www.napsea.eu

DELIVERABLE 3.4

MODEL INPUT OF SELECTED SCENARIOS

Work Package 3
Measures & Pathways

30-06-2024

Grant Agreement number	101060418
Project title	NAPSEA: the effectiveness of Nitrogen And Phosphorus load reduction measures from Source to sEA, considering the effects of climate change
Project DOI	[10.3030/101060418](https://doi.org/10.3030/101060418)
Deliverable title	Model input of selected scenarios
Deliverable number	3.4.
Deliverable version	1
Contractual date of delivery	30.06.2024
Actual date of delivery	30.06.2024
Document status	Prepared
Document version	1
Online access	Yes
Diffusion	Public (PU)
Nature of deliverable	Data
Work Package	WP3: Measures and Pathways
Partner responsible	Umweltbundesamt (UBA)
Contributing Partners	Helmholtz Centre for Environmental Research, NMI-Agro
Author(s)	Gericke, Andreas; Leujak, Wera
Editor	Rozemeijer, Joachim (Deltares)
Approved by	van der Heijden, L.H.
Project Officer	Christel Millet/Blanca Saez Lacave
Abstract	For the previously selected set of scenarios 1–6, we preprocessed various datasets and produced a set of text files with values for scenario and reference years. The range of processed datatypes also provides useful templates for the envisaged "adapted" scenario 7. The text files need to be further processed to adjust the actual model input for the mQM and C^{n}ANDY models. The scenarios and the data are primarily intended for the modelling of the Rhine and Elbe basins but may complement the tailored scenarios and more detailed data for the Hunze catchment. The flexible script-based workflow can integrate new modelling units as well as new insights at a later stage.
Keywords	Data processing, model input, nitrogen, phosphorus

Contents

Deliverable 3.4 1

Model input of selected scenarios 1

1. LIST OF ABBREVIATIONS 4

2. INTRODUCTION 5

  1.1. The NAPSEA project 5

  1.2. Objectives 5

3. SCENARIO Data 6

  3.1. Wastewater treatment 6

  3.2. Agricultural input 7

    3.2.1. Nitrogen balance 8

    3.2.2. Soil erosion – Soil Health Law 10

    3.2.3. Soil erosion – Farm 2 Fork 12

  3.3. Atmospheric deposition 12

  3.4. Nature-based solutions 14

    3.4.1. Floodplains 14

    3.4.2. Riparian buffers 14

  3.5. All measures 17

  3.6. No measures 17

    3.6.1. Climate change 17

    3.6.2. N balances 17

    3.6.3. Erosion – Rainfall erosivity 17

  3.7. Adapted 18

    3.7.1. N balances 18

    3.7.2. Goal of Nitrates Directive achieved 18

    3.7.3. Soil erosion 18

    3.7.4. Change of land use and land cover (LULC) 19

  3.8. Discussion 20

4. REFERENCES 21

ANNEX 24

1. LIST OF ABBREVIATIONS

C factor ....*Factor of the (revised) universal soil loss equation, interplay of seasonal rainfall erosivity and soil coverage (crop management)*

C^nANDY .... *Coupled Complex Algal-Nutrient Dynamics*

DEM .... *Digital elevation model*

EMEP . *European Monitoring and Evaluation Program (Co-operative Program for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe)*

LULC .... *Land use and land cover*

mHM .... *Mesoscale Hydrologic Model*

mQM .... *Multiscale water Quality Model*

N .... *Nitrogen*

P .... *Phosphorus*

p.e. .... *Population equivalent*

R factor .... *Factor of the (revised) universal soil loss equation, long-term average annual rainfall erosivity*

UWWTD .... *Urban Wastewater Treatment Directive*

UWWTP .... *Urban wastewater treatment plant*

2. INTRODUCTION

1.1. The NAPSEA project

This project addresses the effectiveness of 'Nitrogen And Phosphorus load reduction measures from Source to sEA, considering the effects of climate change' (NAPSEA). The primary objectives of NAPSEA are to support national and local authorities in the selection of effective measures to reduce nutrient loads and to create political support for their implementation. The project applies an integrated approach spanning from pollution sources to sea, considering governance, nutrient pathways and measures, as well as ecosystem health. Geographically, the project focuses on the Wadden Sea catchment area, with specific case studies for the basins of rivers Rhine and Elbe, the catchment of the Hunze, as well as the Wadden Sea itself. NAPSEA serves as a platform to showcase practices in the implementation of socially acceptable, sustainable, and efficient measures.

The Work Package (WP) 3 aims to evaluate the connection between nutrient concentration and load reduction measures as well as the safe ecological boundaries for the Wadden Sea. The efficiency of nutrient reduction and enhanced retention measures will be assessed with a set of scenarios which has to be integrated into the modelling framework in order to prioritize mitigation measures under climate change.

1.2. Objectives

The assessment of the feasibility of measures (Gericke and Leujak 2023) concluded that scenarios should focus on agriculture, optimization of urban wastewater treatment plants (UWWTP), and nature-based solutions. The set of scenarios outlined by Gericke et al. (2024) comprise the wide range of specific measures (Table 1). This report provides an overview of the input data used for the implementation of scenarios 1–4 into the modelling framework for rivers Elbe and Rhine (Task 3.5), and how the data was processed. Scenario 5 will be the combination of these scenarios. The "no measures" scenario 6 relies on climate scenarios and respective changes of the terrestrial water cycle already available at UFZ. The aim is to provide scenario data for the spatial units of the calibrated models (Musolff and Ledesma 2024) which includes the envisioned improvement of the mQM model in Germany. We included the Hunze catchment to allow for comparisons to its tailored, more detailed scenarios and datasets (cf. Table 12 in the Annex).

Depending on the scenario results and reduction needs to reach the safe ecological boundaries (cf. tasks 4.2 and 4.3), the use of additional data might be needed for scenario 7. Hence, we developed R scripts to process the different types of input data (vector/raster, numerical/categorical) as a flexible basis to integrate additional data or new insights at a later stage. These scripts also enable rapid updates if additional modelling units are delineated. Similar to the database for the calibrated and validated nutrient models (Musolff and Ledesma 2024), we selected European datasets which ideally cover the whole basins of rivers Elbe and Rhine, and national data only if unavailable.

Henceforth, we provide a concise overview of the current input and output files as well as of how the latter were created. Technical details like unit conversion (harmonization) or merging of multiple input files are neglected. We briefly discuss the steps to finalize the model input for the scenario runs and remaining issues.

Table 1. Proposed set of scenarios. All scenarios include climate change impacts in the river basins. More details in Deliverable D3.3 (Gericke et al. 2024).

Scenario	Target of measures	Description	Chapter
1	Wastewater treatment	Nutrient input from urban WWTP	3.1
2	Agricultural input	N input due to agricultural N surplus, P input via soil erosion	3.2
3	Atmospheric deposition		3.3
4	Nature-based solutions	Nutrient retention in wetlands, riparian buffers	3.4
5	All measures	Combination of scenarios 1–4	3.5
6	No measures	Climate and optionally other expected changes	3.6
7	Adapted	Nutrient input needed to achieve safe ecological boundaries	3.7

3. SCENARIO DATA

If not specified otherwise, the scenario data covers the current modelling units of mQM and the NUTS 3 regions for 2016 (Eurostat n.d.; 2018) which overlap with the reference catchment data for the WRRL (EEA 2020) and Switzerland (BAFU 2019) for the Rhine and Elbe basins as well as the Hunze catchment (Waterschap Hunze en Aa's 2016). The modelling units in the output files refer to the columns OBJECTID (Elbe, Rhine) and SiteID (Hunze). For the catchment of the Rhine gauge at Bimmen / Lobith, we set the OBJECTID to 6335060 (J. Ledesma, pers. comm.). The scenarios 3.1–3.5 also include scenario 3.6.

3.1. Wastewater treatment

Spatial coverage: DE x NL x Other x (no valid data for BE and FR)

Nutrient: N x P x

Scenario: Implementation of the provisional agreement on the new UWWTD reached by Council and Parliament (Council of the European Union 2024) in EU member states and the existing regulation in CH (Bundesrat 1999), both targeting at the retention and the concentration of total N and P in the outflow (Table 2), no derogation and changes in the amount of treated wastewater assumed

Table 2. Target values implemented in the data processing. The current load was modified if the target was lower (outflow concentration) or higher (retention) than the current value. Of the two possible loads, the minimum was chosen if both targets apply, or the maximum otherwise.

Region	**Load treated p.e.**	**N**		**P**		**Apply**
		Minimum retention, %	**Concentration, mg L^{-1}**	**Minimum retention, %**	**Concentration, mg L^{-1}**	
EU	10000–150000	80	10	87.5	0.7	one or both
EU	>150000	80	8	90	0.5	both
CH	>=10000*	-	-	80	0.8	both

* UWWTP in Rhine basin

Data sources: Provisional UWWTD data reported under UWWTD data call 2021 (EEA 2023a), publicly available since January 2023, and a data table for Switzerland (P. Fischer, pers. comm.) based on the geodata model "Kläranlagendatenbank (ARA-DB)" (Federal Office for the Environment 2016)

Scenario data: Discharge points (longitude, latitude) with loads (t yr^{-1}) for the reporting year (EU 2019-2020, CH 2020) and outflow loads for the unspecified scenario year, further attributes to filter (active/inactive discharge point, discharge to freshwater or other water-body types), separate files for EU member states and CH with Swiss ids of UWWTP and their discharge points being harmonized with EU scheme (Table 3). The scenario results are exemplarily shown in Figure 1.

