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EVALUATION

Evaluation of the Nitrates Directive
(Council Directive 91/676/EEC)

{SWD(2026) 235 final}

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ANNEX XIV. THE ROLE OF THE NITRATES DIRECTIVE IN REDUCING NITRATE LEVELS IN THE MEMBER STATES

This annex illustrates the impact of the Nitrates Directive (ND), in terms of reducing nitrates pollution, through examples from Member States based on national and EU reporting, and scientific publications. It includes a set of illustrative examples of impacts in nitrate levels across the EU Member States and regions which can be linked to the implementation of the Nitrates Directive. The following criteria were used for the selection of examples to present a variety of relevant aspects, such as: (i) the long-term development of nitrate concentrations in groundwater, root zones, and surface waters; (ii) the lag time between changes in agricultural practices and their impact on nitrate concentrations; (iii) the parallel evolution of the nitrogen balance in agricultural soils and nitrate concentrations in groundwater; (iv) the long-term development of phosphorus concentrations in surface waters; and (v) the development of water quality in geographically diverse regions across the EU27.

The first **four examples cover the whole period of implementation of the Nitrates Directive from 1991 to 2023** and highlight cases of increasing trends that have been reversed as well as of significant reductions in nitrates concentrations during the first two decades of implementation of the directive:

1. Temporal evolution of the groundwater nitrate concentrations in Denmark between 1940s and 2020: the example shows the parallel evolution of the nitrogen balance for agricultural soils and nitrate concentrations in groundwater, as well as the lag time between changes in agriculture practices and their impact on nitrates concentrations.
2. Development of the nitrate load and concentration in surface waters in France between 1990 and 2022: this example shows the impact of changed agricultural practices in reducing nitrates concentrations in surface waters and discusses the lag time between changes in agriculture practices and their impact on nitrates concentrations.
3. Temporal evolution of nitrate concentrations in the root zone and upper oxic groundwater as well as leaching between 1990 and 2023 in a limited number of catchments in Denmark chosen to be representative of the country in general: this example shows the effect of measures taken under the ND in terms of the evolution of nitrates concentrations in the root zone and upper oxic groundwater and modelled leaching.
4. Temporal evolution of nitrate concentrations in the root zone and surface waters in the Netherlands between 1992 and 2023, based on a specific monitoring network: this example shows the effect of measures taken under the ND in terms of the evolution of nitrates concentrations in the root zone, as well as the evolution of average surface water nitrate concentrations in agricultural areas.

The next **three examples focus on the years 2008-2023 corresponding to the last 15 years of the period examined in this evaluation** and are based on the data reported by the Member States under the ND. These examples aim to provide a more nuanced view of nitrate concentration trends in surface and groundwaters across the EU from 2016 to

2023 as reported in section 3 of the evaluation report. While the evolution at EU level shows stagnation of results or even increasing concentrations for surface waters, the picture is not the same in all Member States, as shown in these examples:

5. Temporal evolution of the nitrate concentrations in Austria with a focus on the evolution in the last 15 years studied in the evaluation.
6. Temporal evolution of the nitrate concentrations in Romania with a focus on the evolution in the last 15 years studied in the evaluation.
7. Temporal evolution of the nitrate concentrations in surface waters in Slovakia with a focus on the evolution in the last 15 years studied in the evaluation.

A last example illustrates the interplay between the Nitrates Directive and the UWWTD in the Danube River between 1996 and 2021. It shows the rapid improvements resulting from the UWWTD implementation especially in P reductions, and the effects, albeit slower and less significant, of the Nitrates Directive in continuous reduction of nitrates concentrations. This is despite a continuous contribution of legacy nitrogen (accumulated nitrogen in soil, saturated zone and groundwater before 1991) and the fact that agricultural inputs in the lower Danube region have increased significantly since 1991.

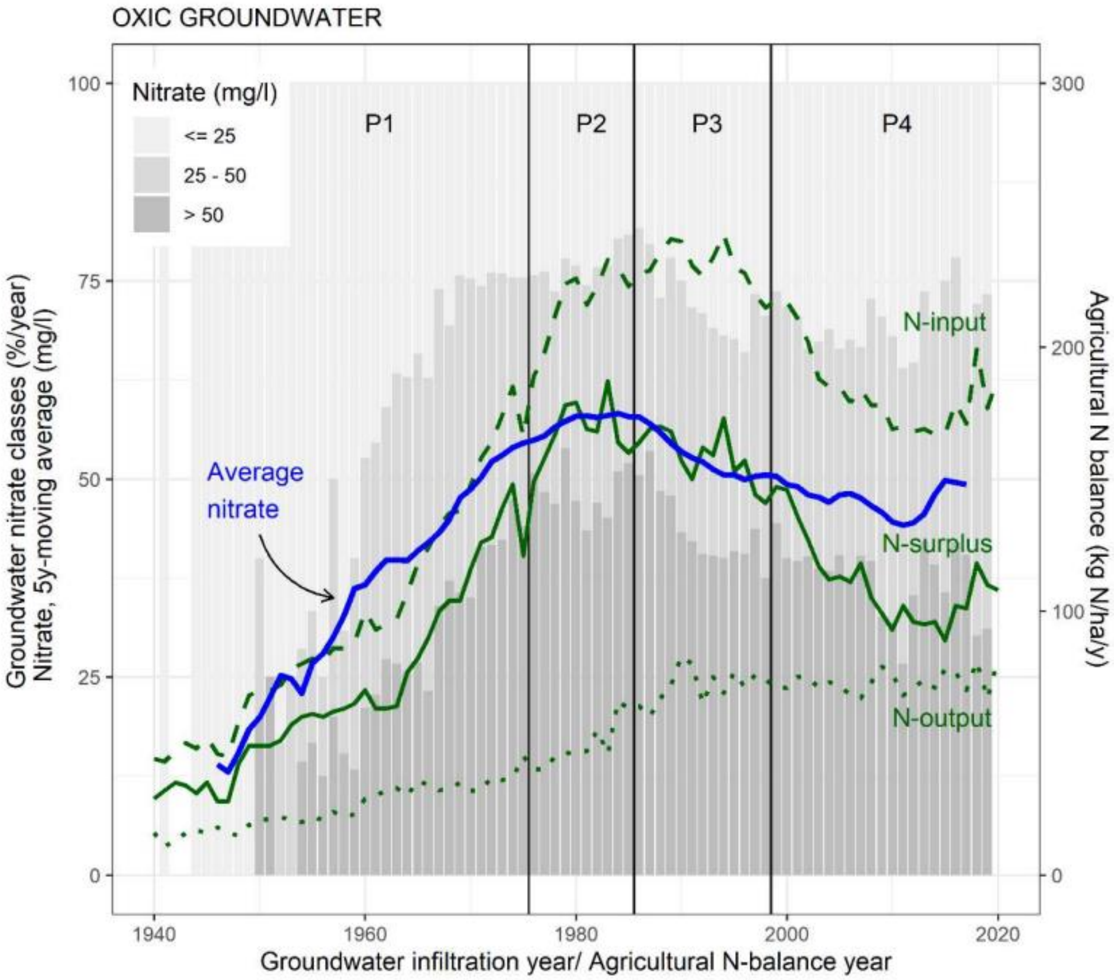
8. Trends in nitrogen and phosphorus dynamics along the Danube River between 1996 and 2021

1. Development of nitrates in Denmark groundwater between 1940s and 2020

Denmark measured nitrate concentrations in a sample of groundwater points dated according to the year of infiltration. The Figure 1 also shows the evolution of nitrogen inputs, offtake in crops and the nitrogen balance. (Source: Report of Denmark under Article 10 of the Nitrates Directive for the period 2020-2023.)[1]

Groundwater age determination allows a relationship to concentrations of nitrate with "time of recharge" instead of "time of sampling". In this way, direct comparison between nitrate in groundwater and N loss from agriculture is possible.

Figure 1 Long-term evolution of nitrates in groundwater in Denmark



According to the Danish Report, statistical nitrate trend analyses at a national level using CFC dating (using CFC gasses dissolved in groundwater as a dating method) gave a strong indication of a trend reversal of nitrate in Danish oxic groundwater since the 1980s due to reduced nitrogen leaching in Danish agriculture (Hansen et al., 2011). A recent assessment by Hansen & Larsen (2016) and Hansen et al. (2017) using both CFC and tritium/helium dating, support these earlier findings showing significant correlation between nitrate in oxic groundwater and nitrogen surplus in agriculture at the overall Danish national level (Figure 1).

