Science of the Total Environment 954 (2024) 176611

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

# The state of nitrogen in rivers and streams across sub-Saharan Africa

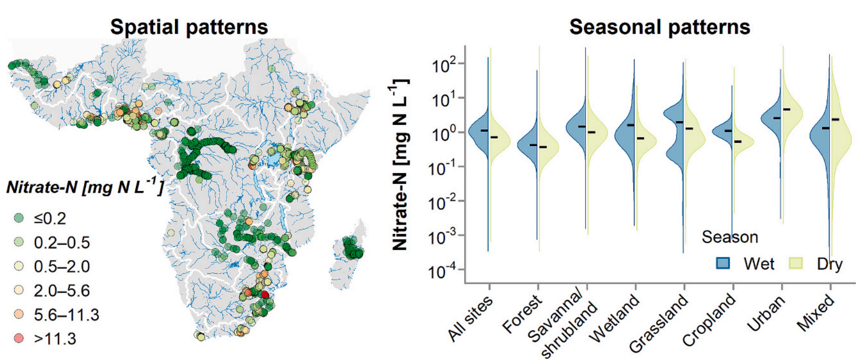
Suzanne R. Jacobs *, Lutz Breuer

Centre for International Development and Environmental Research, Justus Liebig University Giessen, Senckenbergstr. 3, 35390 Giessen, Germany
Institute for Landscape Ecology and Resources Management (ILR), Justus Liebig University, Heinrich-Buff-Ring 26, 35392 Giessen, Germany

## HIGHLIGHTS

- A total of 243 studies report nitrogen data from rivers across sub-Saharan Africa.
- Most data have been collected in the Nile basin and South Africa.
- Managed land cover types have higher nitrogen concentrations in rivers.
- Nitrogen to phosphorus ratios are higher at sites with natural land cover types.
- Hydro-biogeochemical processes that drive spatiotemporal patterns are understudied.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

Editor: JV Cruz

*Keywords:*
Land cover
Seasonality
Nitrate
Nitrous oxide
Spatiotemporal patterns
Hydro-biogeochemical processes

## ABSTRACT

The nutrient status of rivers and streams is less researched in sub-Saharan Africa than in many other inhabited regions of the world. Given the expected population growth, intensification of agriculture, increased pressure on natural ecosystems and projected climate change in sub-Saharan Africa, it is crucial to quantify and understand drivers behind spatiotemporal patterns of nitrogen concentrations and loads in rivers and streams. Such knowledge can support sustainable management of water resources with the goal to provide clean water, create and maintain healthy ecosystems and prevent excessive pollution of water resources with nitrogen compounds, as is found in large parts of North America, Europe and Asia. This review provides a synthesis of the current available data from peer-reviewed literature ($n$ = 243) on particulate and dissolved nitrogen in rivers and streams in sub-Saharan Africa, looking into seasonal and land cover-related differences. The review shows that data on nitrogen concentrations in rivers and streams is available for 32 out of the 48 countries (67 %) in sub-Saharan Africa, highlighting large data gaps given the size of the region. Differences in nitrogen concentrations between land cover types are reported, with highest median total nitrogen (3.9 mg N L$^{-1}$) and nitrate (1.2 mg N L$^{-1}$) concentrations observed at sites characterised by settlement and industry. In contrast, natural land cover types, like forest, have higher median (N:P) ratios (> 14.6) than cropland and urban areas (< 12.0). The analysis of paired samples from dry and wet seasons reveals varying effects of seasonality on the concentration of different nitrogen compounds between land cover types. However, the processes driving these spatiotemporal differences are still poorly understood. These findings highlight the need for a targeted research agenda for Africa

* Corresponding author at: Centre for International Development and Environmental Research, Justus Liebig University Giessen, Senckenbergstr. 3, 35390 Giessen, Germany.
*E-mail address:* suzanne.r.jacobs@zeu.uni-giessen.de (S.R. Jacobs).

https://doi.org/10.1016/j.scitotenv.2024.176611
Received 23 November 2023; Received in revised form 9 September 2024; Accepted 27 September 2024
Available online 28 September 2024

to advance our understanding of the role of rivers and streams in nitrogen cycling in different ecosystems and their interaction with anthropogenic and natural drivers of change.