Data processing: For the spatial selection, the mQM modelling units were combined with the basins of Rhine and Elbe as well as the Hunze catchment. The discharge points (EU) and available coordinates (CH) falling into the two river basins were selected. For the EU data, the separate tables for discharge points, UWWTP, and agglomerations were joined. Agglomerations were grouped according to their generated load into the two size classes of the UWWTD (see Table 2). As several agglomerations can belong to one discharge point, we determined the dominant size class based on the total generated load per size class. Based on this size class, the targets in Table 2 were applied to the concentration and retention. For Switzerland, the design capacity was used to determine the size class. The retention was determined as 1 – outflow load / inflow load and the concentration as ratio of outflow load and treated wastewater. Any zero value was treated as missing value. In a few cases, implausible non-negative retention values and suspiciously high concentrations occurred but were neither removed nor altered.

NOTE: The original data does not contain valid load data for Belgium and France. Consequently, outflow loads are not (explicitly) considered in the model setup. Similarly, we have to assume unchanged outflow loads for the scenarios.

Table 3. Structure of output files for wastewater treatment plants *with example values. Columns dcpState, dcpWB, and DateClosing should be used to exclude unsuitable data.*

Column name	Description	Example
country	Country code	DE
dcpCode	Id discharge point	DEDP_SH53020
uwwCode	Id UWWTP	DETP_SH53020
Name	UWWTP name	Büchen
dcpState	State of discharge point	Active
DateClosing*	Closing date (if any)	NA
dcpWB*	type of receiving water body	discharge into freshwater
lon	Longitude of discharge point	10.6276
lat	Latitude of discharge point	53.4986
LoadEnteringUWWTP*	Load entering UWWTP (p.e.)	14832
Capacity	Design UWWTP capacity (p.e.)	11000
pe.class	Class (cf. Table 2)**	[10000,150000)
Q_m3yr-1	Treated wastewater, m^3 yr^{-1}	520185
pollutant		N
parameter		Load
unit	Unit of parameter	t a-1
scenario	Scenario code (none = reference)	None
value	Value of parameter	3.3344
napsea_scenario		1
source	Data source	EEA 2023, own calculation
comment		UWWTD rules applied to Waterbase reported under UWWTD data call 2021, discharge points

* Only EU data, ** based on generated load of agglomerations (EU) or design capacity (CH)

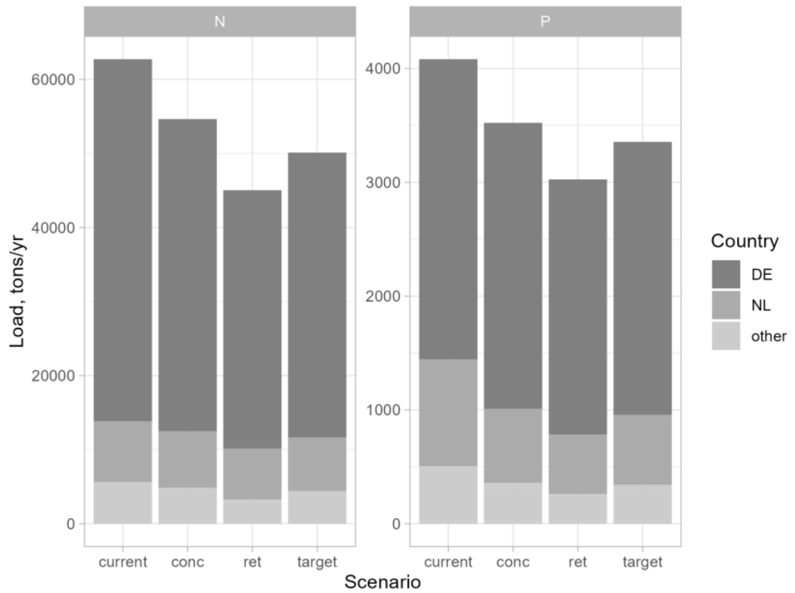

Figure 1. Scenario impact on outflow loads for the selected active UWWTP discharging into freshwater without Switzerland. The scenarios refer to the reference year ("current") as well as the UWWTD targets (conc-concentration, ret-retention, target-overall target).

3.2. Agricultural input

The agricultural input consists of the soil-surface N balances as the main source for N and the soil erosion for P. Accordingly, the first one is intended for the mQM model, the last one for the C^nANDY model. The scenarios 3.2.2 and 3.2.3 are mutually exclusive.

The agricultural P balances are not considered as the current annual balances are already close to zero, even negative. Furthermore, P accumulates in topsoil unlike N. The current values and the impact of planned measures are expected to be insufficient to (significantly) reduce the high P concentration in topsoil after decades of intensive fertilization (cf. Gericke and Leujak 2023).

3.2.1. Nitrogen balance

Spatial coverage: DE x NL x Other

Nutrient: N x P

Scenario:

- DE: Anticipated trends in agriculture (Haß et al. 2022) and implementation of the current Fertilizer Ordinance (DüV 2021) until 2030
- NL: Anticipated trends in agriculture and implementation of the measures of the 7th Action Program until 2027 (cf. Table 6 in Gericke et al. (2023))

Data sources:

- DE: tabular N balances data at NUT 3 level provided by U. Häußermann (University Gießen, pers. comm.), calculated within the DüngEval project using the RegNBil approach (Häußermann et al. 2020)
- NL: modelled average nitrate leaching from agricultural land for different regions, sectors, and scenarios (van Boekel et al. 2021), the models LWKM, WOGWOD, and DSG were applied to derive the impact of the different measures on the nitrate concentration in leachate

Scenario data:

- DE: Area-weighted average of soil-balance N surplus including atmospheric deposition in kg/ha complemented by the atmospheric deposition and utilized agricultural area for modelling units. The processed data comprises three reference years (2019–2021) and the scenario year 2030 (Table 4). The scenario effect strongly depends on the selected reference year given the recent decrease in N surplus (Figure 2).
  The values for the atmospheric deposition and utilized agricultural areas are separately provided to facilitate the harmonization with the data for scenario 3.3 (for scenario 3.5) and to adjust the N surplus for different agricultural land in the input for the calibrated mQM model and the scenario input.
- NL: Average change in nitrate concentrations in leachate can be derived when mQM units for the Rhine basin are available. The relative change can either be used as a proxy for the change in N surplus or used to adjust the modelled nitrate concentration.

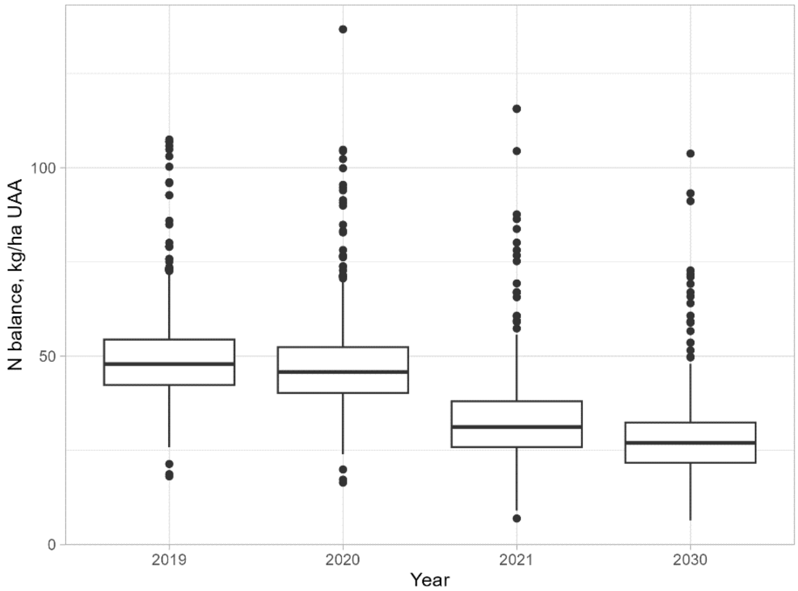

Figure 2. Distribution of average soil-surface N balance (surplus) for mQM modelling units in Germany, output for NAPSEA scenario 2 (column napsea_scenario=2).

Table 4. Structure of output files for the nitrogen balances with example values. Separate columns for N deposition and utilized agricultural area.

Column name	Description	Example
id	mQM unit	1
year		2019
country	Country code	DE
scenario	Scenario code	None
description	Scenario description	NA
UAA_ha	Utilized agricultural area in ha	119534.967035326
N balance	Nitrogen balance incl. atmospheric deposition	38.569231338481
N deposition	Atmospheric deposition	6.37575399054416
unit	Unit of N balance and deposition	kg N ha-1 UAA
source	Data source	DüngEval project (Häußermann et al. 2024)
comment		N balances including biogas, N deposition after Pineti III + IV, area-weighted NUTS3 values
napsea_scenario	Primary purpose of scenario data	2

Data processing:

- DE: The modelling units were intersected with the German NUTS 3 regions to obtain the area-weighted average values for the mQM model. The area-specific N balances and N deposition were converted to total values beforehand and re-calculated afterwards. The currently processed data addresses different scenarios in NAPSEA (as indicated by the value in the column napsea_scenario):
    - None: baseline for this scenario (napsea_scenario=2)
    - DV21: Fertilizer Ordinance not implemented, only anticipated agricultural trends (napsea_scenario=6), see scenario 3.6.2
    - C*: DüngEval scenario code, measures beyond Fertilizer Ordinance for scenario 7 (napsea_scenario=7), see scenario 3.7.1
- NL: The modelling units will be intersected with the regions for which scenario data is available to obtain the area-weighted average concentration for agricultural areas in the modelling units (Table 5). Since the measures are mainly implemented on sandy and loess soils, the effects of measures in clay soils are assumed to be neglectable.
    - Reference 2019: current situation as baseline for this scenario
    - Reference 2027: additional measures not implemented measures for scenario 3.6.2
    - C: most stringent scenario, without voluntary (DWA) measures for this scenario, with voluntary measures for scenario 3.7.1 (alternatively, scenario B)

Table 5. Modelled average nitrate concentration in leachate for different regions, sectors as well as the reference year 2019 and scenarios for 2027 (van Boekel et al. 2021) in mg L^{-1}. The difference between the reference values for 2019 and 2027 reflects the autonomous development of the Dutch agriculture. Scenarios B and C go beyond the planned measures for the scenario 'Reference 2027' and optionally include the effect of voluntary measures of the Dutch Deltaplan Agrarisch Waterbeheer (DAW) program (cf. Gericke and Leujak 2023).

