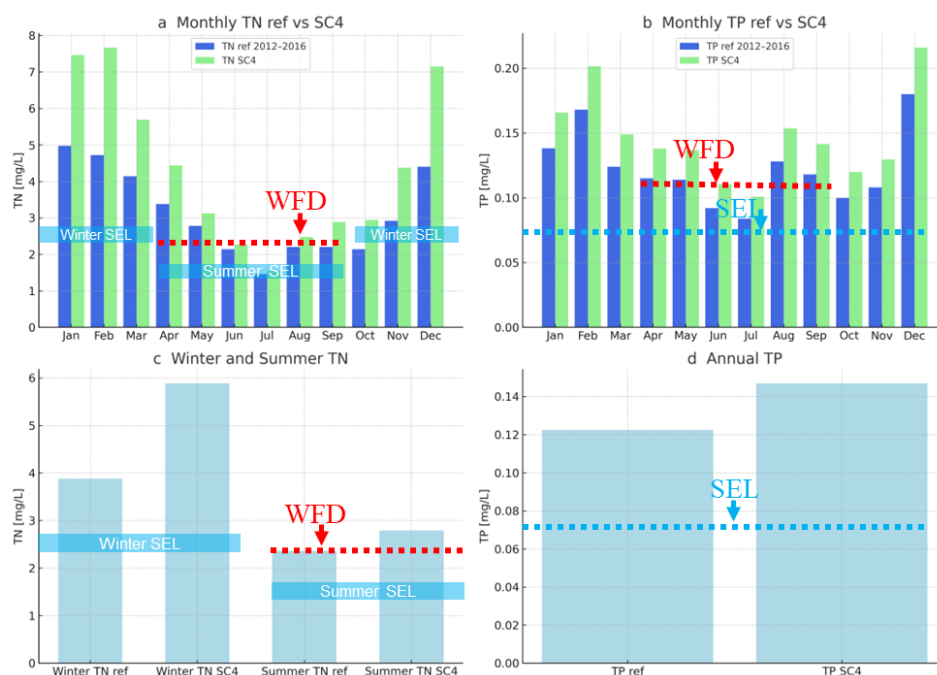


Fig A.4. Monthly TN and TP results ref vs SC4

SC5 Convert to beans

Background

This scenario is inspired by the ongoing protein transition and the anticipated increase in demand for plant-based proteins sources. Consequently, in this scenario, all arable farmland was substantially converted to cultivation of protein-rich bean. Bean cultivation offers multiple potential benefits, including reduced nutrient losses and improved soil health.

Implementation

Implementing this scenario involves more than just changing the land use. Table A.5 gives the complete list of changes in the model. These changes were made for all arable land in the Hunze catchment.

Table A.5. Convert arable into beans.

Parameter	SWAT File	Modification	Impact on Water Quality	Explanation
Land Use Code	.hru_crop.dat	Change cropland (AGRL) to beans (legumes) (BEAN). Adjust crop growth cycle and rooting depth.	↓ Runoff, ↓ N, ↓ P	Beans (legumes) improve soil fertility and infiltration while reducing erosion.
SCS Curve Number (CN2)	.mgt	Lower CN2 (80 → 70) to reflect better infiltration due to legumes' deep rootings.	↓ Runoff, ↑ Infiltration	Deep roots increase infiltration, reducing surface runoff.
USLE C (Erosion Factor)	crop.dat	Reduce USLE C (0.2 → 0.1) due to better soil cover from beans.	↓ P loss	Beans provide more soil cover compared to other row crops, reducing erosion risks.
Manning's n (Surface Roughness)	.hru	Increase Manning's n (0.1 → 0.15) to reflect rougher cover from bean crops.	↓ Runoff velocity, ↓ Erosion	Higher crop coverage slows down surface water flow, minimizing erosion.
Soil Saturated Hydraulic Conductivity (SOL_K)	.sol	Increase by 15% due to enhanced soil structure.	↑ Infiltration, ↓ Surface runoff	Legumes enhance soil structure, increasing permeability and water retention.
Management Operations	.mgt	Seasonal planting, occasional cover cropping to improve soil fertility.	↓ Erosion, ↑ Soil stability	Cover cropping in winter reduces soil degradation and retains nutrients.
Fertilizer Input (N, P)	.mgt	Decrease synthetic fertilizer by ~40% due to biological nitrogen fixation.	↓ N runoff, balanced soil P availability	Legumes fix atmospheric nitrogen, reducing the need for synthetic fertilizers.