[1] See also Hansen et al 2017 "Groundwater nitrate response to sustainable nitrogen management" (DOI:10.1038/s41598-017-07147-2)

In the period 1940-1985, nitrate concentrations in groundwater were increasing in wells monitoring recharged groundwater due to the development of Danish agriculture with increasing input of N fertilizers and N surplus. Since then, a decreasing trend in the oxic groundwater has been observed from 1985 – 2012. The age of groundwater in the oxic groundwater monitoring points is up to 50 years. Thus, an increase in nitrate concentrations still takes place in many monitoring points due to the high input of nitrogen in agriculture in the period from 1940-1985. Figure 1 also shows that in the last decade or so, the decrease in nitrogen surplus has halted, and instead a minor increase can be detected, probably due to changes in regulatory practices.

To underpin these conclusions, the development in the nitrate concentration in individual monitoring points, i.e. screens, in the national groundwater monitoring network with oxic groundwater has been investigated with a linear regression analysis of nitrate time series from the individual monitoring points, as published in Hansen et al. (2017). Figure 2 shows the accumulated result of the 665 calculated nitrate trends for the individual monitoring points distributed over the four (infiltration) periods with both statistically significant and non-significant trends at a 95% confidence level. Figure 2 shows a clear trend towards a declining nitrate content in oxic groundwater, both when only the development in the statistically significant trends is considered and when both significant and non-significant trends are examined. It also shows that there has not been any major change in the nitrate trends from the 1986-1996 period to the 1999-2020 period.

Figure 2 Long-term evolution of nitrate concentration trends in groundwater in Denmark

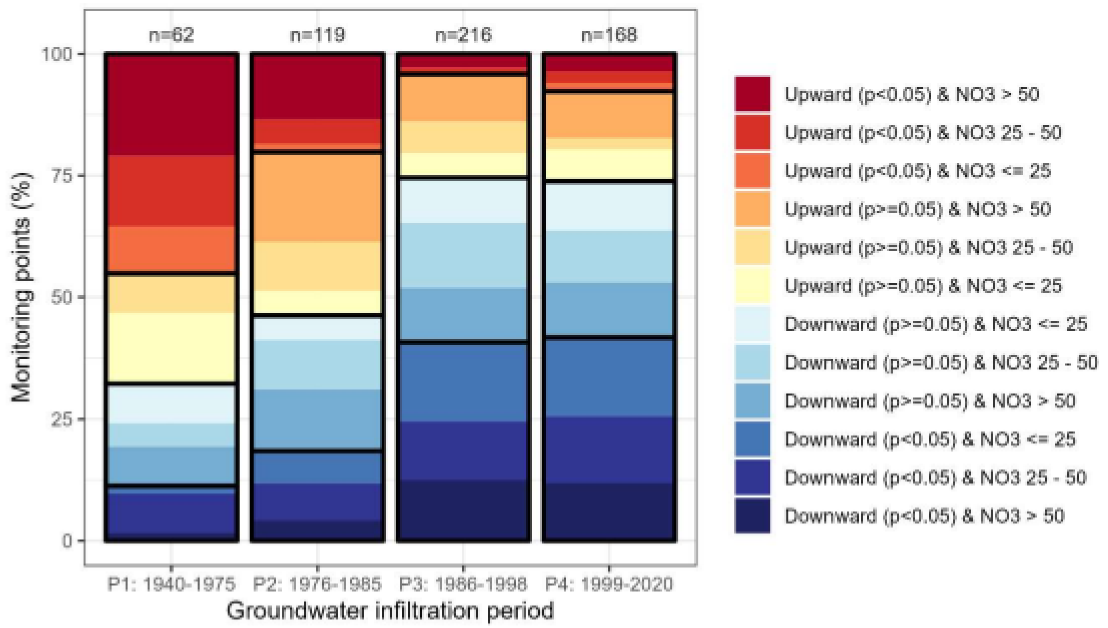


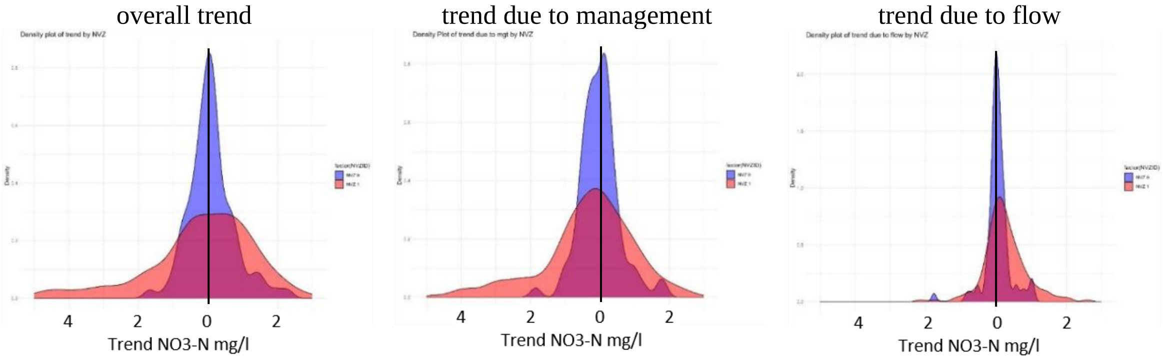
Figure 3.27. National groundwater monitoring network: Oxic groundwater only: 665 nitrate trends in in oxic groundwater for 4 periods based on the year of groundwater formation. The analysis includes a total of 6,193 samples from 364 screens, where the time series cover at least 8 years. At the top of each column is the number of monitoring points with trends for the period. Both statistically significant and non-significant nitrate trends are shown at 95% confidence levels. The figure is based on data collected from 1988-2012 (Thorling et al., 2024).

2. Development of the nitrate load and concentration in surface waters in France between 1990 and 2022

A scientific publication from the Joint Research Centre “30 years of nitrate load and concentration in French rivers: environmental and policy impacts”[2] examines three decades of nitrate trends in France’s surface waters, focusing on the effectiveness of the EU Nitrates Directive (91/676/EEC) and related nutrient management strategies. Excess nitrates from agriculture remain a key water quality issue across Europe, with France among those affected. Additionally, France alone represents more than 17 % of all utilised agricultural area in the EU. Using long-term data (1990–2022), Weighted Regressions on Time, Discharge, and Season (WRTDS) a statistical model was applied to distinguish between changes driven by management practices (e.g., fertilizer regulation, manure control, wastewater treatment) and those caused by hydrological variability (e.g., rainfall and flow changes).

The study analysed 268 monitoring stations across France and nine major river basins (Adour, Dordogne, Garonne, Loire, Meuse, Rhine, Rhône, Seine, Vilaine), covering nearly half the French territory. Results show that management measures under the Nitrates Directive have significantly reduced nitrate loads, particularly in Nitrate Vulnerable Zones (NVZs), where mandatory best practices were implemented. Across France, nitrate loads decreased by roughly 30,000 tons of nitrate nitrogen since the 1990s. Within NVZs, management-driven nitrate reductions averaged –0.6 mg NO_3-N L^{-1} yr^{-1}, while outside NVZs the effect was significantly lower. This also translated to trend in the nitrate concentrations, where one of the findings was that the beneficial impact of management, in terms of reducing nitrate levels, was significantly more pronounced within NVZ areas. Hydrological factors, however, often counteracted these gains, with flow-related changes increasing nitrate concentrations at many sites (Figure **3**).

Figure 3 Trend in NO3-N concentrations in mg/l (blue – outside NVZs, red – inside NVZs)



[2] Bouraoui F., Udias A., Vigiak O., Grizzetti B., 2026. “30 years of Nitrates Directive in a changing climate: Environmental and policy impacts on nutrient pollution of French rivers”. Journal of Hydrology: Regional Studies. Vol.65, 103445, ISSN 2214-5818, https://doi.org/10.1016/j.ejrh.2026.103445.

In NVZs, which are typically regions of intensive agriculture, showed higher absolute nitrate concentrations than non-NVZ areas, but also stronger improvement trends.

Furthermore, temporal analyses revealed an approximately five-year lag time between reductions in agricultural nitrogen inputs and observable water quality improvements, exceeding the Directive's four-year reporting cycle. This lag suggests that assessments of policy effectiveness may underestimate long-term progress.

At the river basin scale, six of the nine major basins (Adour, Garonne, Dordogne, Rhine, Seine, and Vilaine) exhibited clear declines in nitrate loads and concentration in surface waters linked to management, while others such as the Rhône and Meuse showed persistent increases, likely due to legacy nitrate sources in soils and groundwater. The overall nitrate export from the nine major rivers fell by nearly 19% (≈61 million kg N) between 2003 and 2022, with about half of this decline attributed to nutrient management measures and half to hydrological changes.

Figure 4 Annual nitrate concentration for no flow impact (window 15) and no flow interannual variability (window 7) for the most downstream part of the large French river basins.

