Front. Agr. Sci. Eng.
https://doi.org/10.15302/J-FASE-2023526
Verso: Front. Agr. Sci. Eng.
Recto: Aslıhan URAL-JANSSEN et al. Nutrient emissions from agriculture to air and water in Europe
RESEARCH ARTICLE

HOTSPOTS OF NUTRIENT LOSSES TO AIR AND WATER: AN INTEGRATED MODELING APPROACH FOR EUROPEAN RIVER BASINS

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Received July 28, 2023;
Accepted October 27, 2023.
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SUPPLEMENTARY MATERIALS

Supplementary Text 1: Developments in the new MARINA-Nutrients model for Europe

The new MARINA-Nutrients model for Europe was built upon the existing approaches of MARINA[1,2] and MITERRA-Europe models[3]. Our improvements of the new MARINA-Nutrients model for Europe are listed below:

- Addition of atmospheric P deposition over agricultural areas by using the MITERRA-Europe model outputs, previous MARINA-Nutrients model versions did not have P deposition;
- Accounting for losses of N to air and leaching from animal housing and storage systems based on the MITERRA-Europe model outputs. The N emissions to air (e.g., NH_3, N_2O) and leaching (i.e., NO_3, P_2O_5) are calculated as a function of emission and leaching fractions (Velthof et al.[3] for further description);
- Accounting for direct (e.g., application of synthetic fertilizers and animal manure, grazing) and indirect (e.g., N_2O emissions from leaching and ammonia) losses of N to air from agricultural land;
- Including human waste that does not go to sewage systems as a diffuse source for the inputs of N and P to land and rivers.

Supplementary Text 2: Study area

We studied 601 basins (i.e., 593 river basins and 8 sub-basins) in the European Union including the United Kingdom (EU-28). The total area of these basins is 5,768,449 km^2 with a range of 1303–288,123 km^2. In the study area, 15 rivers discharge into the Arctic Ocean, 160 rivers discharge into the Atlantic Ocean, 147 rivers discharge into the Baltic Sea, 10 rivers discharge into the Black Sea (9 river basins and 8 sub-basins of the Danube River), 166 rivers discharge into the Mediterranean Sea and 96 rivers flow into the North Sea.

River basins were delineated based on the global drainage direction map on 30-arcmin resolution[4]. The drainage area of the Danube (797,289 km^2) was divided into eight sub-basins following Strokal et al.[1] to better indicate the spatial variation in river export of nutrients[5]. These sub-basins include upstream (i.e., Upstream, Drava, Sava, and Tisza), middlestream (i.e., Siret, Prut and Middlestream) and downstream (i.e., Downstream delta) sub-basins.

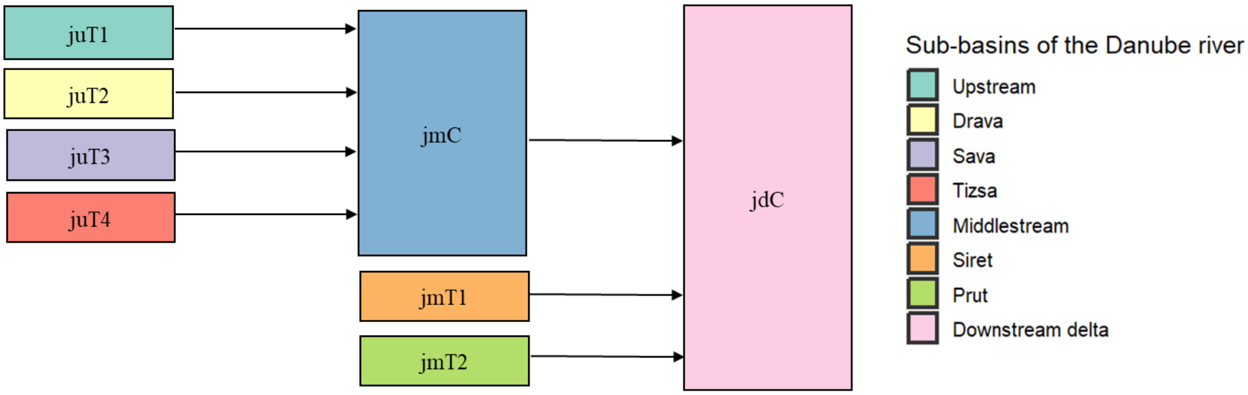

Fig. S1 Upstream tributary (juT), middle stream tributary (jmT) and main channel (jmC), and downstream main channel (jdC) sub-basins of the Danube River[5]. The sub-basins were delineated by Strokal et al.[5] based on the Drainage Direction Map (DDM30)[4]. The main channel was defined using the Strahler Order of the Drainage Direction Map (DDM30) following Strokal et al. [1]. The outlet of Downstream delta is the river mouth where nutrients are discharged to the sea. The fraction of the sub-basin area (0–1) draining directly to the main channels (i.e., ${}^{\mathrm{juT}}A_{jmC}$, ${}^{\mathrm{juT}}A_{jdC}$, ${}^{\mathrm{jmT}}A_{jdC}$, ${}^{\mathrm{jmC}}A_{jdC}$) was calculated as the fraction to the total area of these sub-basins (0–1) following Strokal et al.[1] (Table S4 for explanations of the variables).

Table S1 Comparison of strengths and weaknesses of MITERRA-Europe[3] and MARINA-Nutrients[1] models

Model name	Strengths	Weaknesses
MITERRA-Europe	+ Simplified processes for air and water emissions from agriculture + First model to assess synergistic and antagonistic effects of agricultural measures on the emissions + Includes agricultural policy scenario simulations and analysis (e.g., Nitrates Directive)	– No seasonal and annual dynamics – Only processes occur at soil surface considered – Not the whole food system considered (only crop and animal production) – For scenario analysis the model depends on other models (e.g., CAPRI) to provide changes in the activity data/driving factors
MARINA-Nutrients	+ Nutrient forms (i.e., DIN, DON, DIP, DOP) + Modelling of nutrient flows from land to coastal waters at basin/sub-basin scale + Source attribution for nutrients + Upstream, middlestream, downstream sub-basin contribution to pollution + Scenario analysis to reduce future water pollution	– No seasonality – Steady state model

Table S2 Comparison of inputs, processes and outputs of MITERRA-Europe[3] and MARINA-Nutrients[1] models

Model name	Input data	Modelling processes	Output data
MITERRA-Europe	• Main inputs ○ livestock numbers ○ livestock distribution ○ animal production ○ feed ○ crop areas ○ crop yields ○ fertilizer consumption	• Calculations are annual and on a deterministic basis ○ GHG and NH_3 emissions ○ N leaching ○ The surplus of gross N balance ○ The soil N balance ○ The soil P balance	• Annual at country, NUTS2 and EU-27 levels ○ GHG emissions (CH_4, N_2O and NO_x) ○ NH_3 emissions ○ N leaching ○ N and P balance ○ soil organic C stock changes
MARINA-Nutrients	• Point sources of nutrients ○ Sewage ▪ Wastewater treatment ▪ Direct discharges ○ Manure (direct discharges) • Diffuse sources of nutrients ○ Atmospheric N deposition ○ Biological N_2 fixation ○ Fertilizer application ○ Manure application • Human population • Meteorology • Hydrology • Land use	• Calculation of steady-state annual exports of nutrients at the outlets of sub-basins and at the river mouth ○ Mass-balance approach ▪ Dissolved inorganic N and P ▪ Dissolved organic N, P, and C • Calculation of wastewater treatment removal and river retention of nutrients • Scenario simulations (2050)	• Annual nutrient export at the river mouth ○ Dissolved inorganic N and P ○ Dissolved organic N and P • Source attribution of nutrient export at the river mouth ○ Sub-basin contributions to nutrient export at the river mouth

Table S3 Equations of the new version of the MARINA-Nutrients model for Europe to quantify inputs of N and P to land, rivers and to the seas by the European basins adjusted from Strokal et al.[1]