Results

The predicted concentrations in SC5 indicate that the current WFD standards for summer average concentrations will be met for both TN and TP. For TN, the safe ecological limits for both winter and summer concentrations will also be met. For P, however, the monthly predicted concentrations vary around the safe ecological limit, and the predicted yearly average TP concentration slightly exceeds the safe ecological limit.

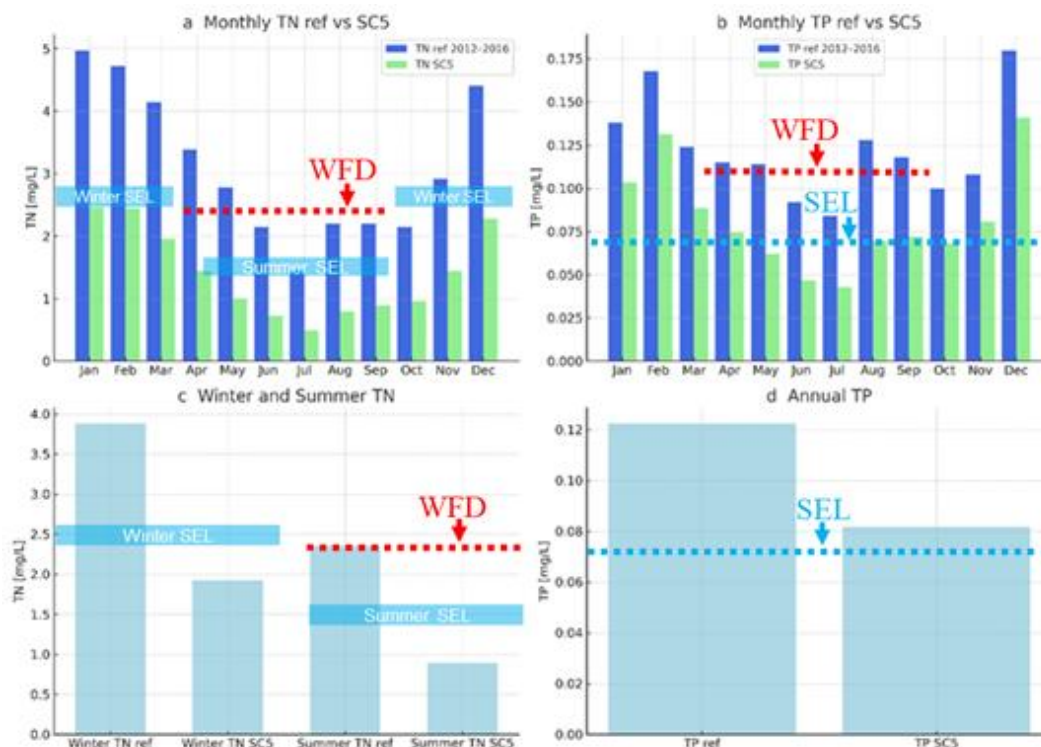


Fig A.5. Monthly TN and TP results ref vs SC5

SC6 WWTP improved

Background

The WWTP in Gieten is a relevant source of TN and TP for the downstream part of the Hunze and the loads entering the lake Zuidlaardermeer. The Water Board Hunze en Aa's has already planned upgrades to the WWTP aimed at further reducing the TP concentrations in the effluent. These improvement are already partly implemented but not yet fully operational. Once completed, the maximum concentration for TP in the effluent is expected to decrease to 0,27 mg/l (currently 0,50 mg/l). In this scenario, The TN concentrations remain unchanged.

Implementation

The TP concentrations in the WWTP effluent is capped at a maximum of 0,27 mg/l.

Results

The predicted concentrations in SC6 indicate a modest reduction in the TP concentrations. This reduction is sufficient to meet the current WFD target for summer average TP concentrations. However, the safe ecological limits for annual average TP concentrations remain unattainable under this scenario.