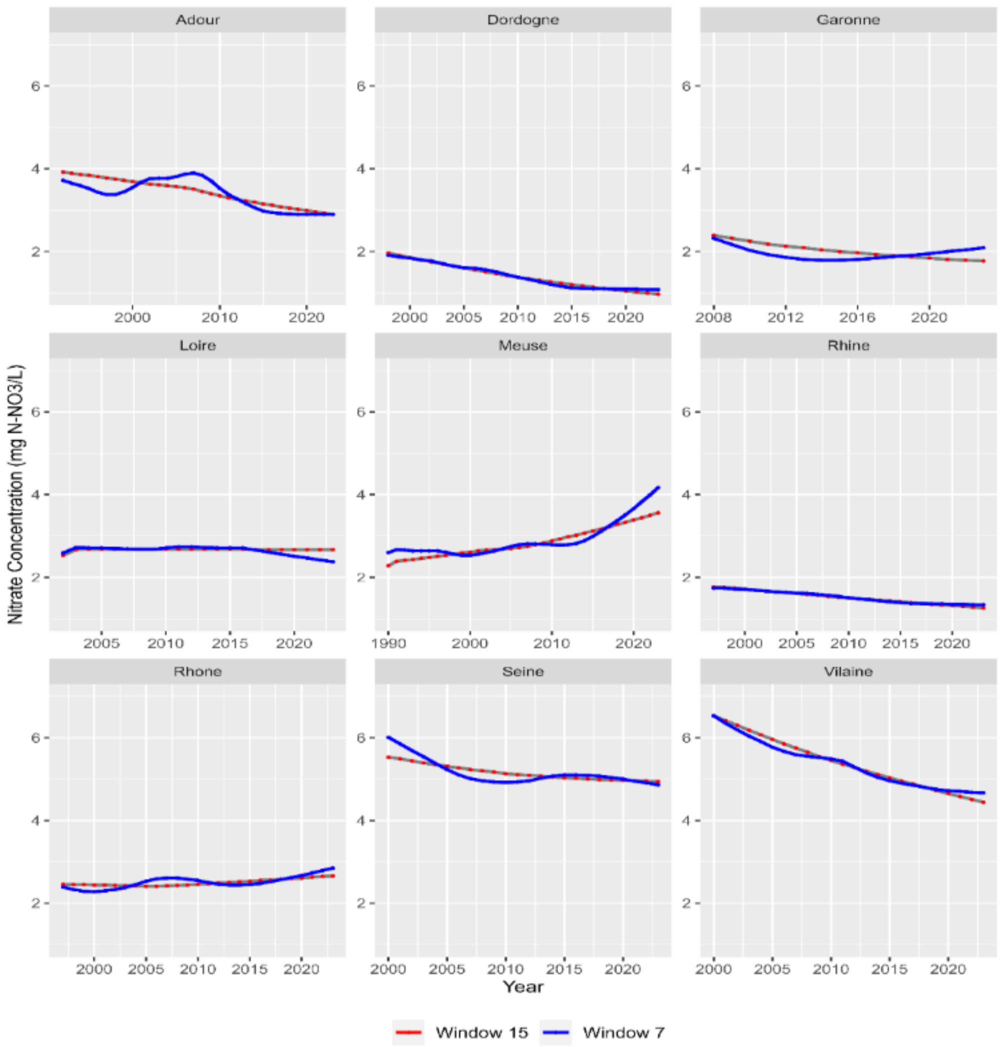
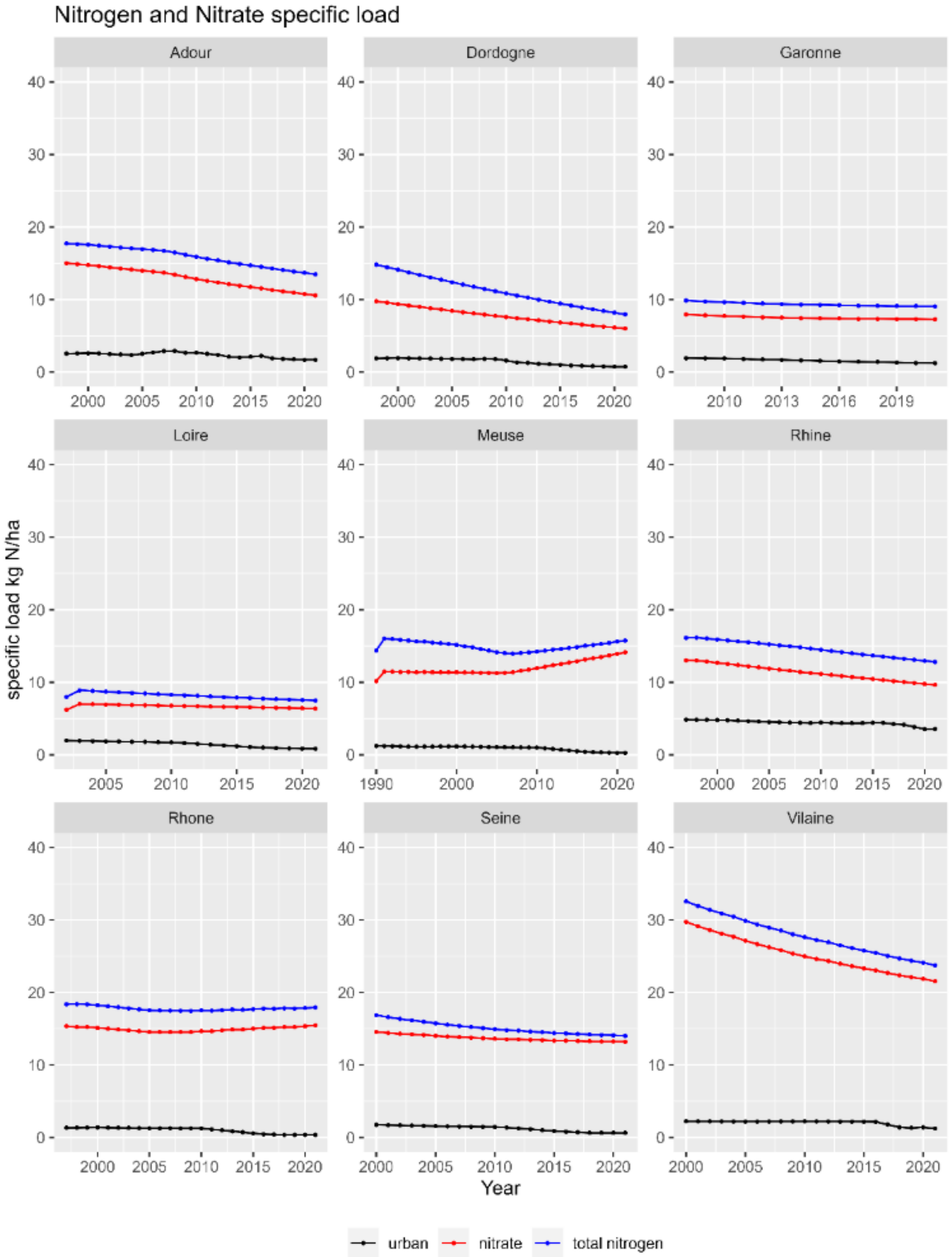


Figure 5 Specific nitrate loads attributable to management (no-flow impact)



Despite these improvements, nitrate reductions have been smaller than those observed for phosphorus, resulting in a rising nitrogen-to-phosphorus ratio that risks destabilizing aquatic ecosystems and promoting eutrophication.

The study emphasizes that nitrate management is complicated by diffuse agricultural sources, groundwater legacy effects, and climate-driven hydrological changes. The study argues for integrated nutrient management, combining stricter enforcement of the Nitrates Directive with complementary measures such as precision farming, and floodplain restoration.

3. Evolution of nitrate leaching and nitrate concentrations in Denmark between 1990-2023

To evaluate the effects of the measures of the nitrates action programme, Denmark has implemented a specific monitoring programme (Agricultural Catchment Monitoring Programme) in 6 small agricultural catchments measuring nitrate concentrations in root zone water (1m below ground level) and concentrations in upper oxic groundwater (1.5-5m below ground level)-. Contrary to measuring impact on overall groundwaters which may take several decades to become visible, this type of monitoring will very rapidly show the effect of the measures on nitrates leaching. Denmark has monitoring data going back to the start of the implementation of the Nitrates Directive and has further developed modelling of the effects of measures on the evolution of nitrate leaching from 1991 to 2023. [3]

Measurements of nitrate in water leaving the root zone and in upper oxic groundwater

Based on data from the Agricultural Catchment Monitoring Programme of Denmark, the development of nitrate concentrations in the root zone (flow-weighted) and upper oxic groundwater are shown as annual average values for loamy and sandy soils in, respectively, for the period 1990/91 to 2022/23 (see Figure 6). The figures clearly show that nitrates concentrations have decreased in the period 1991-2015.

In the loamy catchments, the measured nitrate concentrations in root zone water decreased from 61-155 mg/1 in the 5-year period 1990/91-1994/95 to 37-66 mg/1 in the 5-year period 2011/12-2015/16. In the latest 5-year period 2018/19-2022/23 the nitrate concentrations have varied from 66 to 116 mg/l. In the sandy catchments, the nitrate concentration decreased from 73-192 mg/l in the 5-year period 1990/91-1994/95 to 54-73 mg/l in the 5-year period 2011/12-2015/16. In the latest 5-year period 2018/19-2022/23 the concentrations have varied from 61 to 113 mg/l.