## 1. Introduction

Nitrogen (N) is an essential nutrient for plant growth and development and, thus, for the production of food, feed, fuel and fibres. The application of nitrogen is therefore seen as a key mechanism to increase agricultural productivity. Although fertilizer use is still limited across the African continent due to high costs, low returns and insufficient knowledge (Liu et al., 2010), low nitrogen use efficiency (Anas et al., 2020) and excessive nitrogen losses through soil erosion and nutrient leaching have contributed to increased N loads into water bodies across the continent (Liu et al., 2010; Masso et al., 2017; Otu et al., 2011). Atmospheric deposition (Bakayoko et al., 2021; Galy-Lacaux and Delon, 2014), urban population growth and insufficient wastewater treatment (Nyenje et al., 2010) further contribute to deteriorating water quality in many rivers and lakes. Nitrogen inputs from urban waste water in developing countries are expected to increase by a factor of 2.5 or 3.5 between 2000 and 2050 (Van Drecht et al., 2009), which could have a devastating effect on water quality and the health of aquatic ecosystems.

Compared to, for example, Europe, large parts of North America and Southeast Asia, riverine nitrogen loads in Africa are still considered relatively low (McDowell et al., 2021). Nevertheless, the excess input of nutrients has already led to eutrophication and is a key cause for the degradation of aquatic ecosystems (Le Moal et al., 2019). It has, for example, increased the occurrence of harmful algal blooms and the invasion of water hyacinth (*Eichhornia crassipes* (Mart.)) in lakes receiving nutrient-rich water from rivers in South Africa (Coetzee and Hill, 2012) and Ethiopia (Fetahi, 2019), as well as in Lake Victoria (Gichuki et al., 2012), affecting economic activities and aquatic biodiversity. Eventually, nutrients in rivers and streams reach estuaries and coastal waters, where they can cause a decline in oxygen. In combination with warming oceans due to climate change, this could result in increased emissions of the potent greenhouse gas nitrous oxide ($N_2O$), reduce biodiversity and alter the structure of food webs (Doney, 2010). The expansion of hypoxic areas along the African coast could have drastic consequences for the livelihoods and food security of those who depend on fisheries and aquaculture (Breitburg et al., 2018).

The irrefutable link between human activities on land and potential downstream consequences highlights the need to understand the sources, processes and fate of nitrogen in surface water. The objective of this review is to provide a synthesis of the current state of scientific knowledge on spatiotemporal patterns of particulate and dissolved nitrogen in rivers and streams across sub-Saharan Africa, particularly regarding drivers of these patterns, such as land cover and seasonality. Based on this synthesis, critical research gaps have been identified that will need to be addressed in the near future to be able to develop management strategies and interventions for sustainable nutrient management, to avoid degradation of aquatic ecosystems and ensure good water quality across the continent.

## 2. Methods

### 2.1. Literature search

To identify relevant studies, a Web of Science search using a Boolean search string was carried out. The search string included all names of countries that are part of sub-Saharan Africa, terms related to nitrogen and phosphorus, as well as different pools and fluxes, and terms related to land use/land cover, land management or ecosystems (Table S1). This initial broad search, carried out in October 2023, which also included stocks and fluxes in other compartments, like the soil and atmosphere, yielded 6826 studies. These studies were screened based on their title and abstract to identify literature that concerned nitrogen in water only (but including groundwater, surface runoff and leaching), reducing the number of studies to 339. Through the identification of relevant literature from reference lists, an additional 20 references were added. The full text of 359 studies was finally screened for a final decision on inclusion based on the geographical location, subject (flowing surface water), availability of data on one or more nitrogen compounds and data quality. Data quality was assessed based on the availability of sufficient details about data collection and analysis to allow interpretation of the results presented in the publication and readability of figures, in case data would have to be extracted, which would influence the accuracy of the extracted values. A total of 52 studies (21 %) included in the analysis did not clearly report the units (e.g. mg $NO_3$ $L^{-1}$ or mg $NO_3$-N $L^{-1}$) for dissolved forms of nitrogen and/or phosphorus, which could lead to incomparability of data. An initial set of 153 studies was subjected to data extraction. A second search was conducted in July 2024, since a number of relevant publications were missing from the original set of studies. The search was widened by including studies that used the keyword ‘water quality’ rather than only (specific forms of) nitrogen. This second search resulted in an additional 1712 publications, of which 153 were subjected to detailed screening and 90 studies were retained, resulting in a final set of 243 studies.