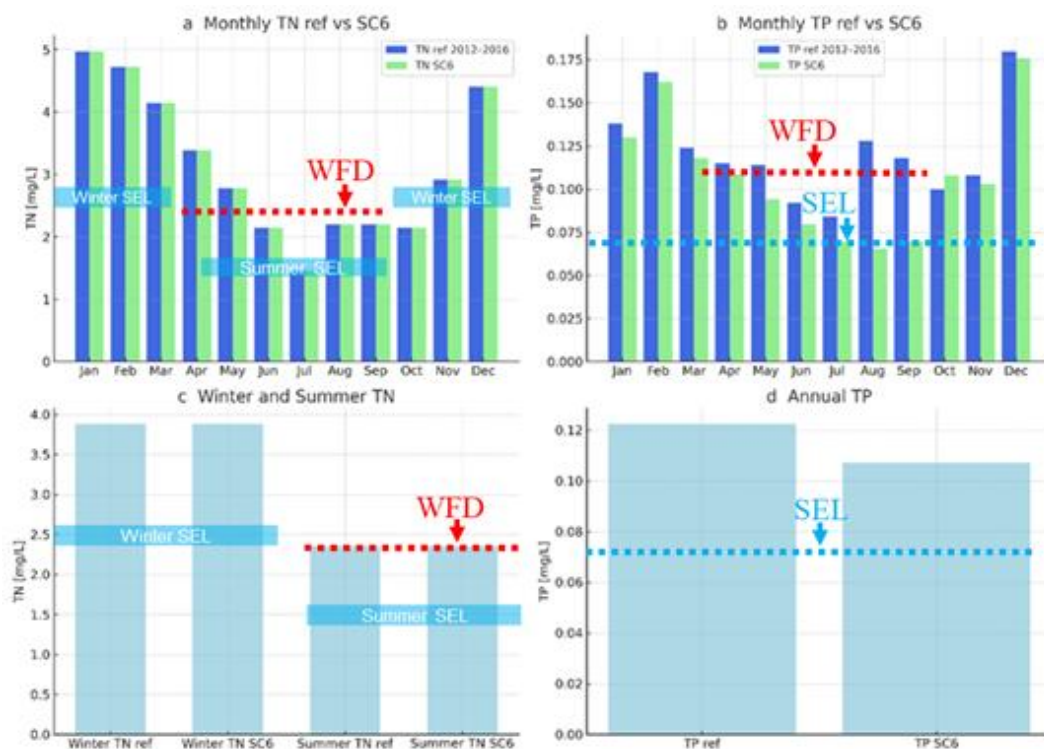


Fig A.6. Monthly TN and TP results ref vs SC6

SC7 WWTP enhanced purification / summer peak buffering

Background

The WWTP in Gieten is a relevant source of TN and TP for the downstream part of the Hunze and the loads entering the lake Zuidlaardermeer. In this scenario, a higher purification efficiency of the WWTP is assumed for both TN and TP. This improvement could be achieved, for example, by implementing larger buffer systems that can reduce the input peaks during heavy summer rainfall events.

Implementation

The winter loads from the WWTP are reduced by 10% and the summer loads by 20%, for both TN and TP.

Results

The predicted concentrations in SC7 show notable reductions in both TN and TP, contributing to summer concentrations well below the WFD targets. The predicted reductions are more pronounced during the summer months, partly due to the larger assumed load reduction in this period, and partly because the relative contribution of the WWTP effluent is bigger in summer. Although the safe ecological limits are not fully achieved in this scenario, the summer concentrations for TN approach the summer safe ecological limit.