In the upper oxic groundwater (1.5-5.0 m below ground level), nitrate concentrations were lower than in the root zone water, especially in loamy catchments, indicating nitrate reduction between the bottom of the root zone and the uppermost groundwater.

In the oxic groundwater, the largest decrease in nitrate concentrations is observed in the first half of the monitoring period. For the loamy catchments, the average nitrate concentration is below the groundwater limit value of 50 mg/l in the whole monitoring period. For the sandy catchments, the average nitrate concentration in the oxic groundwater is above the limit value of 50 mg/l for most of the monitoring period. In 2023, the average nitrate content is 72 mg/l and 36 mg/l in the sand and loamy catchments, respectively. In contrast to the early years, there appears to be a trend of increasing nitrate concentrations since around 2015 in the loamy catchments and since around 2007 or 2012 in the sandy catchments.

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[3] Source: Danish Ministry for the Green Transition (2024) Report on the implementation of the Nitrates Directive in Denmark for 2020-2023.

Figure 6 Development of nitrate concentrations in the root zone (flow-weighted) and upper oxic groundwater in Denmark

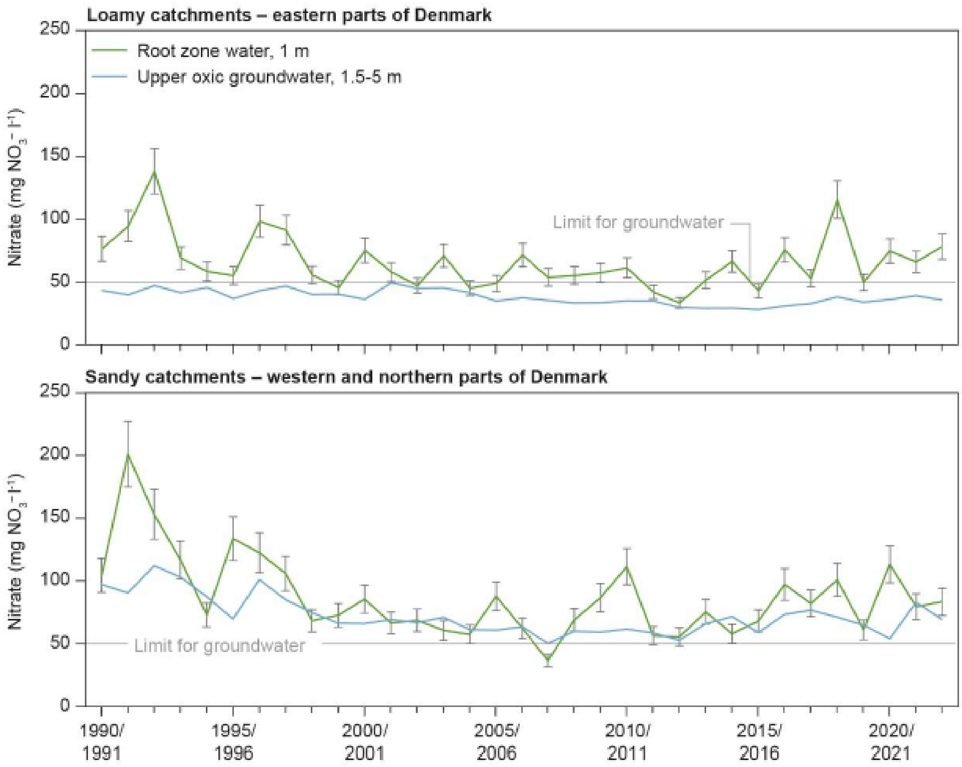


FIGURE 4.8 Annual flow-weighted nitrate concentrations measured in root zone water (1 m below ground level) and annual average nitrate concentrations measured in upper oxic groundwater (1.5-5 m below ground level), in the Agricultural Catchment Monitoring Programme 1990/91 to 2022/23. Error bars on the root zone data indicate variation in percolation as precipitation varied on local scale within a DMI 10 x 10 km^2 precipitation grid. Further details om the variation in data, i.e. standard deviations on measured groundwater concentrations, are presented in the annual report for the Agricultural Monitoring Programme (Blicher-Mathiesen et al., 2024).

Evolution in nitrate leaching 1990-2023

The modelled nitrate leaching from the agricultural areas in the monitored catchments in Denmark was calculated using collected data for crops and fertilization for the period 1990 to 2023 (representing the hydrological years 1990/91 to 2023/24). The modelling[4] shows the effects on nitrate leaching of measures introduced to mitigate nutrient losses from agriculture. The modelled leaching is shown in Figure 7 below as an average for sandy and loamy catchments, respectively.

[4] The modelling is carried out for climate normalised growth conditions, i.e. averaging the model output for a 20-year period: The model is run for each year in the 20-year period and model outputs are then averaged for the period. The climatic data used cover the period 1990-2010. Actual measurements of nitrate leaching will show higher annual variations than the climatic average of the modelled values as the measurements depend on the actual climate. The period 1990-2010 covers a period where the Danish precipitation data were measured using the same method. From 2011, there was a change in both the measurement method and the number of stations available, which may influence the modelled water balance, and thereby influence the modelled nitrate leaching

Figure 7 Simulation of the nitrate leaching in Denmark

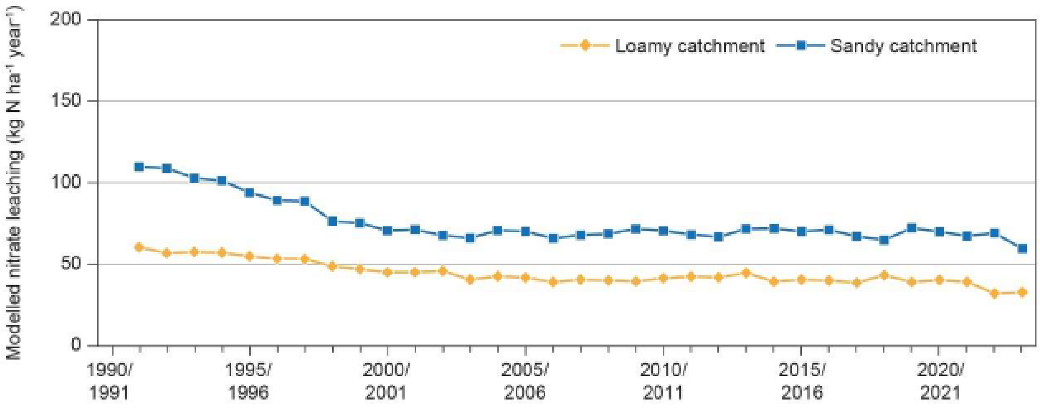


FIGURE 4.7 Simulation of the nitrate leaching using the NLES5 model in a standard climate for the fields of three loamy and two sandy catchments within the Agricultural Catchment Monitoring Programme 1990/91-2023/24.

The Danish Report explains that overall, a decrease in the modelled nitrate leaching of 46 % has been achieved for the entire period 1991 to 2023. The decrease in nitrate leaching is particularly marked in the first period of implementation of the Nitrates Directive, with a 37% decrease from 1991 to 2003.

For the loamy catchments, modelled annual nitrate leaching was relatively stable around 40 kg N ha-1 during the period 2003-2014 decreasing to a level below 40 kg N ha-1 in the period 2015-2022. In 2022/23 and 2023/24 the simulated leaching decreased to 32-33 kg N ha-1 for the loamy catchments, which are the lowest values simulated for the entire period 1991-2023, which is caused by the modelled effect of an increased area with catch crops. For the sandy catchments, the modelled annual nitrate leaching was relatively stable around 70 kg N ha-1 during the period 2003-2022. In 2023/24, the simulated leaching decreased to 60 kg N ha-1 for the sandy catchments. The lower modelled leaching after 2013 is mainly due to more cover crops after cereals and maize.[5]

[5] The trends in nitrate concentrations are not everywhere reflected in similar trends in the nitrate leaching, especially since 2015. The Danish report explains that this may be related to the development in the water balance.

4. Development of the nitrate concentrations in root zone and surface waters in the Netherlands between 1990s and 2023[6]

To evaluate the effects of the measures of the nitrates action programme, the Netherlands has implemented a specific monitoring programme measuring nitrate concentrations in root zone water and in surface waters near a small number of farms in each of the regions representing the different soil types[7]. Contrary to measuring impact on overall groundwaters which may take several decades to become visible, this type of monitoring will very rapidly show the effect of the measures on nitrates leaching. The Netherlands has monitoring data going back to the start of the implementation of the Nitrates Directive for the sandy soil regions and since 1998 for the other regions. Figure 8 provides the evolution of the average root zone nitrate concentration per soil type.