Region	Sector	Reference		without DAW measures		with DAW measures	
		2019	2027	Scenario B	Scenario C	Scenario B	Scenario C
Sand North	Agriculture	42	40	39	37	38	35
	Arable land and horticulture	61	60	58	55	58	52
	Dairy farming	32	29	29	28	28	27
Sand Central	Agriculture	43	38	38	37	37	35
	Arable land and horticulture	77	70	69	65	70	62
	Dairy farming	40	36	36	35	35	33
Sand South	Agriculture	65	55	54	52	53	48
	Arable land and horticulture	95	85	84	79	83	74
	Dairy farming	55	44	44	43	42	39
Loess	Agriculture	72	66	65	63	64	60
	Arable land and horticulture	77	73	73	70	72	67
	Dairy farming	69	61	59	57	58	55

NOTE: The reference years are identical for all scenarios. The structure of the output files may change to include the area share of the German and Dutch values on the modelling units.

3.2.2. Soil erosion – Soil Health Law

Spatial coverage: DE x NL x Other x

Nutrient: N P (x)

Scenario: Implementation of the Soil Health Law which sets a maximum total soil erosion of 2 t ha^{-1} yr^{-1} on arable land for healthy soils (Directorate-General for Environment 2023). The scenario assumes that the reduction of gross soil erosion[1] does not alter the contribution of the erosion processes addressed by the data source (see list below). Additionally, the relative change in the input of particulate P to surface waters equals the change in soil erosion via water and wind erosion as relevant erosion processes.

Data sources: Gridded soil erosion via different processes on arable land (Borrelli et al. 2023), data available from Borrelli et al. (2022). The arable land was obtained from CORINE 2006.

Scenario data: see Table 6

- Average total soil erosion and coefficient of variation with and without upper threshold (Figure 3). In addition to the absolute values (ratio=FALSE), the mean and coefficient of variation was also determined for the ratio scenario/reference (ratio=TRUE).
- Average erosion via the different erosion processes (water erosion, wind erosion, tillage erosion, crop harvesting (SLCH)) as absolute values (ratio=FALSE) or relative to total erosion (ratio=TRUE, Figure 4)

Data processing: The average total erosion as well as the contribution of the four included erosion processes were obtained for the NUTS 3 regions as soil erosion is hardly relevant for N inputs to surface waters. For the scenarios, the total erosion was capped at the upper threshold of 2 t ha^{-1} yr^{-1} (for the other thresholds, see scenario 3.7.2).

Table 6. Structure of output files for the soil erosion with example values.

Column name	Description	Example
id	NUTS 3 code	DE600
year		2010-2020
parameter	Erosion process or total erosion	total erosion
scenario	Scenario code is upper limit of total erosion (none or NA = no limit)	none
ratio	parameter = total erosion: ratio to reference year (TRUE) or absolute value (FALSE) parameter <> total erosion: ratio to total erosion (TRUE) or absolute value (FALSE)	FALSE
area	Area covered by values, in m^2	78765856
mean	Average value	1.58915078639984
coefficient_of_variation	Coefficient of variation (only scenarios)	1.47996163368225
unit	Unit of value	t ha-1 a-1
comment		total soil erosion on arable land with scenario=upper limit, zonal statistics
napsea_scenario	Primary purpose of scenario data	2
source	Data source	Borrelli et al. 2023

[1] Without sediment deposition (remobilization) during the transport towards the surface water

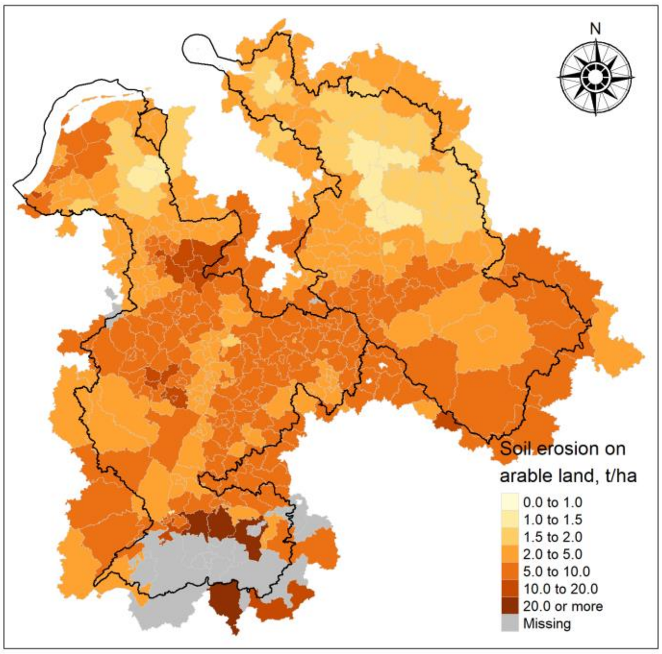

Figure 3. Total soil erosion on arable land aggregated at NUTS 3 level. The scenario caps the values at 2 t ha^{-1}.

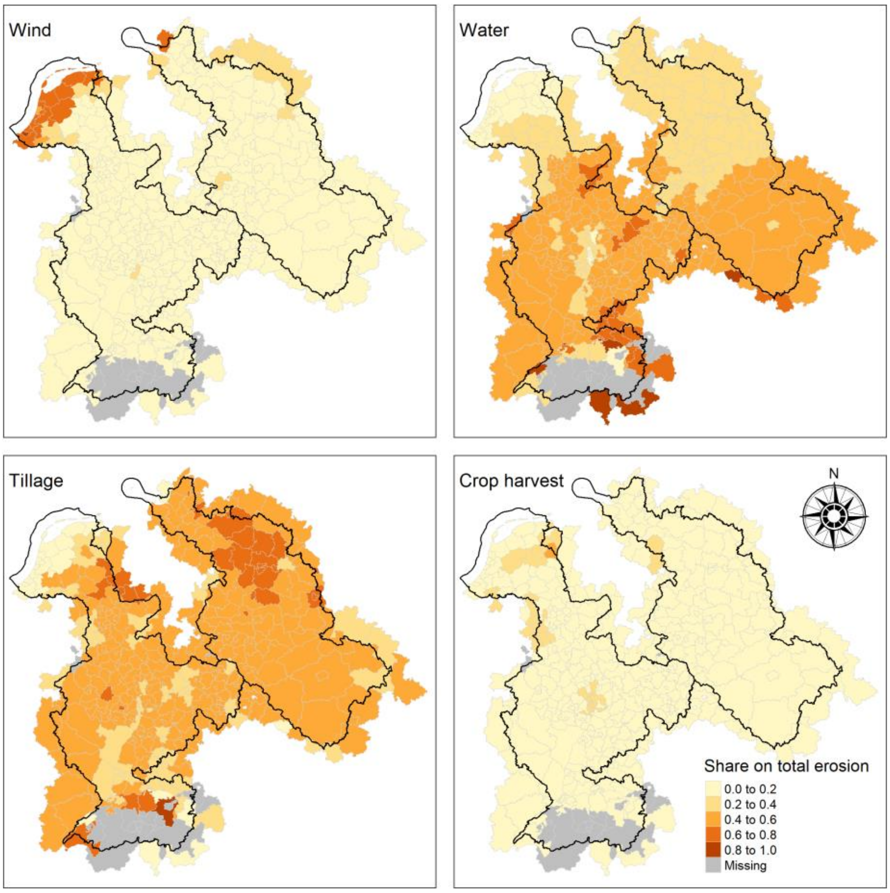

Figure 4. Contribution of erosion processes to total soil erosion, average values at NUTS 3 level.

3.2.3. Soil erosion – Farm 2 Fork

Spatial coverage: DE x NL x Other x (without Switzerland)

Nutrient: N P (x)

Scenario: 25% organic farming on arable land which reduces the risk of soil erosion due to higher average soil coverage with sod-based crop rotations. The scenario assumes that reduction on soil erosion also applies to the P delivery. As the scenario is based on the C factor of the revised universal soil loss equation, only changes to sheet and rill erosion by water are considered[2].

Data sources: Average C factor for Germany and C factor for typical sod-based crop rotation for organic farming provided by Auerswald et al. (2021), current average share of organic farming on arable land (Eurostat 2023)

Data processing: The approach does not allow for spatial variability. If the current C factor of 0.124 represents the current share of organic farming of 5%, and is representative for the whole study areas, increasing the share to 25% would result in C=0.109, i.e. about 12% lower soil erosion if other agricultural changes are neglected (cf. Gericke et al. 2024). For Switzerland, we assume no change in soil erosion as sod-forming crops are also common in conventional farming (Auerswald et al. 2021).

NOTE: The alternative to scenario 3.2.2 assumes an optimal impact as the Farm 2 Fork Strategy refers to agricultural land not arable land.

3.3. Atmospheric deposition

Spatial coverage: DE x NL x Other (only EMEP data)

Nutrient: N x P

Scenario: Implementation of the National Emissions Reduction Commitments (NEC) Directive everywhere and the Dutch legislation on Natura2000 areas (NL data), implementation and enforcement of current and planned legislation (EMEP data)

Data sources: Gridded deposition of total nitrogen calculated with PINETI III approach (Schaap et al. 2018) for DE (A. Moravek, pers. comm.), the OPS model (Sauter et al. 2023) for NL (RIVM 2023; Hoogerbrugge et al. 2022), and the EMEP MSC-W model (EMEP MSC-W 2022; Simpson et al. 2012) for the whole study area (EMEP 2022; Denby et al. 2022)[3], climate change is not considered

Table 7. Structure of output files for the atmospheric deposition with example values. Currently, the modelling units do not cover the Netherlands.