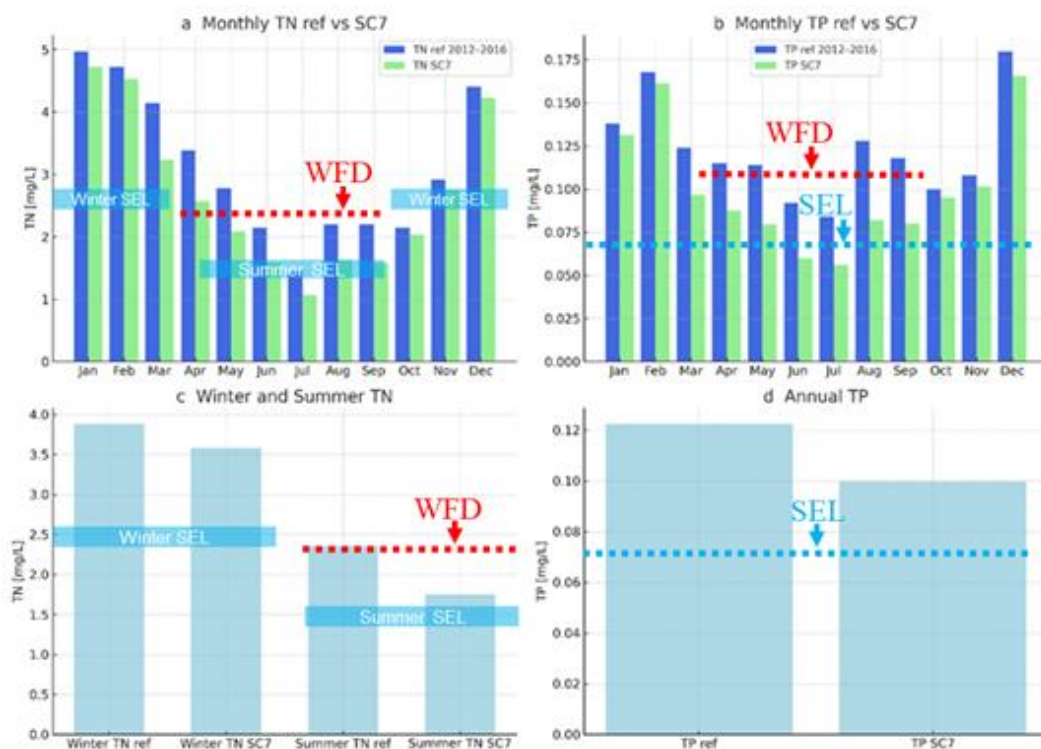


Fig A.7. Monthly TN and TP results ref vs SC7

SC8 Optimize crop nutrient uptake efficiency

Background

In this scenario, we examine the impact of increasing the nutrient uptake efficiency in arable agriculture. In practice, a higher nutrient uptake efficiency can be achieved through various measures, such as timing and dosing of fertilisation, choosing nutrient efficient crops varieties, cultivation of catch crops, and improving soil health.

Implementation

The nutrient uptake by crops on all arable fields was increased by 10%.

Results

The predicted concentrations in SC8 show relatively small reductions for both TN and TP. The summer concentrations are just below the current WFD targets in this scenario. The safe ecological limits for TN and TP are not met.