Equation	Number
$RSdif_{F.y.j} = WSdif_{E.y.j} \times G_{F.j} \times FE_{ws.F.j}$	Main equation
	Eq. 1
$RSdif_{DIN.fe.j} = WSdif_{N.fe.j} \times G_{DIN.j} \times FE_{ws.DIN.j}$	Eq. 2
$RSdif_{DIN.ma.j} = WSdif_{N.ma.j} \times G_{DIN.j} \times FE_{ws.DIN.j}$	Eq. 3
$RSdif_{DIN.dep.ant.j} = WSdif_{N.dep.ant.j} \times G_{DIN.j} \times FE_{ws.DIN.j}$	Eq. 4
$RSdif_{DIN.fix.ant.j} = WSdif_{N.fix.ant.j} \times G_{DIN.j} \times FE_{ws.DIN.j}$	Eq. 5
$RSdif_{DIN.hum.uncon.j} = WSdif_{N.hum.uncon.j} \times G_{DIN.j} \times FE_{ws.DIN.j}$	Eq. 6
$RSdif_{DIN.dep.nat.j} = WSdif_{N.dep.nat.j} \times FE_{ws.DIN.j}$	Eq. 7
$RSdif_{DIN.fix.nat.j} = WSdif_{N.fix.nat.j} \times FE_{ws.DIN.j}$	Eq. 8
$G_{DIN.j} = 1 - (WSdif_{N.ex.j} / WSdif_{DIN.gross.j})$	Eq. 9
$FE_{ws.DIN.j} = CR_{DIN} \times Rnat_{j}$	Eq. 10[a]
$WSdif_{DIN.gross.j} = WSdif_{N.fe.j} + WSdif_{N.ma.j} + WSdif_{N.dep.ant.j} + WSdif_{N.fix.ant.j} + WSdif_{N.hum.uncon.j}$	Eq. 11
$RSdif_{DON.fe.j} = WSdif_{N.fe.j} \times G_{DON.j} \times FE_{ws.DON.j}$	Eq. 12
$RSdif_{DON.ma.j} = WSdif_{N.ma.j} \times G_{DON.j} \times FE_{ws.DON.j}$	Eq. 13
$RSdif_{DON.hum.uncon.j} = WSdif_{N.hum.uncon.j} \times G_{DON.j} \times FE_{ws.DON.j}$	Eq. 14
$RSdif_{DON.lech.ant.j} = Area_{j} \times Agr_{fr.j} \times EC_{DON} \times f_{DON}(Rnat_{j})$	Eq. 15[b]
$RSdif_{DON.lech.nat.j} = Area_{j} \times (1 - Agr_{fr.j}) \times EC_{DON} \times f_{DON}(Rnat_{j})$	Eq. 16[b]
$G_{DON.j} = 1 - (WSdif_{N.ex.j} / WSdif_{DON.gross.j})$	Eq. 17
$FE_{ws.DON.j} = CR_{DON} \times Rnat_{j}$	Eq. 18[c]
$WSdif_{DON.gross.j} = WSdif_{N.fe.j} + WSdif_{N.ma.j} + WSdif_{N.hum.uncon.j}$	Eq. 19
$WSdif_{N.ma.j} = N_{ma} + N_{gr}$	Eq. 20
$WSdif_{N.hum.uncon.j} = WSdif_{N.hum.uncon.urb.j} + WSdif_{N.hum.uncon.rur.j}$	Eq. 21
$WSdif_{N.hum.uncon.urb.j} = Nexc_{hum.uncon.urb.j} \times (1 - fr_{NH3.hum})$	Eq. 22[d]
$WSdif_{N.hum.uncon.rur.j} = Nexc_{hum.uncon.rur.j} \times (1 - fr_{NH3.hum})$	Eq. 23[d]
$Nexc_{hum.uncon.urb.j} = E^{N}_{hum.j} \times Pop_{uncon.urb.j}$	Eq. 24
$Nexc_{hum.uncon.rur.j} = E^{N}_{hum.j} \times Pop_{uncon.rur.j}$	Eq. 25
$RSdif_{DIP.fe.j} = WSdif_{P.fe.j} \times G_{DIP.j} \times FE_{ws.DIP.j}$	Eq. 26
$RSdif_{DIP.ma.j} = WSdif_{P.ma.j} \times G_{DIP.j} \times FE_{ws.DIP.j}$	Eq. 27
$RSdif_{DIP.dep.ant.j} = WSdif_{P.dep.ant.j} \times G_{DIP.j} \times FE_{ws.DIP.j}$	Eq. 28
$RSdif_{DIP.hum.uncon.j} = WSdif_{P.hum.uncon.j} \times G_{DIP.j} \times FE_{ws.DIP.j}$	Eq. 29
$RSdif_{DIP.wth.ant.j} = Area_{j} \times Agr_{fr.j} \times EC_{DIP} \times f_{DIP}(Rnat_{j})$	Eq. 30[e]
$RSdif_{DIP.wth.nat.j} = Area_{j} \times (1 - Agr_{fr.j}) \times EC_{DIP} \times f_{DIP}(Rnat_{j})$	Eq. 31[e]
$G_{DIP.j} = 1 - (WSdif_{P.ex.j} / WSdif_{DIP.gross.j})$	Eq. 32
$FE_{ws.DIP.j} = CR_{DIP} \times Rnat_{j}$	Eq. 33[f]
$WSdif_{DIP.gross.j} = WSdif_{P.fe.j} + WSdif_{P.ma.j} + WSdif_{P.dep.ant.j} + WSdif_{P.hum.uncon.j}$	Eq. 34
$RSdif_{DOP.fe.j} = WSdif_{P.fe.j} \times G_{DOP.j} \times FE_{ws.DOP.j}$	Eq. 35
$RSdif_{DOP.ma.j} = WSdif_{P.ma.j} \times G_{DOP.j} \times FE_{ws.DOP.j}$	Eq. 36
$RSdif_{DOP.hum.uncon.j} = WSdif_{P.hum.uncon.j} \times G_{DOP.j} \times FE_{ws.DOP.j}$	Eq. 37
$RSdif_{DOP.lech.ant.j} = Area_{j} \times Agr_{fr.j} \times EC_{DOP} \times f_{DOP}(Rnat_{j})$	Eq. 38[g]
$RSdif_{DOP.lech.nat.j} = Area_{j} \times (1 - Agr_{fr.j}) \times EC_{DOP} \times f_{DOP}(Rnat_{j})$	Eq. 39[g]
$G_{DOP.j} = 1 - (WSdif_{P.ex.j} / WSdif_{DOP.gross.j})$	Eq. 40
$FE_{ws.DOP.j} = CR_{DOP} \times Rnat_{j}$	Eq. 41[h]
$WSdif_{DOP.gross.j} = WSdif_{P.fe.j} + WSdif_{P.ma.j} + WSdif_{P.hum.uncon.j}$	Eq. 42
$WSdif_{P.ma.j} = P_{ma} + P_{gr}$	Eq. 43
$WSdif_{P.hum.uncon.j} = WSdif_{P.hum.uncon.urb.j} + WSdif_{P.hum.uncon.rur.j}$	Eq. 44
$WSdif_{P.hum.uncon.urb.j} = Pexc_{hum.uncon.urb.j}$	Eq. 45[i]