### 2.2. Data extraction

Metadata from each study, such as study area, study design, period of data collection, and the number of sampling sites and samples, was entered in a Microsoft Excel sheet. General information about the study area, such as elevation range, mean annual precipitation and temperature, were also included. A new row was added for each site for which data on any form of nitrogen, including $N_2O$, was available. Where required, units were converted to mg N $L^{-1}$ for concentrations and to kg N $ha^{-1}$ $y^{-1}$ for export. Only $N_2O$ concentrations are reported in μg N $L^{-1}$, and fluxes of $N_2O$ to the atmosphere in μg N $m^{-2}$ $h^{-1}$. Means and standard deviations of nitrogen concentrations were extracted from the studies. If standard errors were reported and information on the sample size was available, standard errors were converted to standard deviations. Preferably, data were extracted from tables and supplementary materials, but in case data were only presented in the form of graphs, the PlotDigitizer application (https://plotdigitizer.com/app) was used to extract values. Duplicate data reported in multiple studies were only included once. For example, data for many sites in Borges et al. (2015) were also reported in Bouillon et al. (2012), Teodoru et al. (2015) and Borges et al. (2019). Where available, separate data for dry and wet season conditions were included in the database. If the samples were representative for both dry and wet conditions, samples were classified as ‘All’, and if no clear indication of sampling conditions were stated, they were classified as ‘Not specified’.

For every site, the geographical location (coordinates) was extracted from maps, tables or the main text, if provided. Study sites without specific coordinates were assigned the mean coordinates of the study area or a nearby reference point described in the text. For 10 sites (0.3 % of sites), no (approximate) coordinates could be provided. These sites were therefore excluded from any spatial analyses. When available, the catchment area, elevation and slope were also recorded.

Using the (approximate) coordinates, information on the dominant land cover type in a 1 km buffer zone around each site was extracted from open access geographical data sources (Table 1, Fig. S1). In case the buffer zone covered a large extent (> 30 % of surface area of the buffer zone) of open water or lakes, the buffer zone was increased to 2 km and, if necessary, to 5 km to ensure that sufficient terrestrial surface was

**Table 1**
Data sources and conditions for land cover classification in a 1, 2 or 5 km buffer zone around each site included in the review for which (approximate) coordinates are available ($n = 3140$). The number of sites assigned to each land cover class ($n$) is indicated in the last column.

| Land cover class | Condition | Data source | n |
|---|---|---|---|
| Forest | Mean tree cover ≥60 % AND < 50 % of area is classified as wetland | Based on the International Geosphere-Biosphere Programme (IGBP) classification of closed forest and the high-resolution map of African tree cover 2019 at 100 m resolution (Reiner et al., 2023); inclusion of the condition regarding wetland extent is to prevent forested swamps and wetlands to be classified as forest | 348 |
| Savanna & shrubland | Mean tree cover ≥10 % AND mean tree cover <60 % AND not classified as mixed (see below) | Based on the International Geosphere-Biosphere Programme (IGBP) classification of savanna and shrubland and the high-resolution map of African tree cover 2019 at 100 m resolution (Reiner et al., 2023) | 534 |
| Wetland | ≥ 50 % of area is classified as wetland AND < 50 % of area is classified as settlement | Tropical and Subtropical Wetlands Distribution 2017 (class 20 to 100) at 231 m resolution (Gumbricht et al., 2024); condition regarding settlement extent is to prevent that urbanised wetland areas are classified as wetland | 366 |
| Grassland | Mean tree cover <10 AND not classified as mixed (see below) | Based on the International Geosphere-Biosphere Programme (IGBP) classification of grassland and the high-resolution map of African tree cover 2019 at 100 m resolution (Reiner et al., 2023) | 763 |
| Cropland | ≥ 30 % of area is classified as cropland AND sum of tree cover and percentage of area classified as cropland ≥50 % | Considered representative of both agricultural landscape characterised by croplands as well as mosaic and agroforestry-based agricultural landscapes, based on the global map of cropland extent 2019 at 30 m resolution (Potapov et al., 2022) and the high-resolution map of African tree cover 2019 at 100 m resolution (Reiner et al., 2023) | 421 |
| Urban | ≥ 50 % of area is classified as settlement | World Settlement Footprint 2015 scaled to 30 m resolution (Marconcini et al., 2020) | 348 |
| Mixed | Sum of percentage of area classified as cropland, settlement or wetland ≥50 % AND < 50 % of area is classified as only cropland, settlement or wetland | No clear dominant land cover type, therefore considered mixed land cover | 360 |