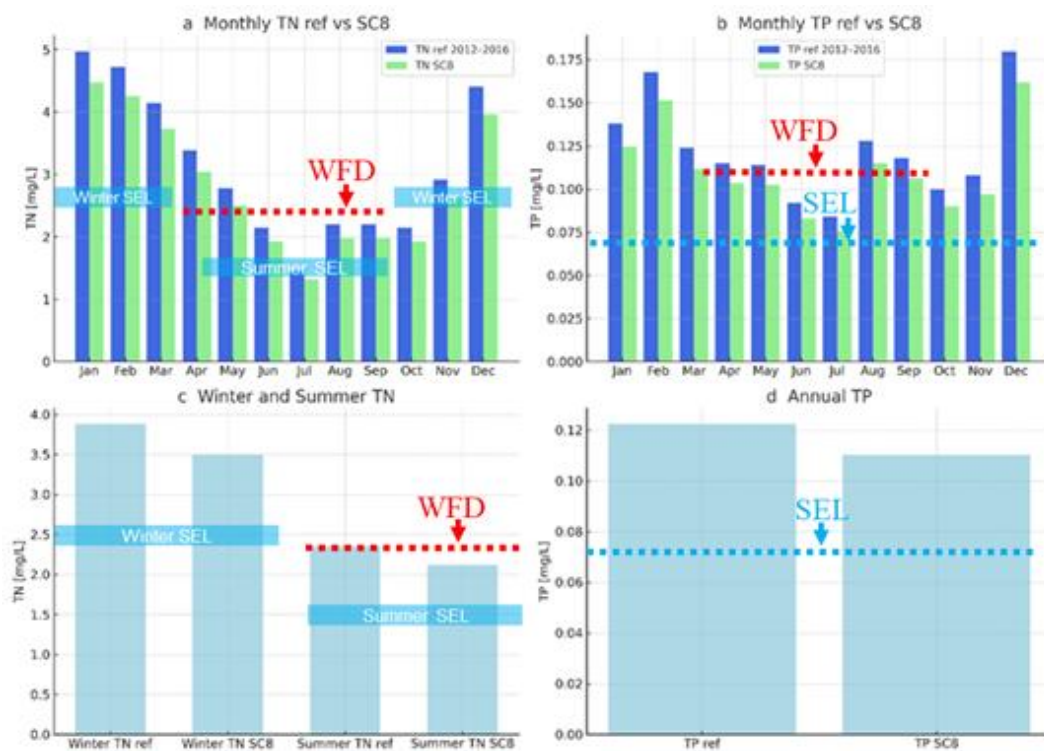


Fig A.8. Monthly TN and TP results ref vs SC8

SC9 Optimize infiltration and reduce overland flow in arable areas

Background

In scenario 9, the potential effects of reducing overland flow in arable fields are evaluated. This can be achieved by enhancing soil infiltration or by slowing down overland flow edge-of-field. In practice, more infiltration can be realised for example by improving the soil health and increasing the surface roughness. Overland flow can be intercepted at edge-of-field using infiltration trenches or sedimentation ponds. In these trenches and ponds overland flow can partly infiltrate or can at least be slowed down which enables sedimentation of suspended solids.

Implementation

The reduction of overland flow was introduced in the model by reducing CN2 parameter (from 75 to 55). CN2 (curve number 2) is an empirical parameter that defines the amount of infiltration and surface runoff. CN2 can vary between 0 (100% infiltration) and 100 (100% overland flow). In addition, the USLE-C parameter was reduced from 0,20 to 0,10. USLE-C is the crop factor of the Universal Soil Loss Equation, an often-used empirical method for estimating erosion. A lower USLE-C factor indicates improved soil protection against erosion, typically resulting from enhanced vegetation cover or improved soil structure.

Results

The predicted concentrations in SC 9 show a clear reduction. The relative concentration reduction is larger for TP than for TN, because overland flow is a more relevant transport route for P. The current WFD targets for summer average TP and TN concentrations are met in this scenario. The safe ecological limits are not met.

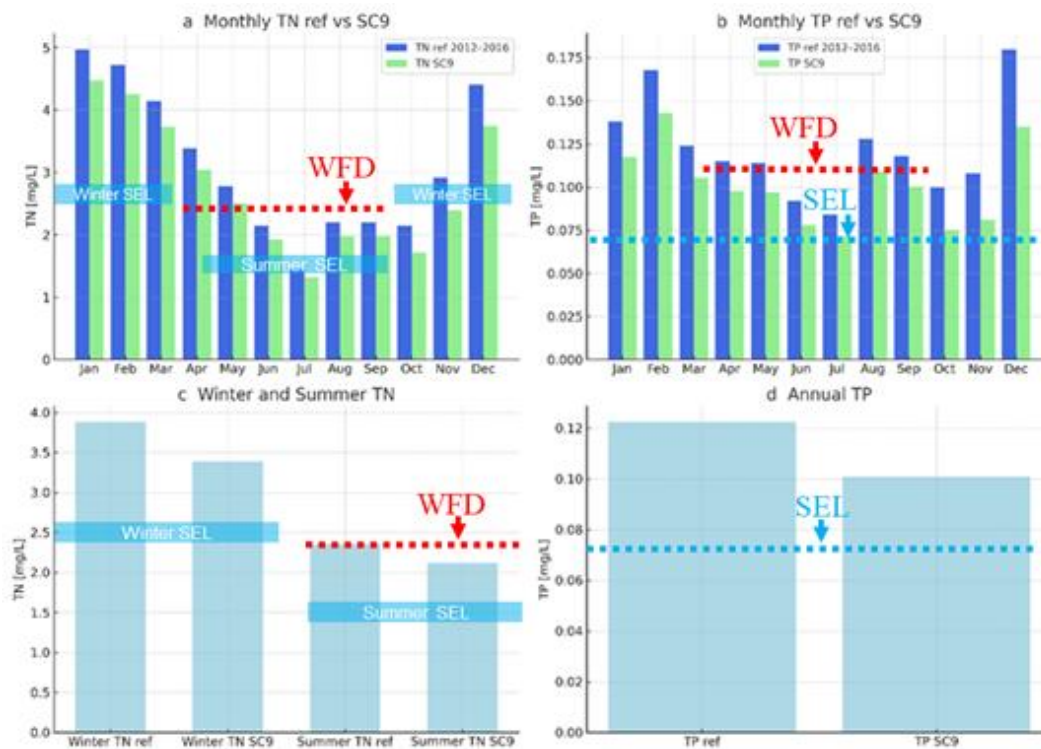


Fig A.9. Monthly TN and TP results ref vs SC9

SC10 Optimize in-stream retention

Background

Nutrient retention within streams can be enhanced by increasing hydrological residence time and by constructing more natural, gradual stream banks to promote the growth of riparian vegetation. Hydrological residence time can be increased through re-meandering and/or widening of the stream. TN can be removed from the system via vegetation uptake or denitrification, while TP can be taken up by vegetation or retained in sediments. To ensure permanent removal of these nutrients, the accumulated vegetation and sediment must be periodically harvested or dredged out of the system.