Figure 8 Nitrate concentration in leachate from agricultural parcels in the Netherlands

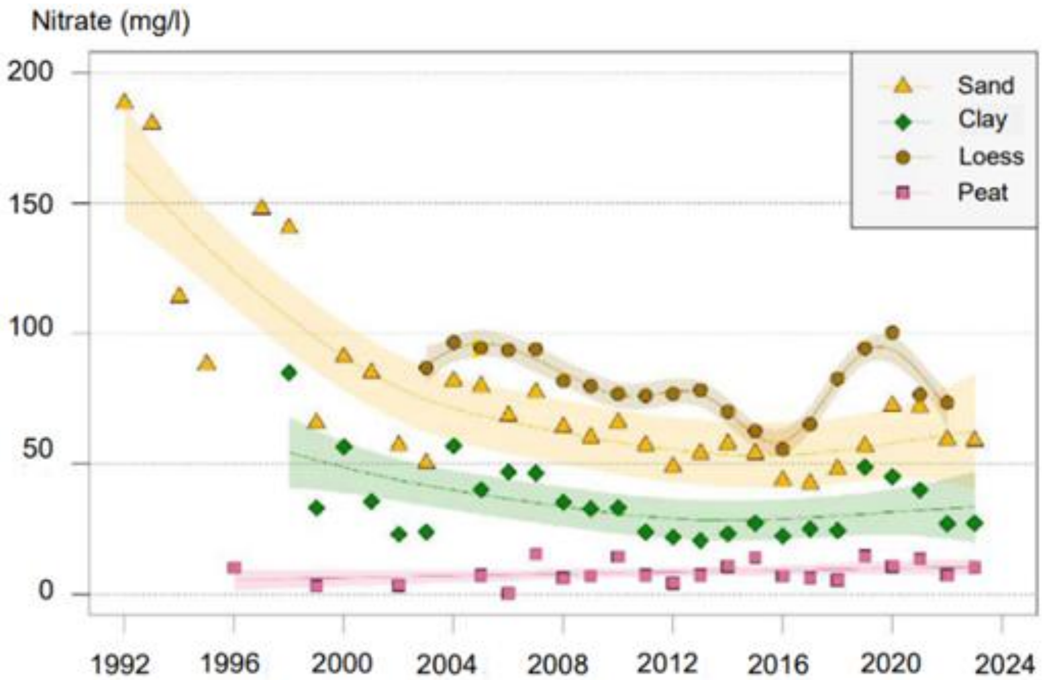


Figure S2 Nitrate concentration (as NO_3 in mg/l) in leachate from agricultural parcels per region in the period 1992–2023. The average concentration over the year is given. The band represents the 95% confidence interval of the fitted trend line.

The nitrate concentrations in leachate from agricultural parcels decreased in the Sand, Loess and Clay region during the period 1992–2012 (see Figure 8). In the Peat region, concentrations were low from the start of the period and did not show a trend. In the period 2012–2017, the decline in nitrate concentrations in the Sand, Clay and Peat

[6] NL report

[7] https://www.rivm.nl/landelijk-meetnet-effecten-mestbeleid

region stagnated. From 2017 onwards, concentrations increased, but from 2020–2021 onwards, nitrate concentrations decreased again in all regions.

As regards surface waters, it is reported that **since the introduction of the Fertilisers Act in 1986 and the entry into force of the European Nitrates Directive, there has been a clear reduction in average nitrate concentrations in winter (the leaching season).** This is illustrated by the following graph reproducing all three types of surface waters (agriculture-specific waters, regional WFD waters and national WFD waters)[8] (see Figure 9).

Figure 9 Average nitrate concentrations in winter (mg/l) in fresh surface waters in the Netherlands, distinguishing between national WFD water, regional WFD waters and agriculture-specific waters

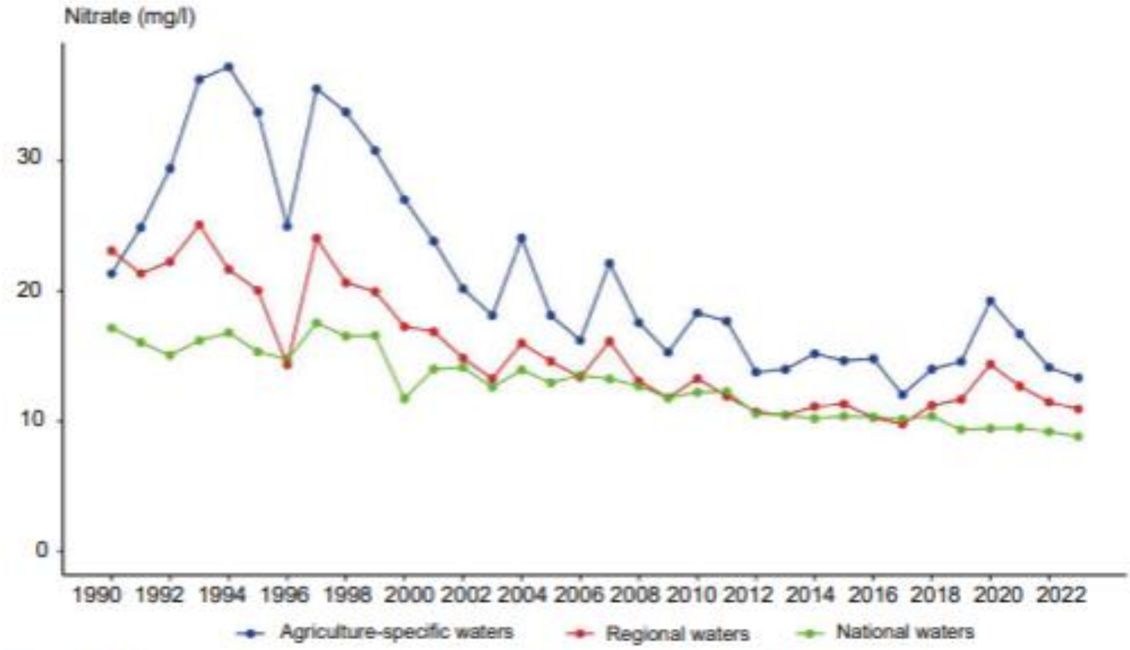


Figure S4 Average nitrate concentrations in winter (in mg NO_3/l) in fresh surface waters in the period 1990–2023, distinguishing between national WFD waters, regional WFD waters and agriculture-specific waters.

The sharpest decline occurred from 1994 until 2012.

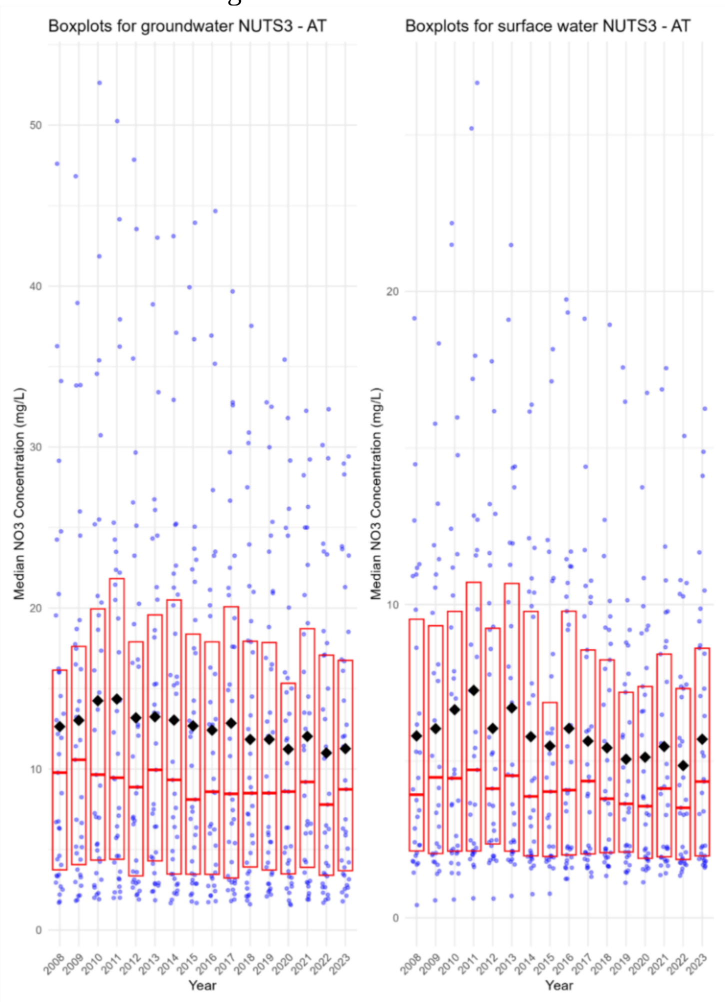
The picture changes when looking at the most recent period. In almost half of the agriculture-specific locations, the average nitrate concentration in winter increased in the period 2020–2023 compared to the period 2016–2019.