Column name	Description	Example
id	mQM unit	985
year		2015
ratio	Value is ratio to 2015 (TRUE) or not (FALSE)	FALSE
source	Data source	PINETI
country	Spatial coverage of data	DE
mean	Average value	18.8497180938721
area	Area covered by German data, in m^2	209153456
coefficient_of_variation	Coefficient of variation of German data	0.0655593648552895
unit	Unit of value	kg ha-1 a-1
comment		gridded data reference and scenario year, zonal statistics
napsea_scenario	Primary purpose of scenario data	3

Scenario data: Average value and coefficient of variation of N deposition in mQM modelling units for the reference years 2015 (DE, NL, EMEP) and 2022 (NL) as well as the scenario years 2030 and 2050 (only EMEP)

[2] The empirical universal soil loss equation and its many descendants and adaptations is the most used (family of) models to estimate soil loss rates especially at larger scales (Borrelli et al. 2021) despite inherent flaws (Alewell et al. 2019). Soil loss is the product of 6 factors which reflect the impact of rainfall and runoff (R factor), the soil erodibility (K), the slope angle (S), erosive slope length (L), soil conservation (P), and the soil coverage and crop management (C). The model considers sheet and rill erosion by water but neglects other agents (like wind), processes (gully erosion, landslides), and typically sediment deposition (cf. Borrelli et al. 2022). Typically, the outcome is a long-term average annual soil-loss rate.

[3] Data: Courtesy of The Norwegian Meteorological Institute, https://www.met.no/en

(Table 7). In addition to the absolute values (ratio=FALSE), the mean and coefficient of variation was also determined for the ratio to the common year 2015 (ratio=TRUE).

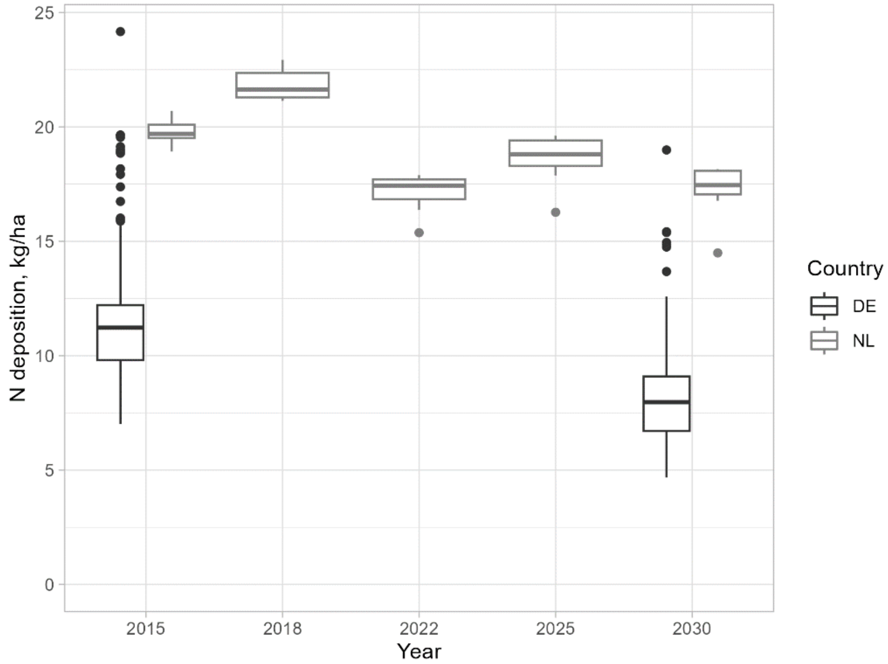

Figure 5. Distribution of average atmospheric N deposition for mQM modelling units according to national data. The data provider is contacted to confirm the pattern in NL.

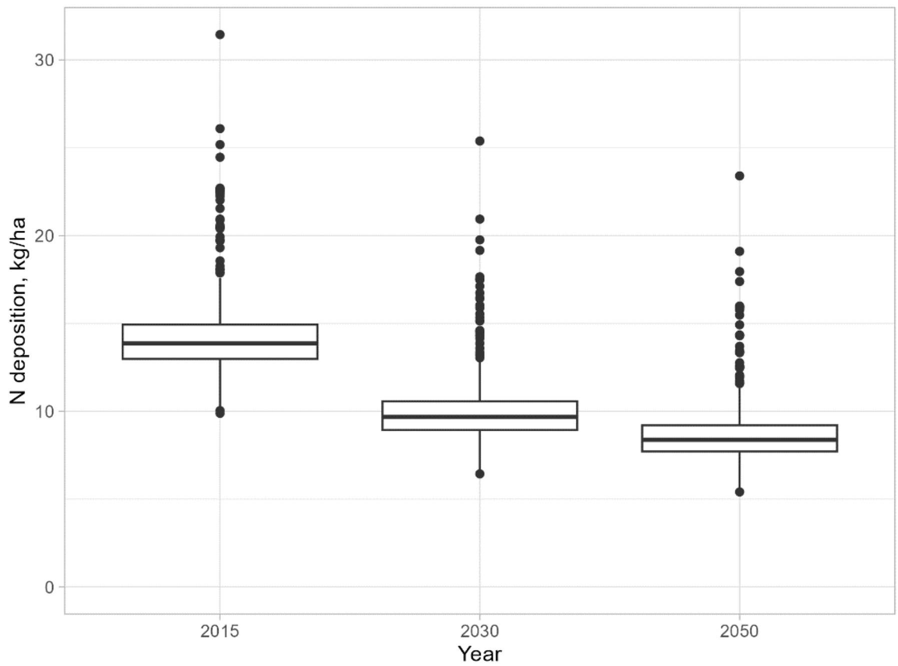

Figure 6. Distribution of average atmospheric N deposition for mQM modelling units according to EMEP data.

The available data did not fully cover the modelling units. To allow to calculate area-weighted means for transboundary modelling units, the national average value is provided with its spatial extent. The scenario effect in NL is affected by the inconsistent meteorology of the reference years and the scenario years (2005–2014) which explains the increase between 2022 and 2025 (Figure 5).

Data processing: The EMEP data is provided as NetCDF files from which we selected the layers WDEP_OXN (wet deposition of oxidized nitrogen), WDEP_RDN (wet deposition of reduced nitrogen), DDEP_RDN_m2Grid (dry deposition of reduced nitrogen per m2 grid), and DDEP_OXN_m2Grid (dry deposition of oxidized nitrogen per m2 grid). The total N deposition was calculated as the sum of these layers. From the gridded data, we calculated the average total N deposition and the coefficient of variation for the mQM units and NUTS 3 regions. The units were harmonized to kg ha^{-1}.

3.4. Nature-based solutions

The scenarios for nutrient retention in floodplains and riparian buffers are work in progress and final scenario data are not yet available. So, new insights might be included in a later stage. The sub-scenarios complement each other. While scenario 3.4.1 affects the modelled in-stream retention, scenario 3.4.2 addresses the nutrient input into the surface waters.

3.4.1. Floodplains

Spatial coverage: DE x NL Other

Nutrient: N x P x

Scenario: Implementation of the EU Nature Restoration Law with 20% more active floodplains in Germany

Data source: Updated dataset after Schulz-Zunkel et al. (2012)

NOTE: The existing database and approach are currently updated (M. Scholz, pers. comm.). For the morphological floodplain along 79 German rivers, a proxy-based approach for the retention potential due to denitrification (N) and sedimentation (P) in the active floodplain was developed and recently improved for N (Kaden et al. 2023). The dataset comprises floodplains with an upstream area above 1000 km^2 (BMU and BfN 2021).

The modelled nutrient retention in tons per year under current conditions and scenario conditions are the sum of all assigned segments (cf. Figure 7). The results are constant over time and will be provided for floodplain segments which are assigned to the modelling units.

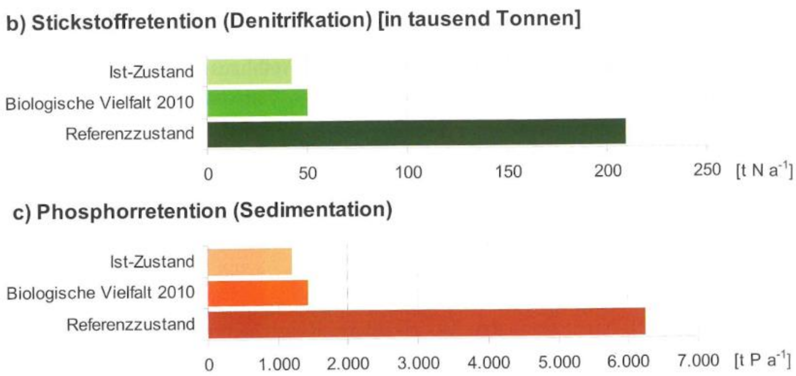

Figure 7. Overall N retention (b) and P retention (c) for reference conditions (Ist-Zustand) and the scenario based on the German National Biodiversity Strategy (Biologische Vielfalt 2010) with 10% more active floodplains where arable land changes to grassland, wetland, and forest along 79 German rivers (source: Schulz-Zunkel et al. 2012). The calculations for the reference conditions and the assumptions for the scenario are currently updated.

3.4.2. Riparian buffers

Spatial coverage: DE x NL x Other x

Nutrient: N (x) P (x)

Scenario: Implementation of §38a of the German Federal Water Act (Wasserhaushaltsgesetz), permanent plant cover of 5 m width on arable land with an average slope of at least 5% within a distance of 20 m from surface waters

Data sources: Land use and land cover (LULC) in riparian zones (EEA 2021), water bodies in EU member states for the reporting within the Water Framework Directive (EEA 2023b), missing water bodies for Luxembourg from a previous version (EEA 2020), digital elevation model (DEM) of 25m-resolution (European Commission – DG ENTR 2012; Eurostat n.d.)