Implementation

The in-stream retention of TN and TP was increased by 10% in the model. This adjustment was applied exclusively to the main stream network.

Results

The predicted concentrations in SC10 show slight reductions in both TN and TP. In this scenario, the current WFD targets are just achieved. However, the safe ecological limits remain unmet.

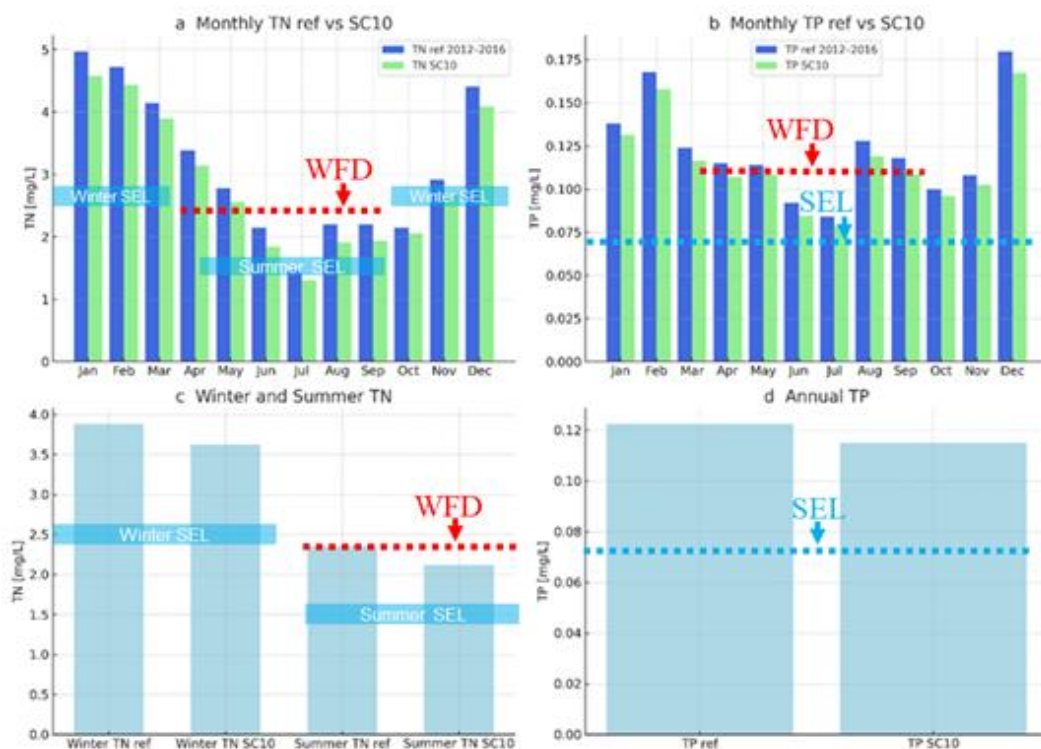


Fig A.10. Monthly TN and TP results ref vs SC10

SC11 Optimize riparian retention 20m

Background

In scenario 11, we explored the potential effect of a 20m-wide-vegetated riparian buffer zone along the main streams. The riparian buffer zone is taken out of agricultural production and is particularly effective in reducing nutrient inputs via overland flow.

Implementation

The riparian filter strip is activated in SWAT for the main streams.

Results

The predicted concentrations in SC11 show modest reductions in both TN and TP. In this scenario, the current WFD targets are just achieved. However, the safe ecological limits remain unmet.