Equation	Number
$\mathrm{WSdif}_{\mathrm{P.hum.uncon.rur.j}} = \mathrm{Pexc}_{\mathrm{hum.uncon.rur.j}}$	Eq. 46[i]
$\mathrm{Pexc}_{\mathrm{hum.uncon.urb.j}} = \mathrm{E}^{\mathrm{P}}_{\mathrm{hum.j}} \times \mathrm{Pop}_{\mathrm{uncon.urb.j}}$	Eq. 47
$\mathrm{Pexc}_{\mathrm{hum.uncon.rur.j}} = \mathrm{E}^{\mathrm{P}}_{\mathrm{hum.j}} \times \mathrm{Pop}_{\mathrm{uncon.rur.j}}$	Eq. 48
$\mathrm{Rnat}_{\mathrm{j}} = \mathrm{Q}_{\mathrm{nat.j}}/\mathrm{Area}_{\mathrm{j}}$	Eq. 49
$\mathrm{RSpnt}_{\mathrm{F.y.j}} = \mathrm{RSpnt}_{\mathrm{E.hum.con.j}} \times \mathrm{FEpnt}_{\mathrm{F.hum.con.j}}$	Main equation Eq. 50 (Eq. 2 in the paper)
$\mathrm{RSpnt}_{\mathrm{DIN.hum.con.j}} = \mathrm{RSpnt}_{\mathrm{N.hum.con.j}} \times \mathrm{FEpnt}_{\mathrm{DIN.hum.con.j}}$	Eq. 51[j]
$\mathrm{RSpnt}_{\mathrm{DON.hum.con.j}} = \mathrm{RSpnt}_{\mathrm{N.hum.con.j}} \times \mathrm{FEpnt}_{\mathrm{DON.hum.con.j}}$	Eq. 52[k]
$\mathrm{RSpnt}_{\mathrm{N.hum.con.j}} = \mathrm{RSpnt}_{\mathrm{N.hum.con.urb.j}} + \mathrm{RSpnt}_{\mathrm{N.hum.con.rur.j}}$	Eq. 53
$\mathrm{RSpnt}_{\mathrm{N.hum.con.urb.j}} = \mathrm{Nexc}_{\mathrm{hum.con.urb.j}} \times (1 - \mathrm{hw}_{\mathrm{frem.N.j}})$	Eq. 54[l]
$\mathrm{RSpnt}_{\mathrm{N.hum.con.rur.j}} = \mathrm{Nexc}_{\mathrm{hum.con.rur.j}} \times (1 - \mathrm{hw}_{\mathrm{frem.N.j}})$	Eq. 55[l]
$\mathrm{Nexc}_{\mathrm{hum.con.urb.j}} = \mathrm{E}^{\mathrm{N}}_{\mathrm{hum.j}} \times \mathrm{Pop}_{\mathrm{con.urb.j}}$	Eq. 56
$\mathrm{Nexc}_{\mathrm{hum.con.rur.j}} = \mathrm{E}^{\mathrm{N}}_{\mathrm{hum.j}} \times \mathrm{Pop}_{\mathrm{con.rur.j}}$	Eq. 57
$\mathrm{E}^{\mathrm{N}}_{\mathrm{hum.j}} = \mathrm{I}^{\mathrm{N}}_{\mathrm{hum.j}} \times 0.365$	Eq. 58
$\mathrm{I}^{\mathrm{N}}_{\mathrm{hum.j}} = 4 + 17 \times [\mathrm{GDP}_{\mathrm{ppp.j}}/68{,}673]^{0.3}$	Eq. 59
$\mathrm{FEpnt}_{\mathrm{DIN.hum.con.j}} = 0.485 + 0.225 \times (\mathrm{hw}_{\mathrm{frem.N.j}} \,/\, 0.88)$	Eq. 60[l]
$\mathrm{RSpnt}_{\mathrm{DIP.hum.con.j}} = (\mathrm{RSpnt}_{\mathrm{P.hum.con.j}} + \mathrm{RSpnt}_{\mathrm{P.det.con.j}}) \times \mathrm{FEpnt}_{\mathrm{DIP.hum.con.j}}$	Eq. 61[m]
$\mathrm{RSpnt}_{\mathrm{DOP.hum.con.j}} = (\mathrm{RSpnt}_{\mathrm{P.hum.con.j}} + \mathrm{RSpnt}_{\mathrm{P.det.con.j}}) \times \mathrm{FEpnt}_{\mathrm{DOP.hum.con.j}}$	Eq. 62[n]
$\mathrm{RSpnt}_{\mathrm{P.hum.con.j}} = \mathrm{RSpnt}_{\mathrm{P.hum.con.urb.j}} + \mathrm{RSpnt}_{\mathrm{P.hum.con.rur.j}}$	Eq. 63
$\mathrm{RSpnt}_{\mathrm{P.hum.con.urb.j}} = \mathrm{Pexc}_{\mathrm{hum.con.urb.j}} \times (1 - \mathrm{hw}_{\mathrm{frem.P.j}})$	Eq. 64[o]
$\mathrm{RSpnt}_{\mathrm{P.hum.con.rur.j}} = \mathrm{Pexc}_{\mathrm{hum.con.rur.j}} \times (1 - \mathrm{hw}_{\mathrm{frem.P.j}})$	Eq. 65[o]
$\mathrm{Pexc}_{\mathrm{hum.con.urb.j}} = \mathrm{E}^{\mathrm{P}}_{\mathrm{hum.j}} \times \mathrm{Pop}_{\mathrm{con.urb.j}}$	Eq. 66
$\mathrm{Pexc}_{\mathrm{hum.con.rur.j}} = \mathrm{E}^{\mathrm{P}}_{\mathrm{hum.j}} \times \mathrm{Pop}_{\mathrm{con.rur.j}}$	Eq. 67
$\mathrm{E}^{\mathrm{P}}_{\mathrm{hum.j}} = \mathrm{E}^{\mathrm{N}}_{\mathrm{hum.j}} \times (1/6)$	Eq. 68[p]
$\mathrm{RSpnt}_{\mathrm{P.det.con.j}} = \mathrm{RSpnt}_{\mathrm{P.det.con.urb.j}} + \mathrm{RSpnt}_{\mathrm{P.det.con.rur.j}}$	Eq. 69
$\mathrm{RSpnt}_{\mathrm{P.det.con.urb.j}} = (1 - \mathrm{hw}_{\mathrm{frem.P.j}}) \times \mathrm{WShw}_{\mathrm{cap.P.det.j}} \times \mathrm{Pop}_{\mathrm{con.urb.j}}$	Eq. 70[o, r]
$\mathrm{RSpnt}_{\mathrm{P.det.con.rur.j}} = (1 - \mathrm{hw}_{\mathrm{frem.P.j}}) \times \mathrm{WShw}_{\mathrm{cap.P.det.j}} \times \mathrm{Pop}_{\mathrm{con.rur.j}}$	Eq. 71[o,r]
$\mathrm{N}_{\mathrm{total.y.j}} = \mathrm{NH}_{3.\mathrm{y.j}} + \mathrm{N}_2\mathrm{O}_{\mathrm{y.j}} + \mathrm{NO}_{\mathrm{X.y.j}}$	Main equation Eq. 72 (Eq. 3 in the paper)
$\mathrm{M}_{\mathrm{F.y.j}} = \left(\mathrm{RSdif}_{\mathrm{F.y.j}} + \mathrm{RSpnt}_{\mathrm{F.y.j}}\right) \times \mathrm{FE}_{\mathrm{riv.F.outlet.j}} \times \mathrm{FE}_{\mathrm{riv.F.mouth.j}}$	Main equation Eq. 73 (Eq. 4 in the paper)
$\mathrm{FE}_{\mathrm{riv.DIN.outlet.j}} = \left(1 - \mathrm{D}_{\mathrm{DIN.j}}\right) \times \left(1 - \mathrm{L}_{\mathrm{DIN.j}}\right) \times \left(1 - \mathrm{FQrem}_{\mathrm{j}}\right)$	Eq. 74
$\mathrm{D}_{\mathrm{DIN.j}} = (1/\mathrm{Q}_{\mathrm{act.j}}) \times \sum_{\mathrm{i=1...n}}(\mathrm{Q}_{\mathrm{act.i}} \times \mathrm{D}_{\mathrm{DIN.i}})$	Eq. 75[s]
$\mathrm{L}_{\mathrm{DIN.j}} = 0.0605 \times \ln(\mathrm{Area}_{\mathrm{j}}) - 0.0443$	Eq. 76[t]
$\mathrm{FE}_{\mathrm{riv.DON.outlet.j}} = \left(1 - \mathrm{FQrem}_{\mathrm{j}}\right)$	Eq. 77
$\mathrm{FE}_{\mathrm{riv.DIP.outlet.j}} = \left(1 - \mathrm{D}_{\mathrm{DIP.j}}\right) \times \left(1 - \mathrm{L}_{\mathrm{DIP.j}}\right) \times \left(1 - \mathrm{FQrem}_{\mathrm{j}}\right)$	Eq. 78[u]
$\mathrm{D}_{\mathrm{DIP.j}} = (1/\mathrm{Q}_{\mathrm{act.j}}) \times \sum_{\mathrm{i=1...n}}(\mathrm{Q}_{\mathrm{act.i}} \times \mathrm{D}_{\mathrm{DIP.i}})$	Eq. 79[v]
$\mathrm{FE}_{\mathrm{riv.DOP.outlet.j}} = \left(1 - \mathrm{FQrem}_{\mathrm{j}}\right)$	Eq. 80
$\mathrm{FQrem}_{\mathrm{j}} = 1 - (\mathrm{Q}_{\mathrm{act.j}}/\mathrm{Q}_{\mathrm{nat.j}})$	Eq. 81
$\mathrm{FE}_{\mathrm{riv.F.mouth.juT}} = {}^{\mathrm{juT}}\mathrm{FE}_{\mathrm{riv.F.outlet.jmC}} \times {}^{\mathrm{juT}}\mathrm{FE}_{\mathrm{riv.F.outlet.jdC}}$	Eq. 82
$\mathrm{FE}_{\mathrm{riv.F.mouth.jmT}} = {}^{\mathrm{jmT}}\mathrm{FE}_{\mathrm{riv.F.outlet.jdC}}$	Eq. 83
$\mathrm{FE}_{\mathrm{riv.F.mouth.jmC}} = {}^{\mathrm{jmC}}\mathrm{FE}_{\mathrm{riv.F.outlet.jdC}}$	Eq. 84
$\mathrm{FE}_{\mathrm{riv.F.mouth.jdC}} = 1$	Eq. 85

Equation	Number
${}^{juT}FE_{riv.F.outlet.jmC} = (1 - [D_{F.jmC} \times {}^{juT}A_{jmC}]) \times (1 - [L_{F.jmC} \times {}^{juT}A_{jmC}]) \times (1 - [FQrem_{jmC} \times {}^{juT}A_{jmC}])$	Eq. 86
${}^{juT}FE_{riv.F.outlet.jdC} = (1 - [D_{F.jdC} \times {}^{juT}A_{jdC}]) \times (1 - [L_{F.jdC} \times {}^{juT}A_{jdC}]) \times (1 - [FQrem_{jdC} \times {}^{juT}A_{jdC}])$	Eq. 87
${}^{jmT}FE_{riv.F.outlet.jdC} = (1 - [D_{F.jdC} \times {}^{jmT}A_{jdC}]) \times (1 - [L_{F.jdC} \times {}^{jmT}A_{jdC}]) \times (1 - [FQrem_{jdC} \times {}^{jmT}A_{jdC}])$	Eq. 88
${}^{jmC}FE_{riv.F.outlet.jdC} = (1 - [D_{F.jdC} \times {}^{jmC}A_{jdC}]) \times (1 - [L_{F.jdC} \times {}^{jmC}A_{jdC}]) \times (1 - [FQrem_{jdC} \times {}^{jmC}A_{jdC}])$	Eq. 89