[8] Meetnet Nutriënten Landbouw Specifiek Oppervlaktewater (MNLSO)

5. Development of the nitrate concentrations in Austria between 2008 and 2023

There has been a positive evolution with decreasing average nitrates concentrations at NUTS3 regional level for groundwater and surface waters between 2011 and 2019, while the decreasing pattern may be less visible in the average for the whole country. This decrease is particularly prominent in NUTS3 regions with high levels of nitrate concentrations: in groundwaters, the highest average concentrations at NUTS 3 level decreased by more than 20 mg/l between 2010 and 2023 and in surface waters, the highest average concentration decreased by more than 10 mg/l between 2011 and 2023. The graphs below display the groundwater and surface water nitrate concentration at NUTS3 level for the entire country on an annual basis. Each blue dot is the average concentration of a NUTS3 for a specific date. The black dots represent the average concentration for the whole country. Red lines represent the 25% quantiles[9].

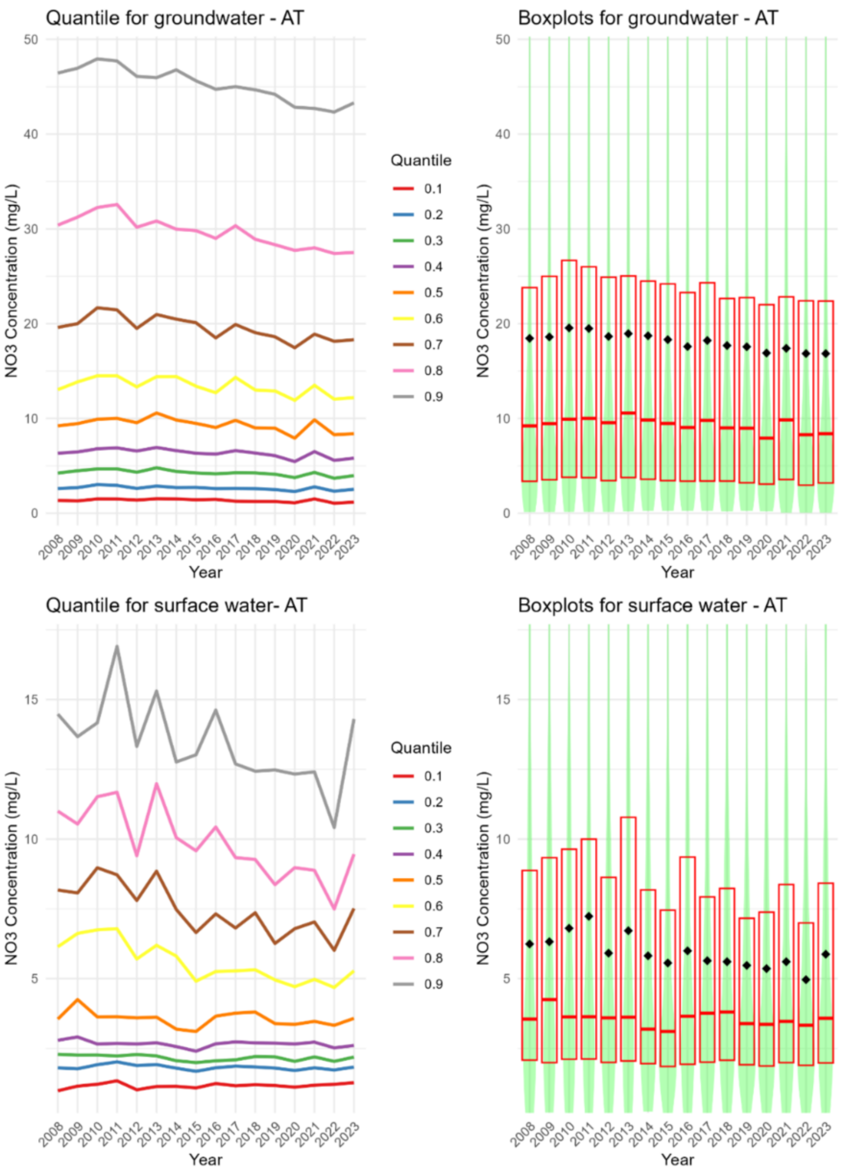
Figure 10 Distribution of annual Nitrate concentration levels (mg/L) in groundwater and surface water in NUTS3-regions in Austria from 2008-2023



[9] scales for groundwater and surface water are different.

This positive evolution is also observed at monitoring point level (Figure 11).[10] The graphs below display the groundwater and surface water nitrate concentration for all monitoring points for the entire country. The left plots show the time series of the quantiles, while the right graphs represent the annual box plots of the concentration. The black dots represent the mean concentration for a specific date. Red lines represent the quartiles. Average nitrate concentration in groundwater has been decreasing since 2010 and levels of nitrate in surface waters are currently lower than decade ago. The decrease in concentrations is particularly noticeable for monitoring points with higher concentrations, specifically within the 0.5 to 0.9 quantiles, while the lower quantiles (0.4 to 0.1) rather show stable concentration levels (left graph).[11]

Figure 11 Distribution of Annual Nitrate Concentrations in mg/L for monitoring points in Austria from 2008 to 2023, Divided into 10 Quantiles



10 The green shade is a violin plot (fit illustrates the distribution of the points, the fatter the violin the more points there are). Be careful the scales for groundwater and surface water are different.

11 Note that all groundwater and surface water quantiles for individual monitoring stations demonstrate an increase in 2023. The cause of this development remains unclear and requires further observations.

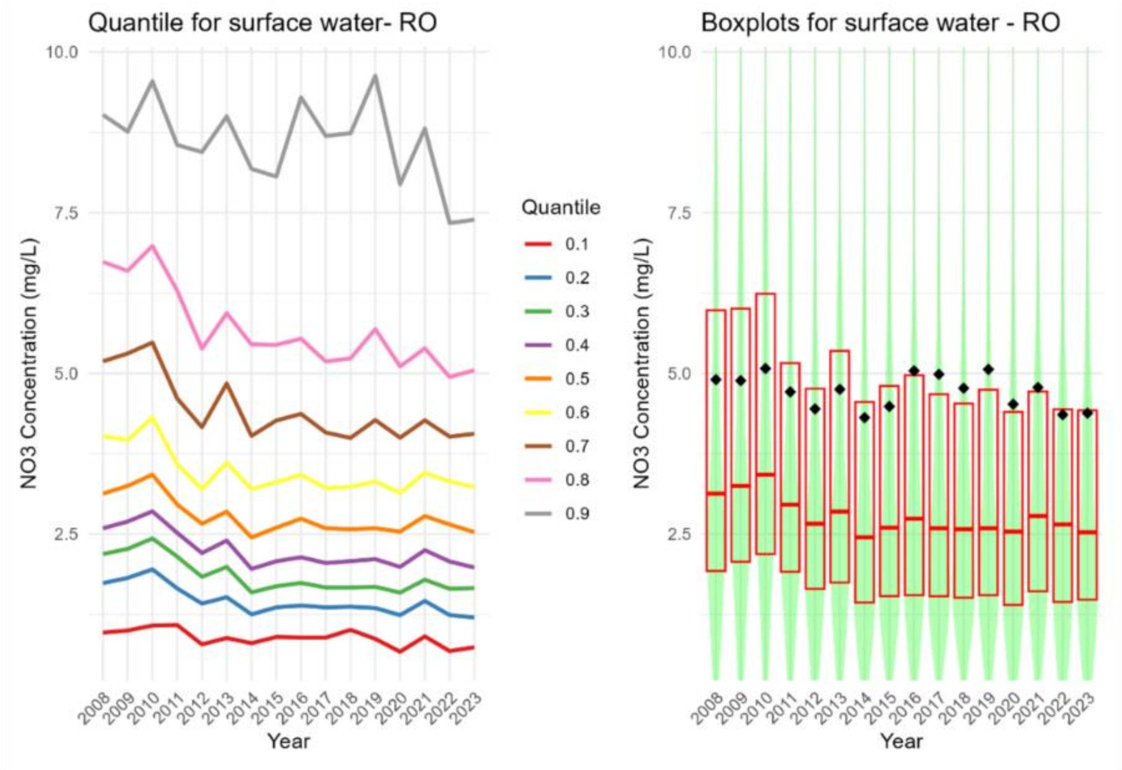
6. Development of the nitrate concentrations in Romania between 2008 and 2023

There has been a positive evolution in surface waters and groundwater in Romania between 2008 and 2023.

An average and median nitrate concentration in surface waters has overall decreased since 2008 (right graph). Most prominent decrease in concentrations is observed in monitoring points with the highest concentrations, but it is seen even in monitoring points with lower nitrates concentration (left graph).

The graphs display the surface water nitrate concentration for all monitoring points for the entire country. The left plots show the time series of the quantiles, while the right graphs represent the annual box plots of the concentration. The black dots represent the mean concentration for a specific date. Red lines represent the quartiles.