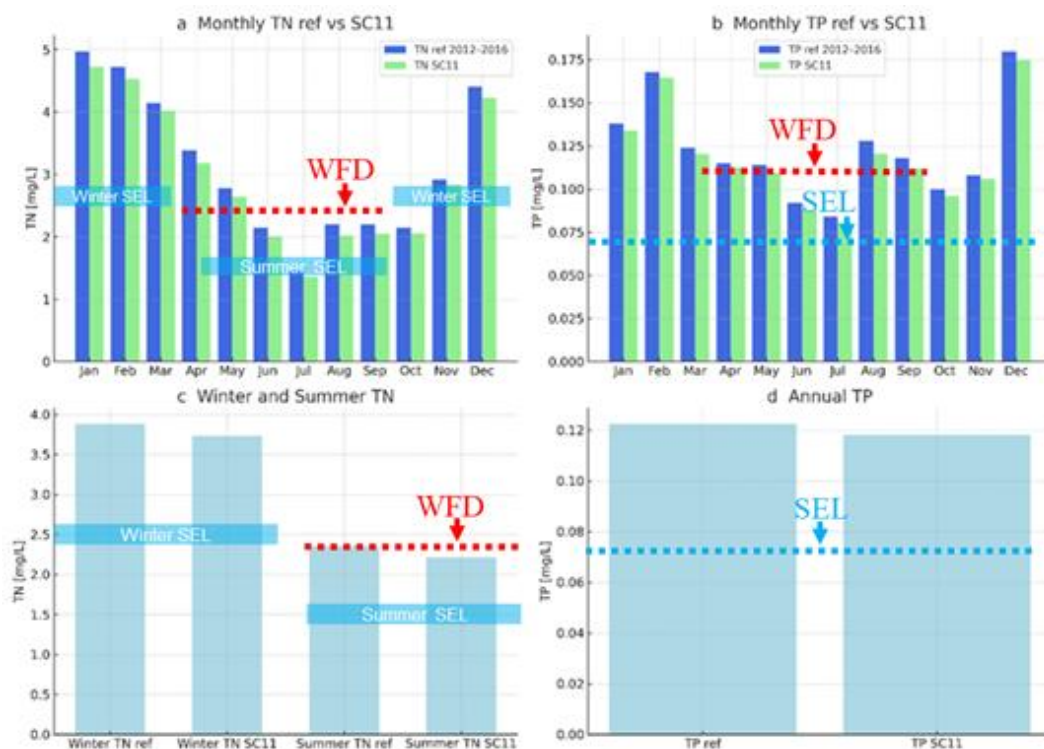


Fig A.11. Monthly TN and TP results ref vs SC11

SC 12 Optimize riparian retention 100m

Background

In scenario 12, we explored the potential effect of implementing a 100m wide vegetated riparian buffer zone along the main streams. The riparian buffer zone is taken out of agricultural production and is particularly effective in reducing nutrient inputs via overland flow.

Implementation

The riparian filter strip is activated in SWAT for the main streams.

Results

The predicted concentrations in SC12 show a modest reductions in both TN and TP. The concentration reductions are around twice the reductions of the 20m buffer zone of scenario 11. The current WFD targets are just achieved in SC12. However, the safe ecological limits remain unmet.