Note: Inputs of N and P to rivers and seas are quantified from point and diffuse sources. Point sources include effluents of treated wastewater from sewage systems to rivers. Diffuse sources include inputs of the pollutants from land via surface runoff. MARINA-Nutrients is short for the soft-linked model system. Abbreviations are explained in Table S4. [a] Uncalibrated approach was used to calculate the fraction of nutrients that is exported from land to rivers in basin j following Li et al.[6]. In this approach, the European basins are clustered based on the climate zones (i.e., subtropic/tropic and other temperature zones). CR_{DIN} is the export coefficient for runoff exporting nutrients from land to surface waters in a form of DIN and derived from Li et al.[6] based on the subtropic/tropic (wet climate) and other temperature zones (dry climate). More nutrient export is expected from land to rivers with higher runoff. Thus, higher export coefficients are considered for basins with runoff $\geqslant 0.1$ m·yr^{-1}. $CR_{DIN} = 0.9$ (unitless)for runoff $\geqslant 0.1$ m·yr^{-1}, and $CR_{DIN} = 0.8$ (unitless) for runoff < 0.1 m·yr^{-1}. CR_{DIN} is relatively higher as the dissolved inorganic forms of N (e.g., NO_3^-) are more mobile in the environment having higher tendency to reach rivers by surface runoff than DON, DOP and DIP[6]. [b] EC_{DON} is the coefficient for leaching of organic matter and derived from Mayorga et al.[7]. EC_{DON} = 280 kg·km^{-2}·yr^{-1}. $f_{DON}(Rnat_j) = Rnat_j^{aDON}$ where a_{DON} is a model parameter to quantify annual runoff (unitless). $a_{DON} = 0.95$[1]. [c] CR_{DON} is the export coefficient for runoff exporting nutrients from land to surface waters in a form of DON and derived from Li et al.[6] (footnote a for further description). $CR_{DON} = 0.02$ (unitless) for runoff $\geqslant$ 0.1 m·yr^{-1}, and $CR_{DON} = 0.01$ (unitless) for runoff < 0.1 m·yr^{-1}. [d] We assumed no direct discharge of the untreated wastewater from population (urban and rural) not connected to sewage systems. Thus, we considered the unconnected population (urban and rural) wastewater as input to the land ($WSdif_{N.hum.uncon.j}$) and adjusted the equation from Strokal et al.[1]. $fr_{NH3.hum}$ is the fraction of N losses from human excretion to the air (0–1) and derived from Mayorga et al.[7]. $fr_{NH3.hum} = 0.24$. [e] EC_{DIP} is coefficient for P weathering and derived from Mayorga et al.[7]. EC_{DIP} = 26 kg·km^{-2}·yr^{-1}. $f_{DIP}(Rnat_j) = [1 + (Rnat_j/a_{DIP})^{-bDIP}]^{-1}$ where a_{DIP} and b_{DIP} are model parameters to quantify annual runoff (unitless). $a_{DIP} = 0.85$ and $b_{DIP} = 2$[1]. [f] CR_{DIP} is the export coefficient for runoff exporting nutrients from land to surface waters in a form of DIP and derived from Li et al. [6] (footnote a for further description). $CR_{DIP} = 0.15$ (unitless) for runoff $\geqslant$ 0.1 m·yr^{-1}, and $CR_{DIP} = 0.1$ (unitless) for runoff < 0.1 m·yr^{-1}. [g] EC_{DOP} is coefficient for leaching of organic matter and derived from Mayorga et al.[7]. EC_{DOP} = 15 kg·km^{-2}·yr^{-1}. $f_{DOP}(Rnat_j) = Rnat_j^{aDOP}$ where a_{DOP} is a model parameter to quantify annual runoff (unitless). $a_{DOP} = 0.95$ [1]. [h] CR_{DOP} is the export coefficient for runoff exporting nutrients from land to surface waters in a form of DOP and derived from Li et al.[6] (footnote a for further description). $CR_{DOP} = 0.02$ (unitless) for runoff $\geqslant$ 0.1 m·yr^{-1}, and $CR_{DOP} = 0.01$ (unitless) for runoff < 0.1 m·yr^{-1}. [i] We assumed no direct discharge of the untreated wastewater from population (urban and rural) not connected to sewage systems. Thus, we considered the unconnected population (urban and rural) wastewater as input to the land ($WSdif_{P.hum.uncon.j}$) and adjusted the equation from Strokal et al.[1]. [j] $FEpnt_{DIN.hum.con}$ is calculated for each basin according to the Global *NEWS-2* as a linear empirical function of N removal during treatment[7–9] as: $FEpnt_{DIN.hum.con} = 0.485 + 0.225 \times (hw_{fremN.j} / 0.8)$ where 0.485 is the fraction of total N (TN) in sewage effluents that is DIN without treatment; 0.225 is the maximum increase in DIN/TN ratio that can be achieved during treatment; $hw_{fremN.j}$ is N removal during treatment in sewage systems of each basin; and 0.8 is the maximum observed value for N treatment (represents Finland)[1]. In this study, the maximum observed value for N treatment was around 0.88 and that is used instead of "0.8" in the equation. [k] $FEpnt_{DON.hum.con} = 0.14$ derived from the Global *NEWS-2* model[7]. [l] $hw_{frem.N.j}$ is the removal fraction of N during treatment in sewage systems in basin j and calculated following the approach of Strokal et al.[10]. $hw_{frem.N.j}$ (0–1) is the same for urban and rural treatment systems. [m] $FEpnt_{DIP.hum.con} = 1$ derived from the Global *NEWS-2* model[1,7]. [n] $FEpnt_{DOP.hum.con} = 0.010$ derived from the Global *NEWS-2* model[7]. [o] $hw_{frem.P.j}$ is the removal fraction of P during treatment in sewage systems in basin j and calculated following the approach of Strokal et al.[10]. $hw_{frem.P.j}$ (0–1) is the same for urban and rural treatment systems. [p] 1/6 is the ratio between human P and human N excretion based on measurements of 27 waste water treatment plants in Austria[9]. [r] $WShw_{cap.P.det.j}$ is the consumption rate of P detergents (from laundry and washing) in basin j and derived from Strokal et al.[10] (kg·cap^{-1}·yr^{-1}). [s] Data on the characteristics of reservoirs and (regulated) lakes were derived from HydroLAKES[11]. $Q_{act.i}$ is actual water discharge for reservoir i (km^3·yr^{-1}) and derived from Messager et al.[11] using the approach of Strokal et al.[1]. $D_{DIN.i}$ is the fraction of DIN retained in reservoir i (0–1) and calculated by the equation: $D_{DIN.i} = 0.8845 \text{ x } (h_i / \tau_{R.i})^{-0.3677}$ using the approach of Strokal, et al.[1]. h_i is depth of reservoir i (meter) and derived from Messager et al.[11] using the approach of Strokal et al.[1]. $\tau_{R.i}$ is water residence time for reservoir i (year) calculated by the equation: $\tau_{R.i} = V_i / Q_{act.i}$ [1]. V_i is volume of reservoir i (km^3·yr^{-1}) and derived from Messager et al.[11] using the approach of Strokal et al.[1]. The maximum value of $D_{DIN.j}$ is set as 0.965 since this is the maximum value of the basins used to calibrate parameters[1]. [t] 0.0605 and 0.0443 in the equation are fitted coefficients and derived from Strokal et al.[1]. $Area_j$ is drainage area of basin j (km^2) and derived from Strokal et al.[1]. The maximum value of $L_{DIN.j}$ is set as 0.65 using the approach of Strokal et al.[1]. [u] The value of $L_{DIP.j}$ is set as 0.9 for dry rivers having runoff of less than 0.1 m·yr^{-1} and as 0.5 for other rivers using the approach of Strokal et al.[1]. [v] $Q_{act.i}$ is actual water discharge for reservoir i (km^3·yr^{-1}) and derived from Messager et al.[11] using the approach of Strokal et al.[1]. $D_{DIP.j}$ is the fraction of DIP retained in reservoir i (0–1) and calculated by the equation: $D_{DIP.i} = 0.85 \times [1 - \exp(-0.0807 \times 365 \times \tau_{R.i})]$ using the approach of Strokal et al.[1]. The maximum value of $D_{DIP.j}$ is set as 0.85 using the approach of Strokal et al.[1].

Table S4 Descriptions of the abbreviations in Table S3 adjusted from Strokal et al.[1]

Parameter	Description	Unit
E	Nutrient element: ○ N ○ P	-
F	Nutrient form: ○ Dissolved inorganic N and P (DIN, DIP) ○ Dissolved organic N and P (DON, DOP)	-
y	Source	-
j	Basin (sub-basins for Danube)	-
i	Reservoir	-
$RSdif_{F.y.j}$	Inputs of nutrient form F (DIN, DON, DIP and DOP) to rivers from a diffuse source y in basin j	$kg \cdot yr^{-1}$ N or P
$RSdif_{F.fe.j}$	Inputs of nutrient form F (DIN, DON, DIP and DOP) to rivers from synthetic fertilizer application (fe) in basin j	$kg \cdot yr^{-1}$ N or P
$RSdif_{F.ma.j}$	Inputs of nutrient form F (DIN, DON, DIP and DOP) to rivers from livestock manure application (ma) in basin j	$kg \cdot yr^{-1}$ N or P
$RSdif_{F.dep.ant.j}$	Inputs of DIN and DIP to rivers from atmospheric deposition (dep) over agricultural land (ant) in basin j	$kg \cdot yr^{-1}$ N or P
$RSdif_{DIN.fix.ant.j}$	Inputs of DIN to rivers from biological N_2 fixation (fix) by agricultural crops (ant) in basin j	$kg \cdot yr^{-1}$ N
$RSdif_{F.hum.uncon.j}$	Inputs of nutrient form F (DIN, DON, DIP and DOP) to rivers from human excretion (hum) unconnected to sewage systems (uncon) in basin j	$kg \cdot yr^{-1}$ N or P
$RSdif_{DIN.dep.nat.j}$	Inputs of DIN to rivers from atmospheric deposition (dep) over natural land (nat) in basin j	$kg \cdot yr^{-1}$ N
$RSdif_{DIN.fix.nat.j}$	Inputs of DIN to rivers from biological N_2 fixation (fix) by natural vegetation (nat) in basin j	$kg \cdot yr^{-1}$ N
$RSdif_{F.lch.ant.j}$	Inputs of DON and DOP to rivers from organic matter leaching (lch) over agricultural areas (ant) in basin j	$kg \cdot yr^{-1}$ N or P
$RSdif_{F.lch.nat.j}$	Inputs of DON and DOP to rivers from organic matter leaching (lch) over natural areas (nat) in basin j	$kg \cdot yr^{-1}$ N or P
$RSdif_{DIP.wth.ant.j}$	Inputs of DIP to rivers from P weathering (wth) in agricultural areas (ant) in basin j	$kg \cdot yr^{-1}$ P
$RSdif_{DIP.wth.nat.j}$	Inputs of DIP to rivers from P weathering (wth) in natural areas (nat) in basin j	$kg \cdot yr^{-1}$ P
$WSdif_{E.fe.j}$	Inputs of nutrient element E (N and P) from synthetic fertilizers (fe) that are applied to agricultural land in basin j	$kg \cdot yr^{-1}$ N or P
$WSdif_{E.ma.j}$	Inputs of nutrient element E (N and P) from animal manure (ma) that is applied to agricultural land in basin j	$kg \cdot yr^{-1}$ N or P
$WSdif_{E.dep.ant.j}$	Inputs of nutrient element E (N and P) from atmospheric deposition (dep) over agricultural land (ant) in basin j	$kg \cdot yr^{-1}$ N or P
$WSdif_{N.fix.ant.j}$	Inputs of N from biological N_2 fixation (fix) by agricultural crops (ant) in basin j	$kg \cdot yr^{-1}$ N
$WSdif_{N.dep.nat.j}$	Inputs of N from atmospheric deposition (dep) over natural land (nat) in basin j	$kg \cdot yr^{-1}$ N
$WSdif_{N.fix.nat.j}$	Inputs of N from biological N_2 fixation (fix) by natural vegetation (nat) in basin j	$kg \cdot yr^{-1}$ N
$WSdif_{E.hum.uncon.j}$	Inputs of nutrient element E (N and P) from excretion of population (hum) not connected to sewage systems (uncon) in basin j	$kg \cdot yr^{-1}$ N or P
$WSdif_{E.hum.uncon.urb.j}$	Inputs of nutrient element E (N and P) from excretion of urban population (urb) not connected to sewage systems (uncon) in basin j	$kg \cdot yr^{-1}$ N or P
$WSdif_{E.hum.uncon.rur.j}$	Inputs of nutrient element E (N and P) from excretion of rural population (rur) not connected to sewage systems (uncon) in basin j	$kg \cdot yr^{-1}$ N or P