Scenario data: Total area of the arable land adjacent to surface water to be turned into riparian (column 'converted arable land' in Table 8) as well as the area of unchanged arable land and other LULC (column 'non-arable land').

The slope threshold results in less new riparian buffers in NL compared to other countries (Figure 8) which coincides with the reported low efficiency of narrow grass buffers under Dutch conditions (Noij, Heinen, and Groenendijk 2012).

Table 8. Structure of output files for the riparian buffers with example values. Currently, the modelling units do not cover the Netherlands. The area refers to the grid resolution and does not consider the assumed buffer width.

Column name	Description	Example
id	NUTS 3 code or mQM unit	1
comment		arable land, slope threshold 5%, zonal statistics
source	Data source	own calculation
country		all
unit	Unit of values	m2
napsea_scenario	Primary purpose of scenario data	4
non-arable land	Area non-arable land along surface water	615902.410205454
arable land	Area remaining arable land along surface water	0
converted arable land	Area arable land turned to riparian buffer	0

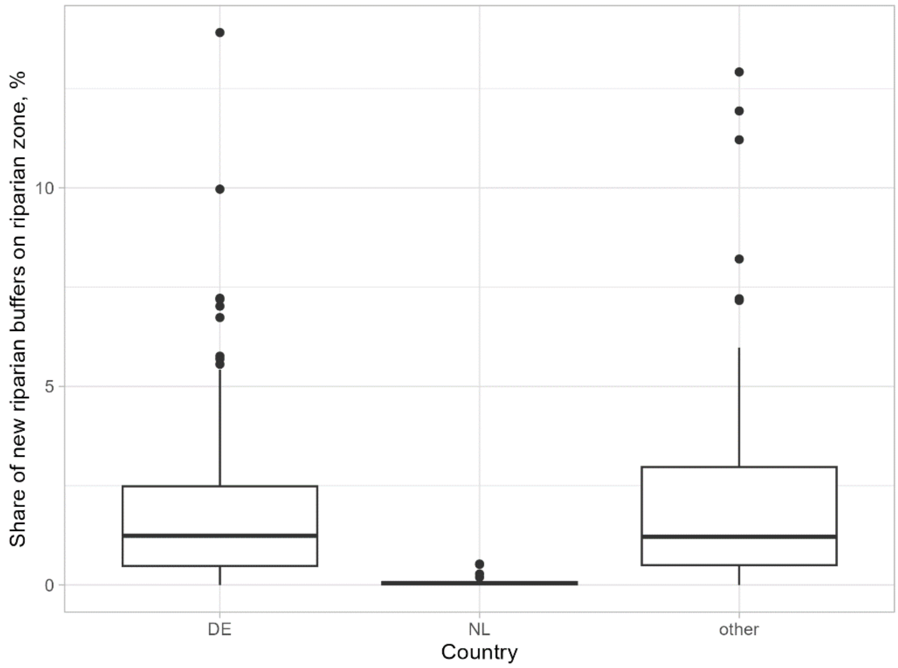

Figure 8. Distribution of share of newly established riparian zones in NUTS 3 regions. The slope threshold results in low values in the Netherlands. The share needs to be adjusted by the average efficiency of riparian buffers to estimate the relative change nutrient retention compared to the current conditions.

Data processing: The arable land in the riparian zone next to surface waters which is expected to be converted to riparian buffers was derived with a simplified grid-based approach:

- Calculate slope in degree from the DEM
- Extract arable land (value=2) and water areas (value=8) from riparian LULC data (polygon)
- Clip water bodies (polygon, line) along these surface waters and combine the two polygon datasets
- Convert vector data to grid data using the slope grid as spatial reference
- Mark arable land on steep terrain as 0 and on flat terrain as 1
- Expand surface water by one grid cell and mark the arable land there (Figure 9)

The slope grid was not resampled as the DEM resolution is close to the required distance of 20 m for the slope calculation. Slopes were considered as 'steep' where the slope angle was above 5%. From the gridded outcome, we derived the areas of flat and steep arable land as well as other LULC adjacent to surface water for the mQM units and NUTS 3 regions.

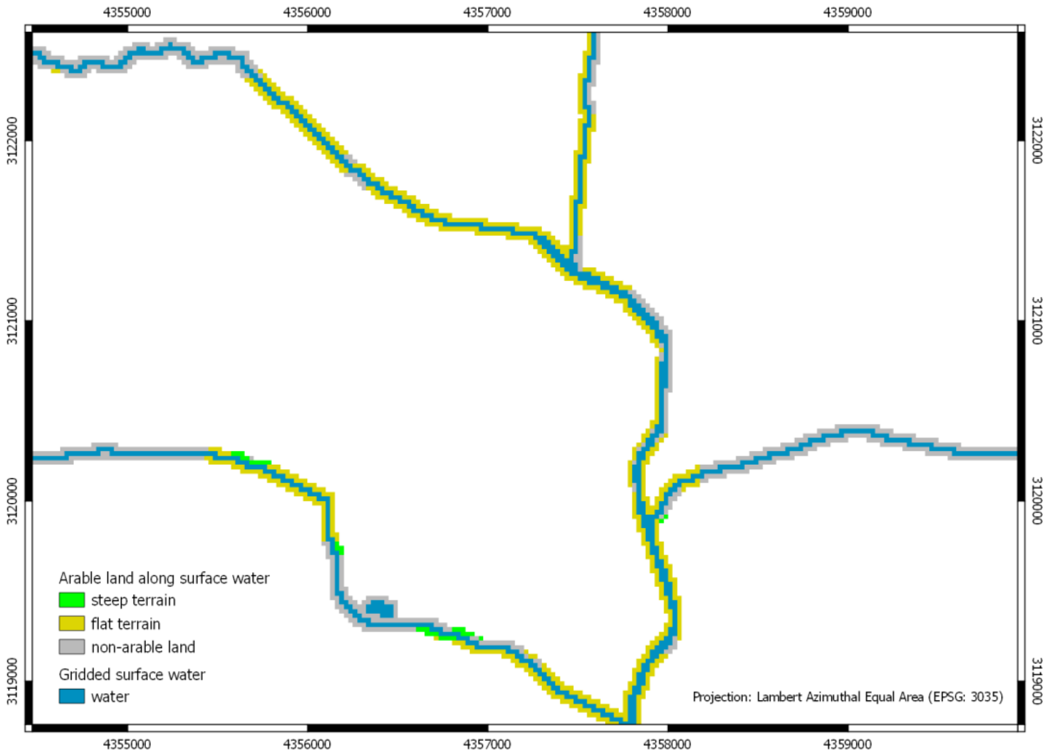

Figure 9. Output of the raster-based approach (detail) to detect arable land adjacent to surface water which are to be converted to riparian buffers (green) and left unchanged (yellow). For the scenario, we combine the share of the new riparian buffers to the riparian area (grey) with average efficiencies for N and P from the literature.

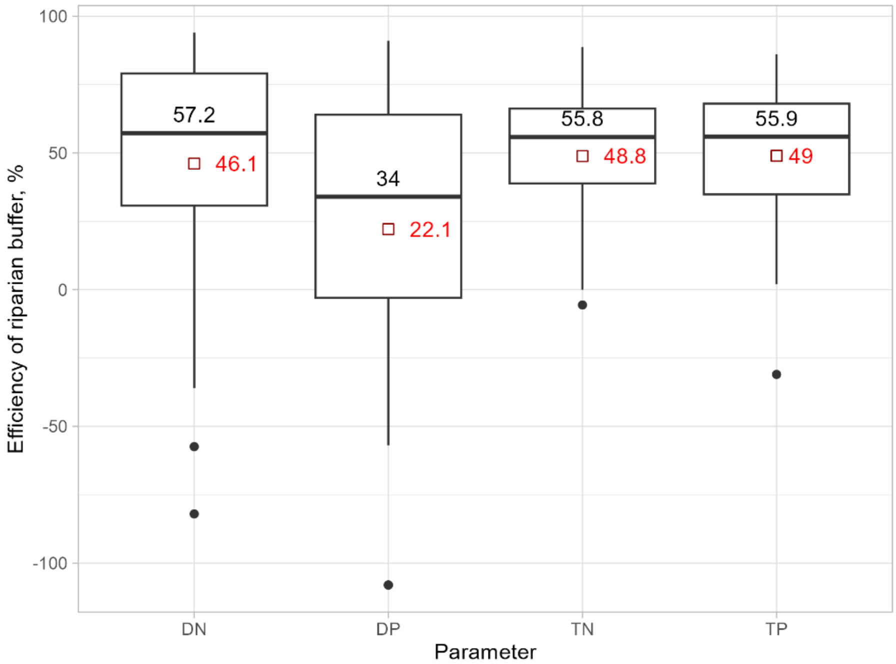

Figure 10. Median (black) and average (red) efficiency of riparian buffers to retain dissolved (DN, DP) and total (TN, TP) N and P for buffers widths between 4 and 6 m (data: Gericke et al. 2020). The sample sizes are unequal. The 97 literature values are dominated by plot studies.

NOTE: The approach neglects various site conditions which influence the efficiency of riparian buffers to retain nutrients (e.g. Gericke et al. 2020) as well as the spatial variability of nutrient inputs within the modelling units. It therefore differs from estimations based on e.g. soil type and the presence of drainage (van Boekel et al. 2021).

To estimate the change of nutrient inputs relative to the calibrated models, the value in the column 'converted arable land' needs to be multiplied by a representative average retention factor of 50% for N and P, assuming a buffer width of 5 m (Figure 10).