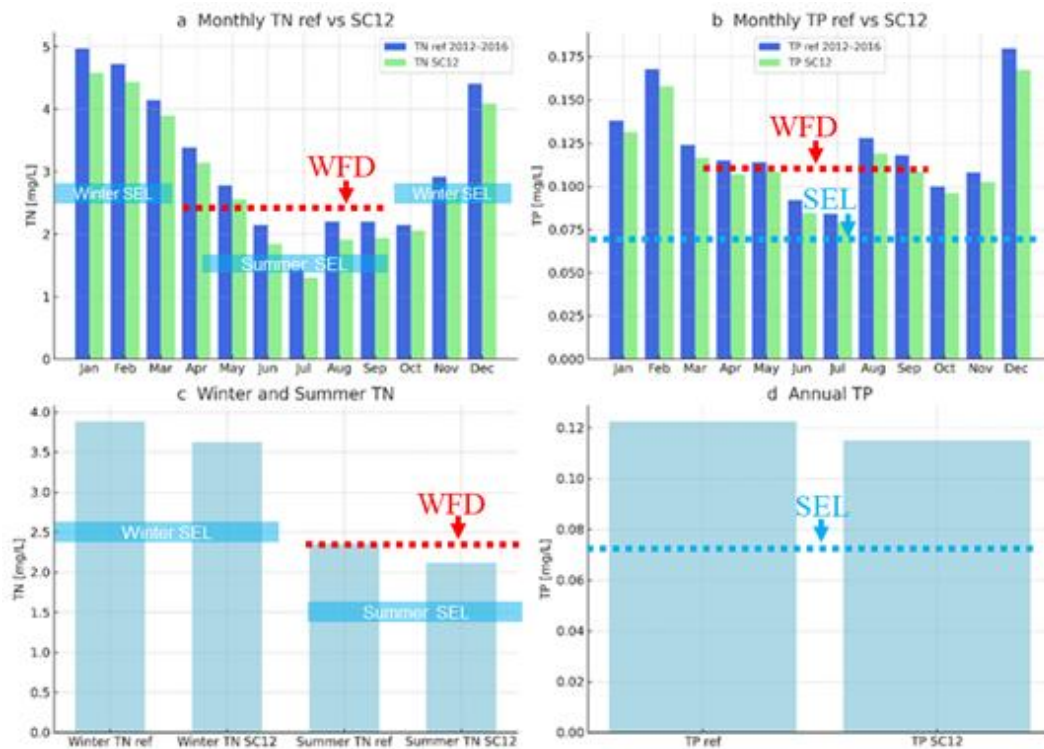


Fig A.12. Monthly TN and TP results ref vs SC12

SC 13 Extend purification wetland

Background

In 2019, 230 ha of agricultural area in the downstream part of the Hunze catchment was converted into a marsh area known as Tusschenwater. An additional 90-hectare expansion of this marsh is currently being prepared. This scenario explores the potential effect of the planned extension. During high-flow events, part of the Hunze discharge is diverted into the marsh, which helps to buffer the peak flows.

Implementation

The extended marsh area was implemented by converting the land use (mainly grassland) into marsh. In addition, the nutrient load peaks during storm events are reduced.

Results

The predicted concentrations in SC13 show clear reductions for TN and TP. In this scenario, the current WFD targets are clearly achieved. However, the safe ecological limits remain unmet.

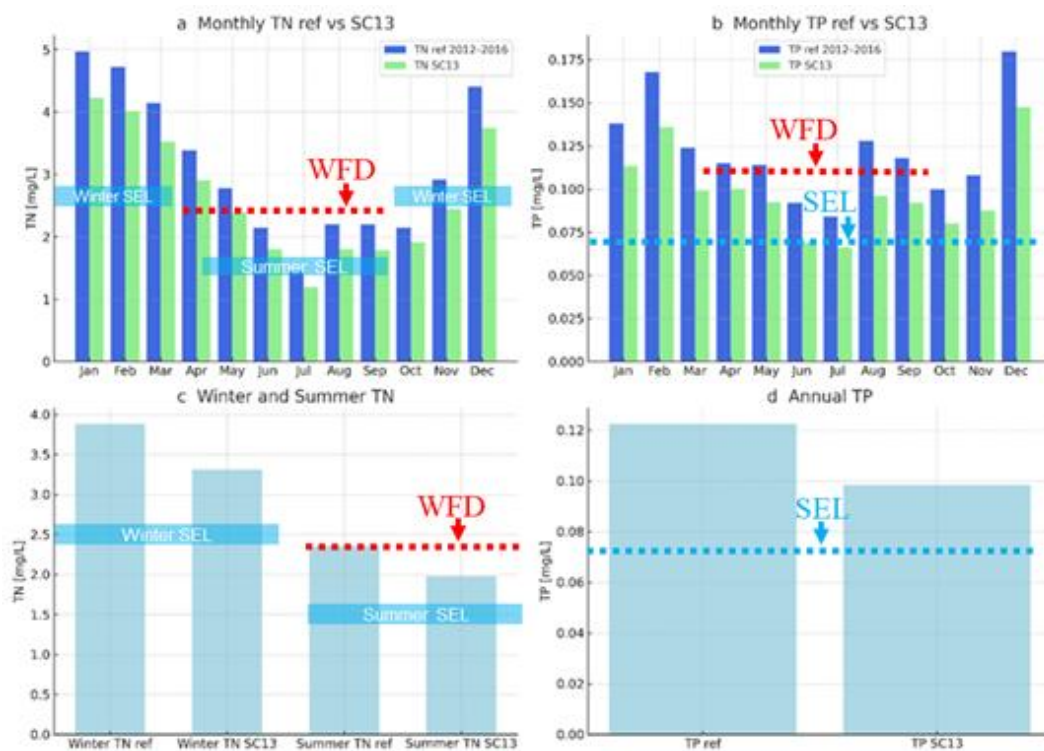


Fig A.13. Monthly TN and TP results ref vs SC13