Parameter	Description	Unit
$\mathrm{WSdif}_{\mathrm{E.ex.j}}$	Export (ex) of nutrient element E (N and P) from crop harvesting and animal grazing in basins j	kg·yr^{-1} N or P
$\mathrm{G}_{\mathrm{DIN.j}}$	Fraction of DIN that is remained in soil after correcting for crop harvesting and livestock grazing in basin j	0–1
$\mathrm{G}_{\mathrm{DON.j}}$	Fraction of DON that is remained in soil after correcting for crop harvesting and livestock grazing in basin j	0–1
$\mathrm{G}_{\mathrm{DIP.j}}$	Fraction of DIP that is remained in soil after correcting for crop harvesting and livestock grazing in basin j	0–1
$\mathrm{G}_{\mathrm{DOP.j}}$	Fraction of DOP that is remained in soil after correcting for crop harvesting and livestock grazing in basin j	0–1
$\mathrm{FE}_{\mathrm{ws.DIN.j}}$	Fraction of DIN that is exported from land to rivers in basin j	0–1
$\mathrm{FE}_{\mathrm{ws.DON.j}}$	Fraction of DON that is exported from land to rivers in basin j	0–1
$\mathrm{FE}_{\mathrm{ws.DIP.j}}$	Fraction of DIP that is exported from land to rivers in basin j	0–1
$\mathrm{FE}_{\mathrm{ws.DOP.j}}$	Fraction of DOP that is exported from land to rivers in basin j	0–1
$\mathrm{CR}_{\mathrm{DIN}}$	The export coefficient for runoff exporting nutrients from land to rivers in a form of DIN	Unitless
$\mathrm{CR}_{\mathrm{DON}}$	The export coefficient for runoff exporting nutrients from land to rivers in a form of DON	Unitless
$\mathrm{CR}_{\mathrm{DIP}}$	The export coefficient for runoff exporting nutrients from land to rivers in a form of DIP	Unitless
$\mathrm{CR}_{\mathrm{DOP}}$	The export coefficient for runoff exporting nutrients from land to rivers in a form of DOP	Unitless
$\mathrm{Rnat}_{\mathrm{j}}$	Annual surface runoff from land to streams in basin j	m·yr^{-1}
$\mathrm{Q}_{\mathrm{nat.j}}$	Natural (nat) river discharge at the outlet of basin j, before water is taken for consumption	km^{3}·yr^{-1}
$\mathrm{Area}_{\mathrm{j}}$	The drainage area of basin j	km^{2}
N_{ma}	Inputs of N from animal manure that is applied to agricultural land by the MITERRA-Europe model	kg·yr^{-1} N
N_{gr}	Inputs of N from animal manure that is stayed on agricultural land during grazing by the MITERRA-Europe model	kg·yr^{-1} N
P_{ma}	Inputs of P from animal manure that is applied to agricultural land by the MITERRA-Europe model	kg·yr^{-1} P
P_{gr}	Inputs of P from animal manure that is stayed on agricultural land during grazing by the MITERRA-Europe model	kg·yr^{-1} P
$\mathrm{Nexc}_{\mathrm{hum.uncon.urb.j}}$	N in human excretion from urban population unconnected to sewage systems in basin j	kg·yr^{-1} N
$\mathrm{Nexc}_{\mathrm{hum.uncon.rur.j}}$	N in human excretion from rural population unconnected to sewage systems in basin j	kg·yr^{-1} N
$\mathrm{fr}_{\mathrm{NH3.hum}}$	Fraction of N losses from human excretion to the air	0–1
$\mathrm{E}^{\mathrm{N}}_{\mathrm{hum.j}}$	Human N excretion in basin j	kg·person^{-1}·yr^{-1}
$\mathrm{I}^{\mathrm{N}}_{\mathrm{hum.j}}$	Protein N intake for basin j	h·person^{-1}·day^{-1}
$\mathrm{GDP}_{\mathrm{ppp.j}}$	Annual gross domestic product (purchasing power parity in 2010)	US$·person^{-1}·yr^{-1}
$\mathrm{Pop}_{\mathrm{uncon.urb.j}}$	Urban population without sewage connection in basin j	People
$\mathrm{Pop}_{\mathrm{uncon.rur.j}}$	Rural population without sewage connection in basin j	People
$\mathrm{Pexc}_{\mathrm{hum.uncon.urb.j}}$	P in human excretion from urban population unconnected to sewage systems in basin j	kg·yr^{-1} P
$\mathrm{Pexc}_{\mathrm{hum.uncon.rur.j}}$	P in human excretion from rural population unconnected to sewage systems in basin j	kg·yr^{-1} P
$\mathrm{E}^{\mathrm{P}}_{\mathrm{hum.j}}$	Human P excretion in basin j	kg·person^{-1}·yr^{-1}

Parameter	Description	Unit
$Agr_{fr.j}$	Fraction of agricultural area in basin j	0–1
EC_{DON}	The coefficient for leaching of organic matter for DON	$kg \cdot km^{-2} \cdot yr^{-1}$
EC_{DIP}	The coefficient for P weathering	$kg \cdot km^{-2} \cdot yr^{-1}$
EC_{DOP}	The coefficient for leaching of organic matter for DOP	$kg \cdot km^{-2} \cdot yr^{-1}$
$f_{DON}(Rnat_j)$	a function of annual runoff for DON from land to streams in basin j	Unitless
$f_{DIP}(Rnat_j)$	a function of annual runoff for DIP from land to streams in basin j	Unitless
$f_{DOP}(Rnat_j)$	a function of annual runoff for DOP from land to streams in basin j	Unitless
$RSpnt_{F.y.j}$	Inputs of nutrient form F (DIN, DON, DIP and DOP) to rivers from a point source y in basin j	$kg \cdot yr^{-1}$ N or P
$RSpnt_{DIN.hum.con.j}$	Inputs of DIN to rivers from urban and rural sewage systems in basin j	$kg \cdot yr^{-1}$ N
$RSpnt_{DON.hum.con.j}$	Inputs of DON to rivers from urban and rural sewage systems in basin j	$kg \cdot yr^{-1}$ N
$RSpnt_{DIP.hum.con.j}$	Inputs of DIP to rivers from urban and rural sewage systems in basin j	$kg \cdot yr^{-1}$ P
$RSpnt_{DOP.hum.con.j}$	Inputs of DOP to rivers from urban and rural sewage systems in basin j	$kg \cdot yr^{-1}$ P
$RSpnt_{N.hum.con.urb.j}$	N in sewage effluents that enter rivers from urban population in basin j	$kg \cdot yr^{-1}$ N
$RSpnt_{N.hum.con.rur.j}$	N in sewage effluents that enter rivers from rural population in basin j	$kg \cdot yr^{-1}$ N
$RSpnt_{P.hum.con.urb.j}$	P in sewage effluents that enter rivers from urban population in basin j	$kg \cdot yr^{-1}$ P
$RSpnt_{P.hum.con.rur.j}$	P in sewage effluents that enter rivers from rural population in basin j	$kg \cdot yr^{-1}$ P
$RSpnt_{P.det.con.urb.j}$	P from detergent consumption that enter rivers from urban sewage systems in basin j	$kg \cdot yr^{-1}$ P
$RSpnt_{P.det.con.rur.j}$	P from detergent consumption that enter rivers from rural sewage systems in basin j	$kg \cdot yr^{-1}$ P
$Nexc_{hum.con.urb.j}$	N in human excretion from urban population connected to sewage systems in basin j	$kg \cdot yr^{-1}$ N
$Nexc_{hum.con.rur.j}$	N in human excretion from rural population connected to sewage systems in basin j	$kg \cdot yr^{-1}$ N
$Pexc_{hum.con.urb.j}$	P in human excretion from urban population connected to sewage systems in basin j	$kg \cdot yr^{-1}$ P
$Pexc_{hum.con.rur.j}$	P in human excretion from rural population connected to sewage systems in basin j	$kg \cdot yr^{-1}$ P
$hw_{frem.N.j}$	Removal fraction of N during treatment in sewage systems in basin j (the same for urban and rural)	0–1
$hw_{frem.P.j}$	Removal fraction of P during treatment in sewage systems in basin j (the same for urban and rural)	0–1
$WShw_{cap.P.det.j}$	Consumption rate of P detergents (laundry and washing) in basin j	$kg \cdot cap^{-1} \cdot yr^{-1}$
$Pop_{con.urb.j}$	Urban population with sewage connection in basin j	People
$Pop_{con.rur.j}$	Rural population with sewage connection in basin j	People
$FEpnt_{DIN.hum.con.j}$	Fraction of DIN entering rivers from urban and rural sewage systems in basin j	0–1
$N_{total.y.j}$	Total emission of N to air by agricultural source y and basin j	$kg \cdot yr^{-1}$ N
$NH_{3.y.j}$	Total emission of NH_3 to air by agricultural source y and basin j	$kg \cdot yr^{-1}$ N
$N_2O_{y.j}$	Total emission of N_2O to air by agricultural source y and basin j	$kg \cdot yr^{-1}$ N
$NO_{X.y.j}$	Total emission of NO_x to air by agricultural source y and basin j	$kg \cdot yr^{-1}$ N
$M_{F.y.j}$	River export of nutrient form F (DIN, DON, DIP and DOP) to sea from source y	$kg \cdot yr^{-1}$ N or P
$FE_{riv.DIN.outlet.j}$	Fraction of DIN that is exported to the outlet of basin j	0–1
$FE_{riv.DON.outlet.j}$	Fraction of DON that is exported to the outlet of basin j	0–1