3.5. All measures

The combination of the scenario data above. Exclude the atmospheric deposition in scenario 3.2 to avoid double counting with scenario 3.3.

3.6. No measures

The use of scenario data other than scenario 3.6.1 for this scenario and scenarios 3.1–3.5 will be discussed.

3.6.1. Climate change

Spatial coverage: DE x NL x Other x

Nutrient: N (x) P (x)

Scenario: Hydrological input for ensemble of climate scenarios for the Representative Concentration Pathway (RCP) 6.0 emission scenario calculated with the mHM model (Samaniego et al. 2018). The selected scenario is the medium scenario of the available scenarios for RCP 2.6, RCP 6.0, and RCP 8.5.

Scenario data: Readily available at UFZ, no data processed

3.6.2. N balances

Spatial coverage: DE x NL Other

Nutrient: N x P

Scenario: Anticipated changes in the agriculture without policy implementation

Data sources: Same as scenario 3.2.1

Scenario data: Integrated in data for scenario 3.2.1 (scenario = "DV21", napsea_scenario = 6)

3.6.3. Erosion – Rainfall erosivity

Spatial coverage: DE x NL x Other x

Nutrient: N P (x)

Scenario: Changes in rainfall erosivity due to changes in rainfall amount and intensity. The scenario is based on the R factor of the revised universal soil loss equation. It is thus limited to sheet and rill erosion by water. The scenario assumes that the relative change in P delivery to surface waters equals the change in soil erosion.

Data sources:

- Gaussian Process Regression ("GPR" in the output file) applied to predict the R factor of the revised universal soil loss equation predominantly for 2010–2020 (Panagos et al. 2015) and around 2041–2060 using the HadGEM global circulation model downscaled with WordClim for RCP 4.5 and the WorldClim climatic datasets as covariates (Panagos et al. 2017), both available from the European Soil Data Centre (Panagos et al. 2022)
- Convection-permitting simulations based on the regional climate model COSMO-CLM for RCP 8.5 emission scenario for 2001–2019 and 2031–2060 (Uber et al. 2024)

Scenario data: Average value and coefficient of variation of the R factor for different time periods (Table 9). In addition to the absolute values (ratio=FALSE), the mean and coefficient of variation was also determined for the ratio scenario/reference (ratio=TRUE).

Table 9. Structure of output files for the erosivity with example values.

Column name	Description	Example
id	NUTS 3 code	DE600
year		2041-2060
source	Data source	GPR (Panagos et al. 2017)
ratio	Value is ratio to reference year (TRUE) or not (FALSE)	FALSE
unit	Unit of value	MJ mm ha-1 h-1 yr-1
mean	Average value	675.786926269531
area	Area covered by values, in m^2	737474432
coefficient_of_variation	Coefficient of variation	0.0326290614902973
comment		gridded R factor RUSLE, zonal statistics
napsea_scenario	Primary purpose of scenario data	6

Data processing: The average R factors were obtained from gridded data for the mQM units and NUTS 3 regions. For the convection-permitting simulation, we created the grids from the published data points by inverse-distance weighting using a radius of 10 km.

3.7. Adapted

The details of this scenario will be discussed based on the outcomes of scenarios 3.5 and 3.6. However, exemplary datasets were already created as templates for the processing of scenario data.

3.7.1. N balances

Spatial coverage: DE x NL x Other

Nutrient: N x P

Scenario: Measures beyond scenario 3.2.1

Data sources: Same as scenario 3.2.1

Scenario data: Integrated in data for scenario 3.2.1 (e.g. scenario code starts with “C” in Germany, napsea_scenario = 7). The DüngEval results with the most notable Germany-wide effects were pre-selected:

- Scenario = C08: amount of N fertilizer reduced to 80 % of plant demand (currently required in hotspot („red“) areas)
- Scenario = C09: site-specific fertilization
- Scenario = C14: conversion to and extensification of permanent grassland within water protection areas

Depending on the required ambition, the Dutch scenarios B (less stringent) and C (more stringent) can be chosen.

3.7.2. Goal of Nitrates Directive achieved

Spatial coverage: DE x NL x Other x

Nutrient: N x P

Scenario: In addition to scenarios 3.2.1 and 3.7.1, we assume in the mQM model that the N concentration in the groundwater (seepage water) is 50 mg L^{-1} N.

Scenario data: No model input data needed.

3.7.3. Soil erosion

Spatial coverage: DE x NL Other

Nutrient: N P (x)

Scenario: Upper threshold of total soil erosion of the Soil Health Law reduced to 1.5 t ha^{-1} yr^{-1} which is slightly above upper limit of soil formation rate in Europe (Verheijen et al. 2009) and 1.0 t ha^{-1} yr^{-1} as recommended by the same authors when considering the impact of soil erosion on water quality

Data sources: Same as scenario 3.2.2

Scenario data: Integrated in data for scenario 3.2.2, the scenario column represents the upper threshold, napsea_scenario = 7

3.7.4. Change of land use and land cover (LULC)

Spatial coverage: DE x NL x Other x

Nutrient: N (x) P (x)

Scenario: Change of LULC related to various RCP and Shared Socioeconomic Pathways as used for the 6th phase of Coupled Model Intercomparison Project (CMIP6) (Hoffmann et al. 2023) as well as under various Nature Futures Framework scenarios to assess the impact of sustainability targets (Dou et al. 2023).

Data sources:

- Gridded LUCAS LULC change dataset with simulated annual maps 1950–2100 (Hoffmann et al. 2023), data available from Hoffmann et al. (2022)
- Gridded LULC data with land-use intensity (low-medium-high) for scenarios in 2050 using an adapted map of Dou et al. (2021) as starting point representing the year 2015 (Dou et al. 2023), data available from Verburg (2023)

Scenario data: Two similar data tables (Tables 10–11) with values for the respective reference and scenario years

Table 10. Structure of output files for the LULC data provided by Hoffmann et al. (2022).

Column name	Description	Example
id	NUTS 3 code or mQM unit	DE600
year		2016
fun	Zonal function used to derive value (Mean/Count/Coefficient of variation)	Mean
value	Area share	0
class	LULC class	1
description	LULC description	Tropical broadleaf evergreen trees
SSP	Shared Socioeconomic Pathway code	SSP4
SSP description	Shared Socioeconomic Pathway	Inequality (A Road Divided)
scenario	RCP	RCP60
unit	Unit of value	
source	Data source	LUCAS LUC (Hoffmann et al. 2023)
comment		gridded projected land use/cover, area share, zonal statistics
napsea_scenario	Primary purpose of scenario data	7

Table 11. Structure of output files for the LULC data provided by Verburg (2023). The grid values (LULC class) were adjusted to match the range of grid values.

Column name	Description	Example
id	mQM unit or NUTS 3 code	1
year		2050
class	Adjusted LULC class	0
description	LULC description	Water
area	Extent of LULC class	263283.610343933
SSP	Shared Socioeconomic Pathway code	SSP1
SSP description	Shared Socioeconomic Pathway	Sustainability (Taking the Green Road)
scenario	Scenario code	nac
scenario description	Scenario description	Nature as Culture
unit	Unit of area	m2
source	Data source	CLUMondo (Dou et al. 2023)
comment		gridded land use/cover reference and scenario year, zonal statistics
napsea_scenario	Primary purpose of scenario data	7

Processing:

- First dataset: Given the climate data for scenario 3.6.1, we selected the results for RCP 6.0. The RCP was combined with the Shared Socioeconomic Pathway “Inequality (A Road Divided)”. For each year between 2016 and 2055 and the NUTS / mQM units, we obtained the average area share from the grid data as well as the coefficient of variation.
- Second dataset: The value range (0–20) in the description of the grid values in Verburg (2023) did not match the actual range of grid values (0–20, 0–21, 1–21). After visual inspection, the grid values were harmonized, and the description extended by the missing entry for water (class value = 0). For each area id, we derived the spatial extent of all (adjusted) land-use classes. All published datasets were processed and indicated by the SSP and scenario columns in the output file. The Nature Futures Framework scenarios nac, nfn, and nfs are based on the SSP1 scenario and focus on Nature’s
    - non-material contributions to society, priority are cultural services (scenario = nac)
    - benefits for society, priority is mitigation of climate change (scenario = nfs)
    - intrinsic value, priority is distribution and protection of vertebrates (scenario = nfn)

3.8. Discussion

The outcome of text files cannot be directly used as input for the NAPSEA models mQM and C^nANDY. Firstly, the available data typically represent different single years in the future while we agreed during the workshop with German stakeholders on April 25, 2024 to model the scenarios until 2050. This issue requires for the mQM model assumptions on how the scenario is achieved, e.g. steadily or stepwise. Secondly, the datasets also differ from the data used to calibrate the models. Therefore, the original model input for the reference year of the scenario should be adjusted by the (relative or absolute) change between the reference and future years in the scenario data. As N balances in kg ha^{-1} depend on the extent of agricultural land in the maps used for the model input and the scenario data, absolute values (in kg) should be derived from the area-specific values.

The values at NUTS 3 level are intended as provisional input for the C^nANDY. Depending on the model requirements regarding the data resolution, the current data could be further aggregated to obtain an average change of P export from the land-use classes or replaced by the raster data itself. Unlike the first requirement, the second one would require changes to the data processing. As mQM currently does not cover NL, all data files with N data do currently not contain data (either as rows or columns) with Dutch data. However, these issues can be rapidly addressed with the established scripts.

Technically, the finalization of the scenario data requires only a few basic steps. However, we have to discuss how to fill gaps and how to harmonize different scenario inputs once the mQM model covers the Netherlands. This is pivotal for the agricultural N input given its dominance over other sources (cf. Gericke and Leujak 2023).