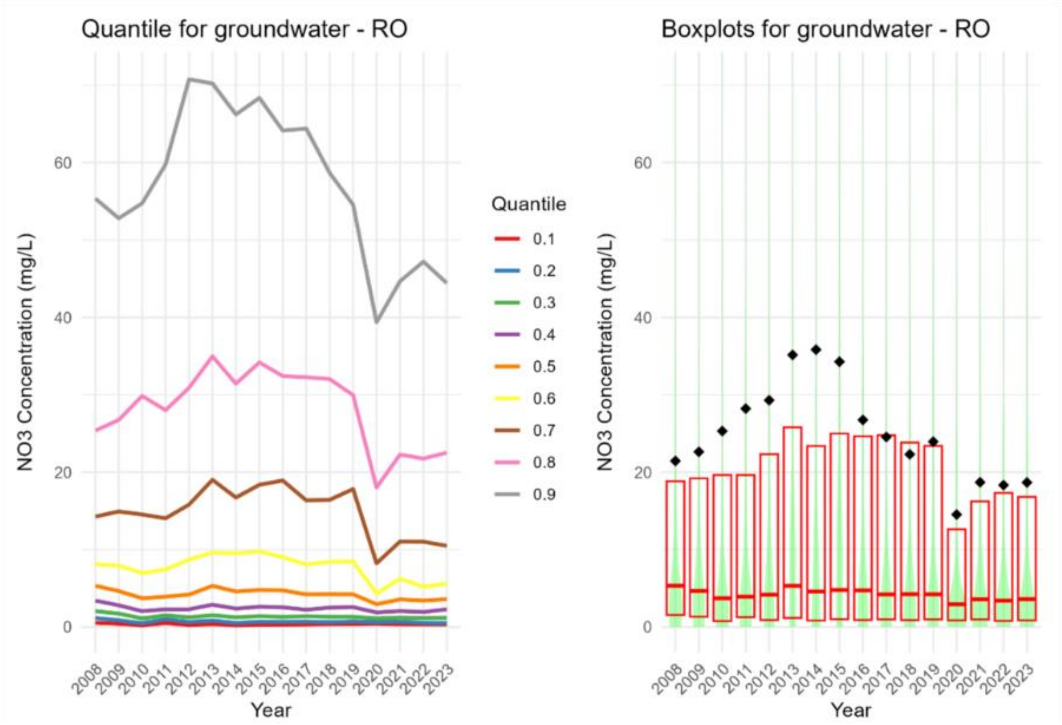
Figure 12 Distribution of Annual Nitrate Concentrations in mg/L for monitoring points in Romania from 2008 to 2023, Divided into 10 Quantiles



Also, in groundwater an average and median nitrate concentration in groundwater has decreased since 2008 (right graph). Even though there was an increase in nitrate concentrations between 2008 and the period 2012-2014, there is a noticeable decrease afterwards. The decrease in nitrate concentrations is particularly noticeable for monitoring points with high concentrations (0.9 quantile), where concentrations decreased significantly since 2012 (left graph). There was also visible improvement in other monitoring points with high concentrations (0.6 to 0.8) when comparing values before and after year 2019. Monitoring points in lower quantiles (0.3 to 0.1) show rather stable concentration levels.

The graphs display the groundwater nitrate concentration for all monitoring points for the entire country. The left plots show the time series of the quantiles, while the right graphs represent the annual box plots of the concentration. The black dots represent the mean concentration for a specific date. Red lines represent the quartiles.

Figure 13 Distribution of Annual Nitrate Concentrations in mg/L for monitoring points in groundwater in Romania from 2008 to 2023, Divided into 10 Quantiles

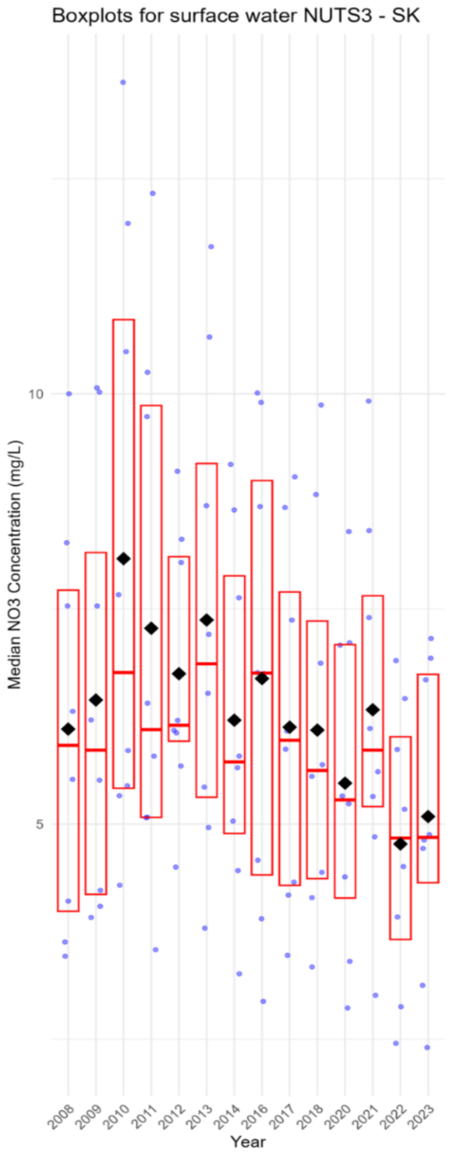


7. Development of the nitrate concentrations in Slovakia between 2008 and 2023

There has been generally decreasing average and median nitrates concentrations at NUTS3 regional level for surface waters in last decade. Gradual decrease is particularly prominent in NUTS3 regions with highest levels of nitrate concentrations with decrease by almost 10 mg/l between 2010 and 2023. Also, the NUTS3 regions with lowest levels of nitrate concentrations show decrease in nitrate concentrations.

The graph displays the surface water nitrate concentration at NUTS3 level for the entire country on an annual basis. Each blue dot is the average concentration of a NUTS3 for a specific date. The black dots represent the average concentration for the whole country. Red lines represent the 25% quantiles.

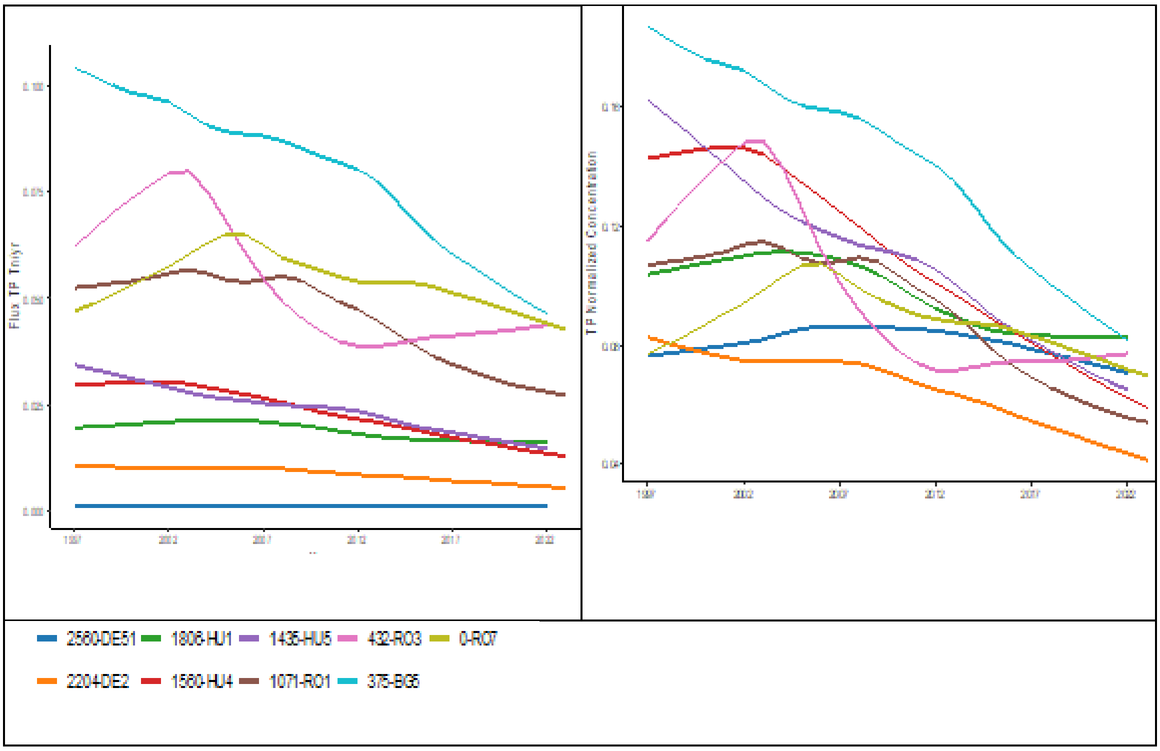
Figure 14 Distribution of annual Nitrate concentration levels (mg/L) in surface water in NUTS3-regions in Slovakia from 2008-2023



8. Trends in nitrogen and phosphorus dynamics along the Danube River between 1996 and 2021

JRC study demonstrates substantial improvements in nutrient-related water quality of the Danube River Basin in the last 25-year (1996-2021)[12]. The most notable findings include dramatic reductions in flow-normalized ammonium loads (approaching 90% in the lower reaches) and significant decreases in phosphorus loads (around 50% at many stations). The study concluded that successes are strongly linked to the effective implementation of point source control measures across the basin, primarily driven by the EU Urban Waste Water Treatment Directive, and national efforts targeting wastewater treatment upgrades and phosphate detergent restrictions. While nitrate loads have also decreased (approximately 20-40% flux reduction at the mouth depending on the specific location), the rate of reduction has been slower, underscoring the persistent challenge posed by diffuse pollution, mainly originating from agricultural sources and influenced by catchment legacy effects.