Parameter	Description	Unit
$FE_{riv.DIP.outlet.j}$	Fraction of DIP that is exported to the outlet of basin j	0–1
$FE_{riv.DOP.outlet.j}$	Fraction of DOP that is exported to the outlet of basin j	0–1
$D_{DIN.j}$	Fraction of DIN retained in reservoirs and lakes in basin j	0–1
$D_{DIP.j}$	Fraction of DIP retained in reservoirs and lakes in basin j	0–1
$L_{DIN.j}$	Fraction of DIN retained in or/and lost from water systems (e.g., denitrification) in basin j	0–1
$L_{DIP.j}$	Fraction of DIP retained in or/and lost from water systems (e.g., sedimentation) in basin j	0–1
$FQrem_j$	Fraction of nutrient form F (generic for DIN, DON, DIP and DOP) removed from water systems in basin j by water consumption	0–1
$Q_{act.j}$	Actual (act) water discharge at the outlet of basin j after water consumption	$km^3 \cdot yr^{-1}$
$FE_{riv.F.mouth.juT}$	Fraction of nutrient form F (DIN, DON, DIP and DOP) exported from the outlet of upstream tributary (juT) to the river mouth	0–1
$FE_{riv.F.mouth.jmT}$	Fraction of nutrient form F (DIN, DON, DIP and DOP) exported from the outlet of middlestream tributary (jmT) to the river mouth	0–1
$FE_{riv.F.mouth.jmC}$	Fraction of nutrient form F (DIN, DON, DIP and DOP) exported from the outlet of middlestream main channel (jmC) to the river mouth	0–1
$FE_{riv.F.mouth.jdC}$	Fraction of nutrient form F (DIN, DON, DIP and DOP) exported from the outlet of downstream main channel (jdC) to the river mouth	0–1
${}^{juT}FE_{riv.F.outlet.jmC}$ ${}^{juT}FE_{riv.F.outlet.jdC}$	Fractions of nutrient form F (DIN, DON, DIP and DOP) exported from the outlet of upstream tributary (upper case: juT) to the outlets of the main channel in middlestream (lower case: jmC) and downstream (lower case: jdC) sub-basins	0–1
${}^{jmT}FE_{riv.F.outlet.jdC}$	Fraction of nutrient form F (DIN, DON, DIP and DOP) exported from the outlet of middlestream tributary (upper case: jmT) to the outlet of the main channel in downstream (lower case: jdC) sub-basins	0–1
${}^{jmC}FE_{riv.F.outlet.jdC}$	Fraction of nutrient form F (DIN, DON, DIP and DOP) exported from the outlet of middlestream subbasin with the main channel (upper case: jmC) to the outlet of the main channel in downstream (lower case: jdC) sub-basin (the outlet of the this downstream subbasin is the river mouth)	0–1
$D_{F.jmC}$ $D_{F.jdC}$	Fractions of DIN and DIP retained in reservoirs of middlestream (jmC) and downstream (jdC) sub-basins with the main channel (C). These fractions were calculated for sub-basins using equations for $D_{DIN.j}$ and $D_{DIP.j}$ from Table S.	0–1
$L_{F.jmC}$ $L_{F.jdC}$	Fractions of DIN and DIP that is lost from surface waters of middlestream (jmC) and downstream (jdC) sub-basins with the main channel (C). These fractions were calculated using the equation for $L_{DIN.j}$ and $L_{DIP.j}$ from Table S.	0–1
$FQrem_{jmC}$ $FQrem_{jdC}$	Fractions of nutrient form F (generic for DIN, DON, DIP and DOP) that are lost from surface waters of middlestream (jmC) and downstream (jdC) sub-basins with the main channel (C) via water consumption. These fractions were calculated using equations for $FQrem_j$ from Table S.	0–1
${}^{juT}A_{jmC}$ ${}^{juT}A_{jdC}$	Drainage area (A) of the main channel (C) in middlestream (lower case: jmC) and downstream (lower case: jdC) sub-basins that exports nutrients from the outlet of upstream tributary (upper case: juT). This drainage area was calculated as the fraction to the total sub-basin area.	0–1
${}^{jmT}A_{jdC}$	Drainage area (A) of the main channel (C) in downstream (lower case: jdC) sub-basin that exports nutrients from the outlet of middlestream tributary (upper case: jmT). This drainage area was calculated as the fraction to the total sub-basin area.	0–1

Parameter	Description	Unit
${}^{\mathrm{jmC}}\mathrm{A}_{\mathrm{jdC}}$	Drainage area (A) of the main channel (C) in the downstream (lower case: jdC) subbasin that exports nutrients from the outlet of middlestream main channel (upper case: jmC). This drainage area was calculated as the fraction to the total sub-basin area.	0−1

Table S5 Description of how model inputs are processed to basins for the MARINA-Nutrients model of this study

Equations from Table S3	Description of how model inputs are processed to basins
Eq. 2, 11, 12, 19, 26, 34, 35, 42	Synthetic fertilizer application to agricultural land was derived from the MITERRA-Europe model outputs (2017) which were calculated by the CAPRI model per crop type[12]. In this study, the synthetic fertilizer application was converted from the NUTS2 regions to basins and sub-basins (for Danube). First, the synthetic fertilizer applied to each NUTS2 region (kg) was divided by the area of this region (km^2) to get the synthetic fertilizer application per NUTS2 region ($kg \cdot km^{-2}$ N or P). Second, the regional data was assigned to 0.5˚resolution ($kg \cdot km^{-2}$ N or P per grid). Third, the gridded synthetic fertilizer application ($kg \cdot km^{-2}$ N or P) was multiplied by the grid area (km^2) to get synthetic fertilizer application per grid (kg N or P). Finally, the synthetic fertilizer application was summed for basins over corresponding grids to get the total amount of synthetic fertilizer applied per basin ($kg \cdot yr^{-1}$ N or P).
Eq. 3, 11, 13, 19, 27, 34, 36, 42	Animal manure application on agricultural land and manure deposited during grazing were derived from the MITERRA-Europe model outputs (2017) which were calculated as a function of excretion rates per animal type, and number of animals in housing and grazing systems[12]. We accounted for losses of N and P during storage (e.g., denitrification of N, leaching of N and P) before manure application. In this study, the animal manure application was converted from the NUTS2 regions to basins and sub-basins (for Danube). First, the animal manure (sum of manure applied and stayed on agricultural land during grazing) for each NUTS2 region (kg) was divided by the area of this region (km^2) to get the animal manure application per NUTS2 region ($kg \cdot km^{-2}$). Second, the regional data was assigned to 0.5˚resolution ($kg \cdot km^{-2}$ per grid). Third, the gridded animal manure application ($kg \cdot km^{-2}$) was multiplied by the grid area (km^2) to get animal manure application per grid (kg N or P). Finally, the animal manure application was summed for basins over corresponding grids to get the total amount of animal manure applied per basin ($kg \cdot yr^{-1}$ N or P).
Eq. 4, 11, 28, 34	Atmospheric deposition on agricultural land was derived from the MITERRA-Europe model outputs[12]. In this study, the atmospheric deposition was converted from the NUTS2 regions to basins and sub-basins (for Danube). First, the atmospheric deposition for each NUTS2 region (kg) was divided by the area of this region (km^2) to get the atmospheric deposition per NUTS2 region ($kg \cdot km^{-2}$). Second, the regional data was assigned to 0.5˚resolution ($kg \cdot km^{-2}$ per grid). Third, the gridded atmospheric deposition ($kg \cdot km^{-2}$) was multiplied by the grid area (km^2) to get atmospheric deposition per grid (kg N or P). Finally, the atmospheric deposition was summed for basins over corresponding grids to get the total amount of atmospheric deposition per basin ($kg \cdot yr^{-1}$ N or P).
Eq. 5, 11	Biological N_2 fixation by agricultural crops was derived from the MITERRA-Europe model outputs[12]. In this study, the biological N_2 fixation was converted from the NUTS2 regions to basins and sub-basins (for Danube). First, the biological N_2 fixation for each NUTS2 region (kg) was divided by the area of this region (km^2) to get the biological N_2 fixation application per NUTS2 region ($kg \cdot km^{-2}$). Second, the regional data was assigned to 0.5˚resolution ($kg \cdot km^{-2}$ per grid). Third, the gridded biological N_2 fixation ($kg \cdot km^{-2}$) was multiplied by the grid area (km^2) to get biological N_2 fixation per grid (kg N). Finally, the biological N_2 fixation application was summed for basins over corresponding grids to get the total amount of biological N_2 fixation per basin ($kg \cdot yr^{-1}$ N).
Eq. 7	Atmospheric deposition over non-agricultural land ($kg \cdot ha^{-1}$ N) was derived from the Integrated Model to Assess the Global Environment (IMAGE) model outputs (2010) which were in 0.5˚resolution[13]. In this study, the atmospheric deposition was aggregated from 0.5˚grids to basins and sub-basins (for Danube). First, the atmospheric deposition ($kg \cdot ha^{-1}$ N per grid) was multiplied by grid area (km^2) and by fraction of non-agricultural area per grid (0–1) to get total atmospheric deposition per grid (kg N). Then, the atmospheric deposition was summed for basins over corresponding grids to get the total amount of atmospheric deposition per basin ($kg \cdot yr^{-1}$ N).
Eq. 8	Biological N_2 fixation by natural vegetation ($kg \cdot ha^{-1}$ N) was derived from the IMAGE model outputs (2010) which were in 0.5˚resolution[13]. In this study, the biological N_2 fixation was aggregated from 0.5˚grids to basins and sub-basins (for Danube). First, the gridded biological N_2 fixation ($kg \cdot ha^{-1}$ N) was multiplied by grid area (km^2) and by fraction of non-agricultural area per grid (0–1) to get biological N_2 fixation per grid (kg N). Then, the biological N_2 fixation was summed for basins over corresponding grids to get the total amount of biological N_2 fixation per basin ($kg \cdot yr^{-1}$ N).
Eq. 15, 16, 38, 39	Leaching of organic matter from agricultural and non-agricultural soils was calculated by using model parameters from Mayorga et al.[7].