The available model data and scenarios are inherently uncertain. For instance, Häußermann et al. (2019) quantifies uncertainties in German N balances which are supposedly valid for the values obtained for scenarios 3.2.1, 3.6.2, and 3.7.1. The UWWTD demands from EU member states that 20% of the agglomerations meet by end of 2033 the targets of scenario 3.1, 40% by 2036, 60% by 2039, and 100% by 2045. Even if we assume the implementation of the revised UWWTD, it remains unclear which UWWTP will achieve the envisioned targets in these years. To which degree such uncertainties should be explicitly considered in the modelling needs to be discussed during the finalization of the scenario data. To support such analyses, we included the coefficients of variation of some of the average values.

4. REFERENCES

Alewell, Christine, Pasquale Borrelli, Katrin Meusburger, and Panos Panagos. 2019. “Using the USLE: Chances, Challenges and Limitations of Soil Erosion Modelling.” *International Soil and Water Conservation Research* 7 (3): 203–25. https://doi.org/10.1016/j.iswcr.2019.05.004.

Auerswald, Karl, Florian Ebertseder, Karin Levin, Ye Yuan, Volker Prasuhn, Nils Ole Plambeck, Annette Menzel, and Max Kainz. 2021. “Summable C Factors for Contemporary Soil Use.” *Soil and Tillage Research* 213 (September): 105155. https://doi.org/10.1016/j.still.2021.105155.

BAFU. 2019. “Topographische Einzugsgebiete Schweizer Gewässer: Teileinzugsgebiete 2 Km^2.” https://data.geo.admin.ch/ch.bafu.wasser-teileinzugsgebiete_2/data.zip.

BMU and BfN. 2021. “Auenzustandsbericht 2021. Flussauen in Deutschland.” Bonn: Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, Bundesamt für Naturschutz. https://dx.doi.org/10.19217/brs211.

Boekel, E. M. P. M. van, Piet Groenendijk, J. Kros, L. V. Renaud, J. C. Voogd, G. H. Ros, Y. Fujita, G. J. Noij, and W. van Dijk. 2021. “Effecten van maatregelen in het Zevende Actieprogramma Nitraatrichtlijn: Milieueffectrapportage op planniveau.” 3108. Rapport / Wageningen Environmental Research. Wageningen: Wageningen Environmental Research. https://doi.org/10.18174/553651.

Borrelli, Pasquale, Christine Alewell, Pablo Alvarez, Jamil Alexandre Ayach Anache, Jantiene Baartman, Cristiano Ballabio, Nejc Bezak, et al. 2021. “Soil Erosion Modelling: A Global Review and Statistical Analysis.” *Science of The Total Environment* 780 (August): 146494. https://doi.org/10.1016/j.scitotenv.2021.146494.

Borrelli, Pasquale, Panos Panagos, Christine Alewell, Cristiano Ballabio, Hugo de Oliveira Fagundes, Nigussie Haregeweyn, Emanuele Lugato, Michael Maerker, Jean Poesen, Matthias Vanmaercke & David A. Robinson, 2022. “Multiple Concurrent Soil Erosion Processes.” Dataset. ESDAC. 2022. https://esdac.jrc.ec.europa.eu/content/multiple-concurrent-soil-erosion-processes.

Borrelli, Pasquale, Panos Panagos, Christine Alewell, Cristiano Ballabio, Hugo de Oliveira Fagundes, Nigussie Haregeweyn, Emanuele Lugato, Michael Maerker, Jean Poesen, Matthias Vanmaercke & David A. Robinson, 2023. “Policy Implications of Multiple Concurrent Soil Erosion Processes in European Farmland.” *Nature Sustainability* 6 (1): 103–12. https://doi.org/10.1038/s41893-022-00988-4.

Bundesrat. 1999. *Gewässerschutzverordnung (GSchV)*. https://www.fedlex.admin.ch/eli/cc/1998/2863_2863_2863/de.

Council of the European Union. 2024. *Proposal for a Directive of the European Parliament and of the Council Concerning Urban Wastewater Treatment (Recast) - Letter to the Chair of the European Parliament Committee on the Environment, Public Health and Food Safety (ENVI)*. *2022/0345/COD*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CONSIL%3AST_7108_2024_INIT.

Denby, Bruce Rolstad, Ágnes Nyíri, Hilde Fagerli, and Zbigniew Klimont. 2022. “UEMEP/EMEP Modelling for the Gothenburg Protocol Review.” In *Transboundary Particulate Matter, Photo-Oxidants, Acidifying and Eutrophying Components*, by EMEP, 65–100. EMEP Status Report 1/2022. Oslo: Norwegian Meteorological Institute. https://emep.int/publ/reports/2022/EMEP_Status_Report_1_2022.pdf.

Directorate-General for Environment. 2023. “Proposal for a Directive on Soil Monitoring and Resilience.” Proposal for a Directive on Soil Monitoring and Resilience. July 5, 2023. https://environment.ec.europa.eu/publications/proposal-directive-soil-monitoring-and-resilience_en.

Dou, Yue, Francesca Cosentino, Ziga Malek, Luigi Maiorano, Wilfried Thuiller, and Peter H. Verburg. 2021. “A New European Land Systems Representation Accounting for Landscape Characteristics.” *Landscape Ecology* 36 (8): 2215–34. https://doi.org/10.1007/s10980-021-01227-5.

Dou, Yue, Cecilia Zagaria, Louise O’Connor, Wilfried Thuiller, and Peter H. Verburg. 2023. “Using the Nature Futures Framework as a Lens for Developing Plural Land Use Scenarios for Europe for 2050.” *Global Environmental Change* 83 (December): 102766. https://doi.org/10.1016/j.gloenvcha.2023.102766.

EEA. 2020. “WISE WFD Reference Spatial Datasets Reported under Water Framework Directive 2016 - PUBLIC VERSION - Version 1.4, Apr. 2020.” https://sdi.eea.europa.eu/data/1f91bcac-2d39-4ce3-b684-8612e4b3ed1b.

EEA. 2021. “Riparian Zones Land Cover/Land Use 2018 (Vector), Europe, 6-Yearly, Dec. 2021.” Data catalogue. December 15, 2021. https://doi.org/10.2909/2afca4ec-76e2-4155-b4e6-7460f9f6ae01.

EEA. 2023a. “Waterbase - UWWTD: Urban Waste Water Treatment Directive – Reported Data.” Dashboard. 2023. https://www.eea.europa.eu/data-and-maps/data/waterbase-uwwtd-urban-waste-water-treatment-directive-9.

EEA. 2023b. “WISE WFD Reference Spatial Datasets Reported under Water Framework Directive 2022 - PUBLIC VERSION - Version 1.5, Jul. 2023.” https://sdi.eea.europa.eu/data/fe9a31a0-9595-41b1-9f33-9dcda219acf3.

EMEP. 2022. “EMEP MSC-W Model Calculations for LRTAP GP Review.” Dataset. 2022. https://emep.int/mscw/2022GP_review_scenarios.html.