Figure 16 Temporal evolution of flow-normalized Total Phosphorus fluxes (left) and concentrations (right) for various stations along the Danube River from 1997 to 2023.



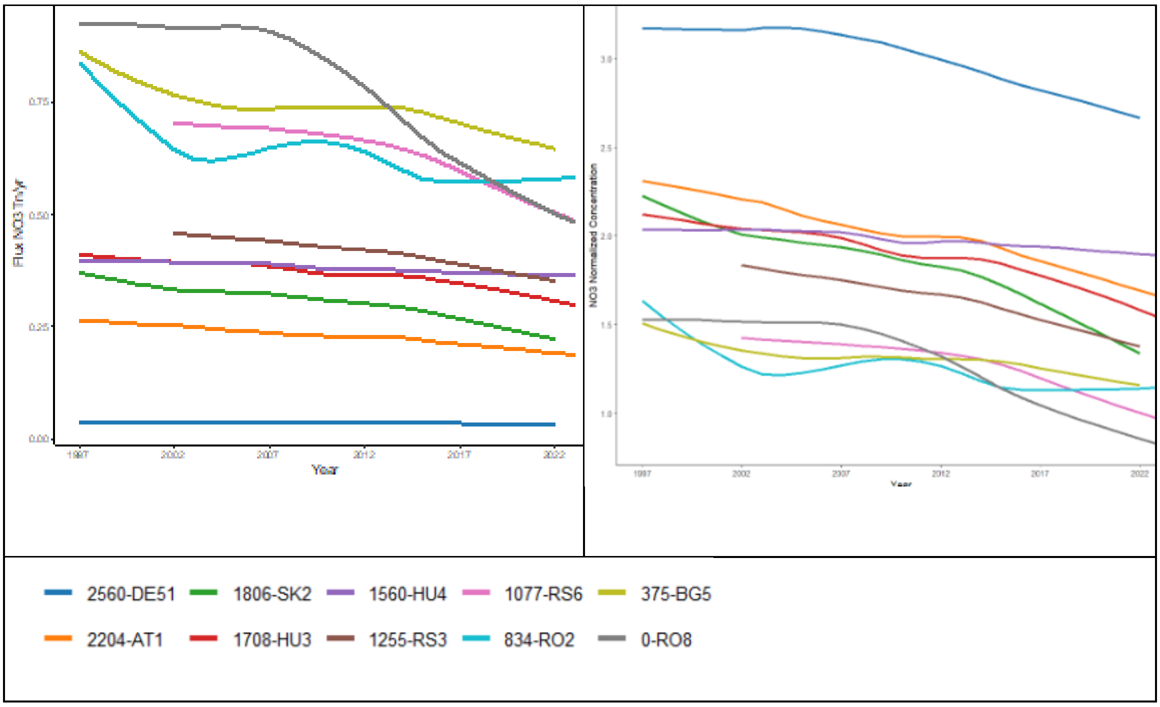
Nitrate reductions, while significant, are less pronounced, reflecting its more diverse sources, including substantial diffuse contributions from agriculture. The application of WRTDS flow-normalization was instrumental in decoupling the influences of

[12] Udias A., Bouraoui F., Vigiak O., Moschini F., Grizzetti B., “Long-term assessment of nutrient dynamics in the Danube River (1996-2021) using flow-normalized indicators: Decoupling hydrological variability from management impacts” (under review).

hydrological variability—including strong seasonal fluctuations and an observed long-term decrease in streamflow, particularly significant in the upper reaches—from changes driven by management actions and other pressures effectively. The WRTDS-derived flow-normalized (FN) trends for NO3-N along the Danube (**Error! Reference source not found.**), which removed the confounding impact of discharge variability, demonstrate a clear trend of reduced concentrations and fluxes across the entire Danube basin over the 1996-2021 period. FN flux reductions ranged from approximately 13% in the upper reaches to over 20% near the river's mouth. In absolute terms, this corresponds to a decrease in the nitrate flux entering the Black Sea, from around 820 tonnes per year in 1996 to approximately 650 tonnes per year in 2021.

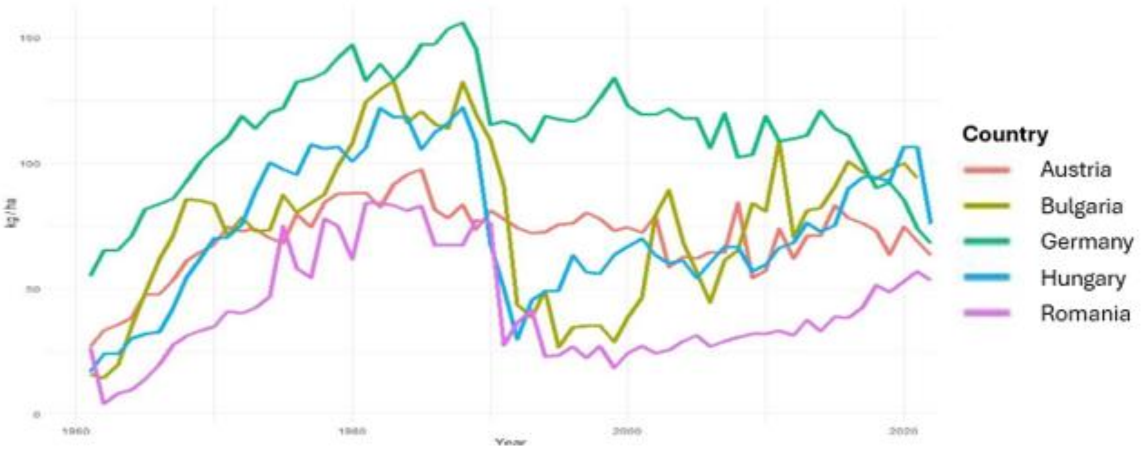
Germany exhibits the highest nitrogen inputs to agricultural land among the countries studied (Figure 18), which aligns with the elevated nitrate concentrations observed in upstream monitoring stations like 2560-DE51 (Figure 17). In the upper Danube Basin declines in nitrate concentrations were modest (approximately 15%).

Figure 17 Temporal evolution of flow-normalized NO3-N fluxes (left) and concentrations (right) for selected representative stations of the Danube River from 1996 to 2021.



Nitrogen applied to agricultural land, especially during periods of high surplus before the 1990s, accumulated in soil organic matter, in the unsaturated zone, and groundwater systems (Van Meter et al., 2016; Wang et al., 2025). The release of this legacy pool of nitrogen into rivers is a slow process, with time lags that can span years to decades (Meals et al., 2010; Vero et al., 2018). Consequently, the decreasing nitrate trends observed in the Danube from 1996 to 2021 likely reflect, in part, the delayed impact of substantial reductions in nitrogen inputs that occurred in the early 1990s (Figure 18), with legacy nitrogen gradually being flushed out.

Figure 18 Evolution of nitrogen application (kg/Ha UUA) from 1960 to 2022 in five Danube countries (data source: FAO)



The EU Nitrates Directive, aimed at improving nitrogen use efficiency and reducing N surpluses from agriculture, has been in effect throughout much of our study period. While fertilizer application rates might have stabilized, the Directive encourages better management practices (e.g., optimized fertilization timing and rates, cover crops) that can reduce the fraction of applied nitrogen lost to the environment (Grizzetti et al., 2021; Bouraoui & Grizzetti, 2014). These ongoing improvements in agricultural management likely contributed to the gradual reduction in the N surplus entering the groundwater systems, and to the observed downward trend in riverine nitrate concentrations. Therefore, the overall enhancement in the Danube's nitrate status likely reflects a multifaceted response: a primary influence of the lagged impact of past large-scale reductions in N inputs from the early 1990s, compounded by the continuous, albeit perhaps more gradual, effects of improved agricultural practices and nutrient management strategies implemented under EU and national policies over the last two to three decades.

LIST OF FIGURES