Equations from Table S3	Description of how model inputs are processed to basins
Eq. 30, 31	Weathering of P-contained minerals on agricultural and natural land was calculated by using model parameters from Mayorga et al.[7].
Eq. 9, 17, 32, 40	Exports of N and P from agricultural land by crop harvesting and animal grazing were derived from the MITERRA-Europe model outputs (2017)[12]. The MITERRA-Europe model calculates N and P in harvested grassland and cropland[3]. In this study, the nutrient exports by crop harvesting and animal grazing were converted from the NUTS2 regions to basins and sub-basins (for Danube). First, the nutrient exports for each NUTS2 region (kg) were divided by the area of this region (km^2) to get the nutrient exports per NUTS2 region (kg·km^{-2}). Second, the regional data was assigned to 0.5°resolution (kg·km^{-2} per grid). Third, the gridded nutrient exports (kg·km^{-2}) were multiplied by the grid area (km^2) to get nutrient exports per grid (kg N or P). Finally, the nutrient exports were summed for basins over corresponding grids to get the total amount of nutrient exports per basin (kg·yr^{-1} N or P).
Eq. 49, 81	Natural water discharges were derived from Variable Infiltration Capacity (VIC) macroscale hydrological model[14]. The water discharges were 30-year average data (1981-2010) for 2010 to avoid the influence of climate extremes, and aggregated from the scale of 0.5° grids to the basins. The water consumption (water use) rates were based on the gridded data of the Global *NEWS-2* model [7,15]. Information on the characteristics of reservoirs and (regulated) lakes (e.g., volume) were derived from HydroLAKES[11]. Actual water discharges (after water consumption) were calculated by using the water consumption rates by Strokal et al. [5].
Eq. 24, 25, 47, 48, 56, 57, 66, 67, 70, 71	Total, urban and rural populations were derived from the NCAR database in 0.125° resolution[16]. Population data was projected to 2020 based on SSP2 scenario[17]. First, the total, urban and rural populations were aggregated from 0.125° to 0.5°grids. Then, the total, urban and rural populations were summed for basins over corresponding grids to get the total, urban and rural populations per basin (people·yr^{-1}).
Eq. 56, 57, 66, 67, 70, 71	Inputs of pollutants from sewage systems were quantified as a function of the population that is connected to sewage systems (0–1), the excretion rates of pollutants per person per year (kg·person^{-1}·yr^{-1}) and removal efficiencies of pollutants during treatment (0–1). The data from country scale was converted to 0.5×0.5° gridded format and aggregated to basins and sub-basins (for Danube) following the approach of Strokal et al.[10]. Fractions of urban and rural population connected to sewage systems were derived from the literature[17]. The country scale projections for 2020 were used based on the SSP2-Moderate (SSP2-M) scenario[17]. This dataset was consistent in terms of urban connection rates with the Joint Monitoring Program (JMP) dataset for 2020 based on national reports[18]. However, the dataset of van Puijenbroek et al.[17] had some inconsistencies in rural connection rates of some countries (0% values). Therefore, we considered the JMP data for those countries (e.g., Croatia, Cyprus, Finland, Ireland, Portugal, Sweden) prior to modelling[18]. For rural connection rates of Austria, Bulgaria, Czechia, Estonia, Hungary, Italy, Latvia, Lithuania, Slovakia, UK; JMP data was higher than the SSP2-M 2020 projections. Thus, the JMP data was used for those countries[18]. Nearly 43% of the rural data was taken from van Puijenbroek et al.[17] projections for 2020 based SSP2-M scenario, and the rest (57%) was from the JMP data[18]. First, the country scale sewage system connection (SC) rates for urban and rural population were assigned to 0.5° resolution (SC rates per grid). Second, the gridded fractions were multiplied by the total population (urban and rural) per grid to get the urban and rural populations with SC per grid. Third, the gridded urban and rural populations with SC were summed for basins over corresponding grids to get the urban and rural populations with SC per basin. Forth, the urban and rural populations with SC were divided by the urban and rural populations per basin. The outcome was the faction of urban population with SC per basin (0–1) and the faction of rural population with SC per basin (0–1).
Eq. 59	Data on gross domestic product at purchasing power parity (GDPppp) was derived from the literature[17]. The country scale projection for 2020 was used based on the SSP2-M scenario [17]. First, the country scale GDPppp was assigned to 0.5° resolution (US$·capita^{-1}·yr^{-1}per grid). Second, the gridded GDPppp was multiplied by the total number of people per grid (USD·yr^{-1}). Third, the GDPppp was summed for basins over corresponding grids to get the GDPppp per basin (USD·yr^{-1}). Finally, the basin GDPppp values were divided by the total population per basin to get the GDPppp per capita per basin (USD·capita^{-1}·yr^{-1}). The unit of GDPppp was adjusted to US$2010 (USD2010·capita^{-1}·yr^{-1})[5].
Eq. 24, 25, 47, 48, 56, 57, 58, 66, 67, 68, 70, 71	Excretion or consumption rates of N and P per capita were calculated as a function of the GDPppp following the approach of van Drecht et al.[9]. The consumption rate of P in detergents (laundry and washing) was taken from van Drecht et al.[9] for 2000. First, this consumption rate was assigned to

Equations from Table S3	Description of how model inputs are processed to basins
	0.5° resolution and used for 2010. Second, the gridded consumption rates of P in detergents was multiplied by the total number of people per grid (kg·yr^{-1} P). Third, the P from detergents consumed by total population per grid was summed for basins over corresponding grids to get the P from detergent consumption by total population per basin (kg·yr^{-1} P). Finally, the P from detergents consumption by total population per basin (kg·yr^{-1} P) was divided by the total population per basins to get the P from detergent consumption per capita per basin (kg·capita^{-1}·yr^{-1} P).
Eq. 54, 55, 60, 64, 65, 70, 71	Fractions of N and P removal in wastewater treatment systems (the same for both urban and rural) were derived from the literature[17]. The country scale fractions of N and P removal in wastewater treatment systems were calculated by using removal efficiencies (pollutant dependent) and fractions of people with treatment types per country from the updated version of van Puijenbroek et al.[17]. First, the country scale fractions of N and P removal in wastewater treatment systems were assigned to 0.5° resolution (fractions of N and P removal per grid). Second, the gridded per capita human excretion (kg·capita^{-1}·yr^{-1} N or P) was multiplied by the population (urban and rural) with SC per grid (people) to get the N and P entering sewage systems per grid (kg·yr^{-1} N or P). Third, the N and P entering sewage systems were summed for basins over corresponding grids (kg·yr^{-1} N or P per basin). Fourth, the N and P entering sewage systems per basin was multiplied by removal fractions per grid to get the N and P removed during treatment per grid (kg·yr^{-1} N or P). Fifth, the N and P removed during treatment were summed for basins over corresponding grids (kg·yr^{-1} N or P per basin). Finally, the N and P removed during treatment per basin were divided by the amount of N and P entering sewage systems per basin to get the removal fractions of N and P in wastewater treatment systems (hw_{fremN} and hw_{fremP}) per basin (0–1).
Eq.72	Reactive N emissions to air (i.e., NH_3, N_2O, NO_x) from animal housing and storage systems were derived from the MITERRA-Europe model outputs (2017) which were calculated by using emissions factors[12]. Reactive N emissions from animal housing and storage systems included NH_3, N_2O and NO_x emissions. In this study, each N emission to air was converted from the NUTS2 regions to basins and sub-basins (for Danube). First, the N emissions for each NUTS2 region (kg) were divided by the area of this region (km^2) to get the N emissions to air per NUTS2 region (kg·km^{-2} N). Second, the regional was assigned data to 0.5˚resolution (kg·km^{-2} N per grid). Third, the gridded N emissions (kg·km^{-2} N) were multiplied by the grid area (km^2) to get N emissions to air per grid (kg N). Finally, the N emissions were summed for basins over corresponding grids to get the total amount of N emissions to air per basin (kg·yr^{-1} N). The N emissions to air from animal housing and storage systems were considered in total N emissions to air from agriculture per basin (kg·yr^{-1} N). Reactive N emissions to air from agricultural soils (i.e., NH_3, N_2O, NO_x) were derived from the MITERRA-Europe model outputs (2017) which were calculated by using emissions factors[12]. Reactive N emissions from agricultural soil contained NH_3 emissions from applications of synthetic fertilizer and animal manure, grazing; N_2O emissions from applications of synthetic fertilizer and animal manure, grazing, biological fixation, cultivated peatland and indirect N_2O emissions (i.e., from N leaching and ammonia); and NO_x emissions from applications of synthetic fertilizer and animal manure, grazing. In this study, each N emission to air was converted from the NUTS2 regions to basins and sub-basins (for Danube). First, the N emissions for each NUTS2 region (kg) were divided by the area of this region (km^2) to get the N emissions to air per NUTS2 region (kg·km^{-2} N). Second, the regional data was assigned to 0.5˚resolution (kg·km^{-2} N per grid). Third, the gridded N emissions (kg·km^{-2} N) were multiplied by the grid area (km^2) to get N emissions to air per grid (kg N). Finally, the N emissions were summed for basins over corresponding grids to get the total amount of N emissions to air per basin (kg·yr^{-1} N). To present the total reactive N emissions from agriculture, we summed the N emissions from animal housing and storage systems and from agricultural soil.

Note: The model equations and data sources are described in Tables S3, S4 and S6.

Table S6 Sources of the MITERRA-Europe model inputs

Input data description	Years	Source
Fertilizer use data at country level in the EU28	2016–2018	[19]
Natural grassland data at NUT2 level	2016–2018	[20]
Animal numbers, crop areas and crop yields[a]	2015	CAPRI model based on Eurostat[21]
Soil data on coarse fragments, texture, pH, organic C content, bulk density and data on perennial grass cover		ESDB and LUCAS[22]
N excretion of animals and CH_4 emissions from manure management and enteric fermentation	2017	Common Reporting formats (CRFs) database[23]
Arable farm size, farming system, crop rotation, livestock units, and areas with organic farming, irrigation, crop cover, and grass cover	2016–2018	[24]
N deposition	2010	[25]
NH_3 emission factors and the implementation of NH_3 mitigation measures on national level		Greenhouse Gas - Air Pollution Interactions and Synergies (GAINS) model[26,27]
N_2O emission factors and global warming potentials		Reports of the Intergovernmental Panel on Climate Change (IPCC) for National Greenhouse Gas Inventories[28]
NO_x emission factors		[29]
N surface runoff fraction: Fraction of soil N input by inorganic and organic fertilizers, calculated as a function of slope class, land use, precipitation surplus, soil type and depth to rock		[3]
N leaching fraction: Fraction of soil N surplus, calculated as a function of soil type, land use, SOC content, precipitation surplus, temperature and rooting depth		[3]

Note: [a] Most of the data is derived from Eurostat, but a gap filling procedure and consistency check is applied[12].