EMEP MSC-W. 2022. “OpenSource Rv4.45 (202203).” https://doi.org/10.5281/zenodo.8337953.
European Commission – DG ENTR. 2012. “EU-DEM Version 1.” https://ec.europa.eu/eurostat/web/gisco/geodata/digital-elevation-model/eu-dem.
Eurostat. 2018. “Nomenclature of Territorial Units for Statistics (NUTS) 2016 - Statistical Units - Data Set.” https://gisco-services.ec.europa.eu/distribution/v2/nuts/.
Eurostat. 2023. “Organic Crop Area by Agricultural Production Methods and Crops (Org_cropar).” September 27, 2023. https://ec.europa.eu/eurostat/databrowser/product/view/ORG_CROPAR.
Eurostat. n.d. “EU-DEM.” Dataset. Accessed June 20, 2024a. https://ec.europa.eu/eurostat/web/gisco/geodata/digital-elevation-model/eu-dem.
Eurostat. n.d. “Territorial Units for Statistics (NUTS).” Dataset. Accessed May 31, 2024b. https://ec.europa.eu/eurostat/web/gisco/geodata/statistical-units/territorial-units-statistics.
Federal Office for the Environment. 2016. “Water: Geodata models.” January 14, 2016. https://www.bafu.admin.ch/bafu/en/home/state/data/geodata-models/water--geodata-models.html.
Gericke, Andreas, and Wera Leujak. 2023. “Feasibility of Measures.” EC report of grant 101060418 Deliverable 2.2. https://napsea.eu/nieuws/.
Gericke, Andreas, Wera Leujak, Andreas Musolff, and Teresa Geidel. 2024. “Set of Scenarios.” EC report of grant 101060418 Deliverable 3.3. https://napsea.eu/nieuws/.
Gericke, Andreas, Hong Hanh Nguyen, Peter Fischer, Jochem Kail, and Markus Venohr. 2020. “Deriving a Bayesian Network to Assess the Retention Efficacy of Riparian Buffer Zones.” *Water* 12 (3): 617. https://doi.org/10.3390/w12030617.
Haß, Marlen, Claus Deblitz, Florian Freund, Peter Kreins, Verena Laquai, Frank Offermann, Janine Pelikan, et al. 2022. “Thünen-Baseline 2022 - 2032: Agrarökonomische Projektionen für Deutschland.” 100. Thünen Report. Braunschweig: Thünen-Institut. https://doi.org/10.3220/REP1667811151000.
Häußermann, Uwe, Martin Bach, Laura Klement, and Lutz Breuer. 2019. “Stickstoff-Flächenbilanzen für Deutschland mit Regionalgliederung Bundesländer und Kreise – Jahre 1995 bis 2017. Methodik, Ergebnisse und Minderungsmaßnahmen.” 131/2019. Texte. Dessau-Roßlau: Umweltbundesamt. https://www.umweltbundesamt.de/publikationen/stickstoff-flaechenbilanzen-fuer-deutschland.
Häußermann, Uwe, Laura Klement, Lutz Breuer, Antje Ullrich, Gabriele Wechsung, and Martin Bach. 2020. “Nitrogen Soil Surface Budgets for Districts in Germany 1995 to 2017.” *Environmental Sciences Europe* 32 (1): 109. https://doi.org/10.1186/s12302-020-00382-x.
Hoffmann, Peter, Vanessa Reinhart, and Diana Rechid. 2022. “LUCAS LUC Future Land Use and Land Cover Change Dataset for Europe (Version 1.1).” Dataset. World Data Center for Climate (WDCC) at DKRZ. 2022. https://doi.org/10.26050/WDCC/LUC_future_EU_v1.1.
Hoffmann, Peter, Vanessa Reinhart, Diana Rechid, Nathalie de Noblet-Ducoudré, Edouard L. Davin, Christina Asmus, Benjamin Bechtel, Jürgen Böhner, Eleni Katragkou, and Sebastiaan Luyssaert. 2023. “High-Resolution Land Use and Land Cover Dataset for Regional Climate Modelling: Historical and Future Changes in Europe.” *Earth System Science Data* 15 (8): 3819–52. https://doi.org/10.5194/essd-15-3819-2023.
Hoogerbrugge, R., G.P. Geilenkirchen, S. Hazelhorst, H.A. den Hollander, M. Huitema, W. Marra, K. Siteur, W.J. de Vries, and R.J. Wichink Kruit. 2022. “Grootschalige concentratie- en depositiekaarten Nederland. Rapportage 2022.” 2022–0059. RIVM-rapport. Bilthoven: Rijksinstituut voor Volksgezondheid en Milieu. https://doi.org/10.21945/RIVM-2022-0059.
Kaden, Ute Susanne, Christiane Schulz-Zunkel, Elmar Fuchs, Peter Horchler, Hans Dieter Kasperidus, Otavio de Moraes Bonilha, Holger Rupp, et al. 2023. “Improving an Existing Proxy-Based Approach for Floodplain Denitrification Assessment to Facilitate Decision Making on Restoration.” *Science of The Total Environment* 892 (September): 164727. https://doi.org/10.1016/j.scitotenv.2023.164727.
Musolff, Andreas, and José Ledesma. 2024. “Calibrated Models.” EC report of grant 101060418 Deliverable 3.2. https://napsea.eu/nieuws/.
Noij, I. G. A. M., M. Heinen, and Piet Groenendijk. 2012. “Effectiveness of Non-Fertilized Buffer Strips in the Netherlands: Final Report of a Combined Field, Model and Cost-Effectiveness Study.” Research report 2290. Alterra Report. Wageningen: Alterra. https://www.wur.nl/en/Publication-details.htm?publicationId=publication-way-343238363934.
Panagos, Panos, Cristiano Ballabio, Pasquale Borrelli, Katrin Meusburger, Andreas Klik, Svetla Rousseva, Melita Perčec Tadić, et al. 2015. “Rainfall Erosivity in Europe.” *Science of The Total Environment* 511 (April): 801–14. https://doi.org/10.1016/j.scitotenv.2015.01.008.
Panagos, Panos, Cristiano Ballabio, Katrin Meusburger, Jonathan Spinoni, Christine Alewell, and Pasquale Borrelli. 2017. “Towards Estimates of Future Rainfall Erosivity in Europe Based on REDES and WorldClim Datasets.” *Journal of Hydrology* 548 (May): 251–62. https://doi.org/10.1016/j.jhydrol.2017.03.006.

Panagos, Panos, Marc Van Liedekerke, Pasquale Borrelli, Julia Köninger, Cristiano Ballabio, Alberto Orgiazzi, Emanuele Lugato, et al. 2022. "European Soil Data Centre 2.0: Soil Data and Knowledge in Support of the EU Policies." *European Journal of Soil Science* 73 (6): e13315. https://doi.org/10.1111/ejss.13315.

RIVM. 2023. "Depositiekaarten." Dataset. October 12, 2023. https://www.rivm.nl/gcn-gdn-kaarten/depositiekaarten.

Samaniego, L., S. Thober, R. Kumar, N. Wanders, O. Rakovec, M. Pan, M. Zink, J. Sheffield, E. F. Wood, and A. Marx. 2018. "Anthropogenic Warming Exacerbates European Soil Moisture Droughts." *Nature Climate Change* 8 (5): 421–26. https://doi.org/10.1038/s41558-018-0138-5.

Sauter, Ferd, Marina Sterk, Eric van der Swaluw, Roy Wichink Kruit, Wilco de Vries, and Addo van Pul. 2023. "The OPS-Model. Description of OPS 5.1.1.0." Rijksinstituut voor Volksgezondheid en Milieu. https://www.rivm.nl/media/ops/OPS-model.pdf.

Schaap, Martijn, Carlijn Hendriks, Richard Kranenburg, Jeroen Kuenen, Arjo Segers, Angela Schlutow, Hans-Dieter Nagel, Anja Ritter, and Sabine Banzhaf. 2018. "PINETI-3: Modellierung Atmosphärischer Stoffeinträge von 2000 Bis 2015 Zur Bewertung Der Ökosystem-Spezifischen Gefährdung von Biodiversität Durch Luftschadstoffe in Deutschland." 79/2018. Texte. Dessau-Roßlau: Umweltbundesamt. https://www.umweltbundesamt.de/publikationen/pineti-3-modellierung-atmosphaerischer.

Schulz-Zunkel, Christiane, Mathias Scholz, Hans Dieter Kasperidus, Frank Krüger, Stephanie Natho, and Markus Venohr. 2012. "Nährstoffrückhalt." In *Ökosystemfunktionen von Flussauen: Analyse und Bewertung von Hochwasserretention, Nährstoffrückhalt, Kohlenstoffvorrat, Treibhausgasemissionen und Habitatfunktion*, by Mathias Scholz, Dietmar Mehl, Christiane Schulz-Zunkel, Hans Dieter Kasperidus, Wanda Born, and Klaus Henle, 48–62. Naturschutz und Biologische Vielfalt 124. Bonn - Bad Godesberg: Bundesamt für Naturschutz. https://www.bfn.de/publikationen/schriftenreihe-naturschutz-biologische-vielfalt/nabiv-heft-124-oekosystemfunktionen.

Simpson, D., A. Benedictow, H. Berge, R. Bergström, L. D. Emberson, H. Fagerli, C. R. Flechard, et al. 2012. "The EMEP MSC-W Chemical Transport Model - Technical Description." *Atmospheric Chemistry and Physics* 12 (16): 7825–65. https://doi.org/10.5194/acp-12-7825-2012.

Uber, Magdalena, Michael Haller, Christoph Brendel, Gudrun Hillebrand, and Thomas Hoffmann. 2024. "Past, Present and Future Rainfall Erosivity in Central Europe Based on Convection-Permitting Climate Simulations." *Hydrology and Earth System Sciences* 28 (1): 87–102. https://doi.org/10.5194/hess-28-87-2024.

Verburg, Peter. 2023. "European Land Use Scenarios for 2050: Using the Nature Futures Framework as a Lens for Developing Alternative Visions for a Sustainable Europe." Dataset. December 11, 2023. https://dx.doi.org/10.34894/NWGCBY.

Verheijen, F. G. A., R. J. A. Jones, R. J. Rickson, and C. J. Smith. 2009. "Tolerable versus Actual Soil Erosion Rates in Europe." *Earth-Science Reviews* 94 (1): 23–38. https://doi.org/10.1016/j.earscirev.2009.02.003.

Waterschap Hunze en Aa's. 2016. "Watersysteemgebied." Dataset. December 1, 2016. https://opendata.hunzeenaas.nl/opendataportaal/srv/dut/catalog.search#/metadata/704ddca1-19cc-4c51-85b6-473d57df8ea8.

ANNEX

Table 12. Preliminary set of scenarios for the Hunze catchment (J. Rozemeijer, pers. comm., slightly modified)

Scenario	Description
Climate change	Meteorology of the ICCP scenario RCP 6.0 (and potentially 2 or 4 of the KNMI-scenarios)
WWTP diverted	UWWTP effluent is diverted to discharge outside the Hunze catchment
WWTP improved	Improved wastewater treatment for P (fully functional; effluent concentrations reduce from 0.5 to 0.27 mg L^{-1})
Convert agriculture to nature	Extreme scenario; all agricultural land used is converted to nature
Convert agriculture to Mammoth grass cultivation	Mammoth grass cultivation (for bio-based building materials) has co-benefits for soil quality, water quality, C sequestration
Convert arable into dairy	Arable (row crops) farming is replaced by dairy farming (grass-maize rotation)
Convert arable into dairy 50%	Only in low areas (just around streams not possible in SWAT setup)
Convert dairy into arable	Dairy farming (grass-maize rotation) is replaced by arable farming (row crops)
Convert to beans	Land use change related to the protein transition; change to field bean (Vicia faba) or soybean
Optimize infiltration	No more overland flow by optimized infiltration (improved soil structure, infiltration trenches, dams between crop rows)
Optimize nutrient uptake	Combination of measures to improve nutrient uptake (soil quality, fertilization method (timing, dosing, type).
Optimize riparian retention	Edge-of-field mitigation options (buffer strips around the ditches and streams; more retention of water, nutrients, sediments)
	Riparian buffer strips representation in SWAT for larger surface water system, for small ditches (not explicitly modeled): reduced overland flow, no fertilizer input around ditches
Optimize in-stream retention	In stream retention: sediment capture and removal (P), more in-stream uptake (P and N), denitrification (N).
Extend purification wetland	In 2019, a 230-ha marsh area (Tusschenwater) was implemented (1.3 million m^3 water storage). This will be extended with an extra 90 ha. Part of Hunze storm water runoff can flow over into this buffer.