Table S7 Description of the data used for model validation

Parameters	Type	Number of basins	Number of observations	Years	Explanation	Reference
DIN, DON, TDN, DIP, TDP	Concentration	45	148	2000–2017	We calculated yearly average concentrations (mg·L^{-1}) out of weekly/monthly measurements prior to compare with the annual model results. We considered only the stations close to or at the river mouth for the study area. Measured loads (kg·yr^{-1}) were calculated from concentrations multiplying by water discharges. Measured yields (kg·km^{-2}·yr^{-1}) were calculated from concentrations dividing by basin areas and multiplying by water discharges.	[30]
DIN, DON, DIP, DOP	Yield	19	34	1990–2000	We compared our annual river export yields (kg·km^{-2}·yr^{-1}) by the observed yields of DIN, DON, DIP and DOP (kg·km^{-2}·yr^{-1}) that were used to validate a nutrient model including Europe (Global *NEWS-2* model) for the period of 1990–2000. Measured loads (kg·yr^{-1}) were calculated from yields multiplying by basin areas. Measured concentrations (mg·L^{-1}) were calculated from yields multiplying by basin areas and dividing by water discharges.	[7]
DIN, TN, DIP, TP	Load	4	16	1990–2012	We compared total N (TN) and total P (TP) loads (kg·yr^{-1}) with the loads of total dissolved N (TDN) and total dissolved P (TDP) from the MARINA-Nutrients model. Our model did not calculate the particulate forms of N (PN) and P (PP) (TN is the sum of DIN, DON and PN; TP is the sum of DIP, DOP and PP). Measured yields (kg·km^{-2}·yr^{-1}) were calculated from loads dividing by basin areas. Measured concentrations (mg·L^{-1}) were calculated from loads dividing by water discharges.	[31]
DIN, DON, TN, DIP, TP	Load	1	9	1980–1993, 2001	See the explanation above for TN and TP, and for the calculations of yield and concentration from load.	[32]
TN, TP	Load	1	4	1997–2003, 2010–2014	See the explanation above for TN and TP, and for the calculations of yield and concentration from load.	[33]
DIN, DIP	Concentration	1	2	2001–2010	Measured loads (kg·yr^{-1}) were calculated from concentrations multiplying by water discharges. Measured yields (kg·km^{-2}·yr^{-1}) were calculated from concentrations dividing by basin areas and multiplying by water discharges.	[34]
TN, TP	Load	5	10	1995	See the explanation above for TN and TP, and for the calculations of yield and concentration from load.	[35]
DIN, DON, TN, DIP, DOP, TP	Load	1	30	2012–2016	See the explanation above for TN and TP, and for the calculations of yield and concentration from load.	[36]
TN, TP	Load	5	10	1995–2014	See the explanation above for TN and TP, and for the calculations of yield and concentration from load.	[37]

Note: Number of basins indicates the river basins where observational data is available. Number of observations indicates total number of observations per data source (observation per parameter per year). Year indicates the period of the measurements or observed data (i.e., load, yield). Explanation describes our methods to process the data for model validation.

Table S8 Inputs of N and P to land, and their export from agricultural land by crop harvesting and animal grazing

Inputs to land and export from agricultural land	N ($Tg\cdot yr^{-1}$)	P ($Tg\cdot yr^{-1}$)
fertilizer application	14	0.63
manure	10.2	0.96
excretion of population not connected to sewage systems	0.29	0.064
biological fixation by crops	1	-
atmospheric deposition over agricultural areas	3.7	0.096
biological fixation by natural vegetation	1.6	-
atmospheric deposition over non-agricultural areas	3.6	-
nutrient export from agricultural land by crop harvesting and animal grazing	18	1.2

Note: Source: MITERRA-Europe model[12] for agricultural land and the IMAGE model[13] for non-agricultural land.

Table S9 Comparison of NH_3, N_2O and NO_x emissions with other modelling studies for Europe ($Gg\cdot yr^{-1}$ N)

N source	Emission source	This study	Other studies			
		EU28 (2017)	EU25 (2002)[a]	EU27 (2000)[b]	EU27 (2000)[c]	EU27 (2000)[d]
NH_3	Housing and storage systems	1487	1428	1189	1279	1048
	Applied fertilizer	677	678	1413	540	798
	Applied manure	959	759		823	683
	Grazing	277	201	271	231	319
	Total	3401	3066	2873	2873	2848
N_2O	Housing and storage systems	22	48	55	54	52
	N applied	217[e]	316[f]	242[f]	208[f]	289[f]
	Grazing	67	67	124	66	92
	Indirect emissions[g]	67	80	43	51	76
	Total	374	511	464	379	510
NO_x	Housing and storage systems	25	32	20	20	0
	N applied	130[h]	16	123	28	23
	Grazing	-	59	63	29	196
	Total	155	107	206	77	219

Note: [a] Results are estimated by IDEAg model in the EU-25 for the year 2002[38]. [b] Results are estimated by INTEGRATOR model in the EU-27 for the year 2000[39]. NH_3 emissions from applied fertilizer include emissions through fertilizer and manure applications[38]. [c] Results are estimated by MITERRA model in the EU-27 for the year 2000[39]. [d] Results are estimated by IMAGE model in the EU-27 for the year 2000[40]. [e] In this study, N applied includes N_2O emissions from synthetic fertilizer and manure applications. [f] N applied includes N_2O emissions through synthetic fertilizer and manure applications, deposition, mineralization, fixation and crop residues[38]. [g] Indirect N_2O emissions include N_2O emissions from N leaching and ammonia. [h] In this study, NO_x emissions from the soil (e.g., synthetic fertilizer and manure applications) are indicated as N applied.

Table S10 Share of diffuse and point sources in river export of N and P in Europe (Gg·yr^{-1} N or P)

River export to seas		Arctic Ocean	Atlantic Ocean	Baltic Sea	Black Sea	Mediterranean Sea	North Sea
TDN	Total export	35	759	456	286	595	576
	Diffuse sources	34.5	672	412	241	481	487
	Point sources	0.6	87	44	45	114	89
TDP	Total export	1.6	29	19	11	31	21
	Diffuse sources	1.5	14	11	6	10	8
	Point sources	0.1	15	8	5	21	13

Source: The new MARINA-Nutrients model for Europe.

Table S11 Comparison of N budget of agricultural land in the EU including N emissions from housing systems and soil (NH_3, N_2O, NO_x and N_2) (kg·ha^{-1}·yr^{-1} N)

Source	MITERRA-Europe (2017)	INTEGRATOR (2010)
Fertilizer	63.5	72
Excretion	57	54
Deposition	17	10
Biological N fixation	4.5	7
Total N input	142	145[a]
Crop uptake	82	92
Emissions to air (NH_3, N_2O, NO_x)	18	19
Losses to surface waters by runoff	9	8
Denitrification (N_2)	26	17
Leaching to groundwater	7	9
Total N output	142	145

Note: Source from MITERRA-Europe model. [a] Results are estimated using INTEGRATOR model for total agricultural land (cropland and grassland) in the EU (including the UK) for the year 2010[41]. Total N input includes biosolids (1 kg·ha^{-1}·yr^{-1}) and mineralization (1 kg·ha^{-1}·yr^{-1}).

Table S12 Comparison of annual total dissolved N (TDN) export to European seas by the source with other modelling studies for Europe ($\text{Gg}\cdot\text{yr}^{-1}$ N)

Pollution source	This study	MARINA-Nutrients (Global, version 1.0 with IMAGE data)	MARINA-Nutrients (Global, version 1.0 with MAgPIE data)	GREEN	IMAGE-GNM	Global *NEWS-2*	Global *NEWS-2*
	2017–2020	2010	2010	2012	2000	2000	1995
Sewage systems	379	444	444	914			
Population unconnected to sewage systems	12	6	6	84			
Agriculture	1435	1243	1407	1900			
Atmospheric deposition (natural)	374	374	346	964			
Biological fixation (natural)	158	158	131				
Organic matter leaching (natural)	343	338	326				
Total	2701[a]	2563[b]	2660[c]	3862[d]	3038[e]	2518[f]	2300[g]

Note: [a] Results are estimated by MARINA-Nutrients model as the river export of total dissolved N (TDN) for the period 2017–2020. TDN is the sum of dissolved inorganic N (DIN) and dissolved organic N (DON). [b] Results are estimated by MARINA-Global-IMAGE model as the river export of total dissolved N (TDN) for the year 2010[13]. [c] Results are estimated by MARINA-Global-MAgPIE model as the river export of total dissolved N (TDN) for the year 2010. [d] Results are estimated by GREEN model as the river export of total N (TN) to the European seas for the year 2012[42]. Atmospheric deposition is the sum of anthropogenic and natural, and sewage systems include industrial wastewater as well. [e] Results are estimated by IMAGE-GNM model as the river export of total N (TN) for the year 2000[43]. [f] Result is estimated by Global NEWS-2 model as the river export of total dissolved N (TDN) for the year 2000[7]. [g] Result is estimated by Global NEWS-2 model as the river export of total dissolved inorganic N (DIN) for the year 1995[8].

Table S13 Comparison of annual total dissolved P (TDP) export to European seas by the source with other modelling studies for Europe ($\text{Gg}\cdot\text{yr}^{-1}$ P)

Pollution source	This study	MARINA-Nutrients (Global, version 1.0 with IMAGE data)	GREEN	GREEN	IMAGE-GNM	Global *NEWS*
	2017–2020	2010	2012	2005	2000	2000
Sewage systems	64	81	142			
Population unconnected to sewage systems	0.5	1	17			
Agriculture	27	23	88			
P weathering (natural)	4	4	44			
Organic matter leaching (natural)	18	18				
Total	114[a]	127[b]	290[c]	282[d]	328[e]	235[f]

Note: [a] Results are estimated by MARINA-Nutrients model as the river export of total dissolved P (TDP) for the period 2017–2020. TDP is the sum of dissolved inorganic P (DIP) and dissolved organic P (DOP). [b] Results are estimated by MARINA-Global-IMAGE model as the river export of total dissolved P (TDP) for the year 2010[13]. [c] Results are estimated by GREEN model as the river export of total P (TP) to the European seas for the year 2012[42]. Sewage systems include industrial wastewater as well. [d] Result is estimated by GREEN model as the river export of total P (TP) to the European seas (i.e., Atlantic Sea, Baltic Sea, Black Sea, Mediterranean Sea, North Sea) for the year 2005[44]. Black Sea includes discharges from Turkey. [e] Results are estimated by IMAGE-GNM model as the river export of total P (TP) for the year 2000[43]. [f] Result is estimated by Global *NEWS-2* model as the river export of total dissolved P (TDP) for the year 2000[7].

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