covered for a reliable land cover classification. The approach has three limitations: (1) land cover information might not be accurate for sites for which no precise coordinates were provided, (2) it only provides information on the area surrounding the site, not on land cover in the upstream catchment and (3) the information might not represent the situation at time of sampling, particularly for older studies. However, this procedure was deemed suitable to obtain objective and reproducible land cover information for most of the sites, as this information was not clearly provided in many studies. Each site was classified according to the conditions provided in Table 1. Sites for which no coordinates were available ($n = 10$) were classified based on information from the corresponding publication.

**Table 2**
Data on nitrous oxide ($N_2O$) concentrations, export and emissions from rivers and streams in sub-Saharan Africa. The number of sites for which data is available is indicated with $n$.

| Land cover | | $N_2O$ concentration | $N_2O$ export | $N_2O$ emissions |
|---|---|---|---|---|
| | | [μg N L$^{-1}$] | [kg N ha$^{-1}$ y$^{-1}$] | [μg N m$^{-2}$ h$^{-1}$] |
| Forest | Mean | 0.64 ± 0.24 | 0.002 ± 0.001* | NA |
| | Median | 0.13 | 0.002 | NA |
| | Range | 0.0–4.2 | 0.001–0.003 | NA |
| | n | 148 | 2 | 0 |
| Savanna | Mean | 0.13 ± 0.014 | NA | NA |
| | Median | 0.11 | NA | NA |
| | Range | 0.027–0.22 | NA | NA |
| | n | 125 | 0 | 0 |
| Wetland | Mean | 0.11 ± 0.00 | NA | NA |
| | Median | 0.11 | NA | NA |
| | Range | 0.0–0.4 | NA | NA |
| | n | 228 | 0 | 0 |
| Grassland | Mean | 0.33 ± 0.051 | NA | 87.6 ± 20.1 |
| | Median | 0.11 | NA | 82.9 |
| | Range | 0.078–1.16 | NA | 41.6–138.2 |
| | n | 177 | 0 | 3 |
| Agriculture | Mean | 0.33 ± 0.16 | NA | 15.3 ± 16.8 |
| | Median | 0.14 | NA | 6.94 |
| | Range | 0.081–2.75 | NA | 5.7–27.04 |
| | n | 46 | 0 | 9 |
| Urban | Mean | 0.11 ± 0.012 | NA | NA |
| | Median | 0.12 | NA | NA |
| | Range | 0.09–0.18 | NA | NA |
| | n | 31 | 0 | 0 |
| Mixed | Mean | 0.15 ± 0.024 | NA | NA |
| | Median | 0.11 | NA | NA |
| | Range | 0.02–0.54 | NA | NA |
| | n | 115 | 0 | 0 |

Finally, data on other water quality parameters (water temperature, electrical conductivity, dissolved oxygen, biological oxygen demand, pH, total dissolved solids, turbidity, total suspended sediments, chlorophyll $a$, total phosphorus, phosphate and dissolved organic carbon) as well as discharge were included, if measured alongside the nitrogen concentrations. The full dataset can be obtained from an open access online repository (Jacobs and Breuer, 2024).

### 2.3. Data analysis

Pooled means (Eq. (1)) and standard deviations (Eq. (2)) were calculated for concentrations and yields of all nitrogen compounds for each land cover type:

$$\overline{x}_{pooled} = \frac{\sum_{i=1}^{N} \overline{x}_i \cdot n_i}{\sum_{i=1}^{N} n_i} \tag{1}$$

where $\overline{x}_{pooled}$ is the pooled mean, $\overline{x}_i$ is the mean for site $i$, $n_i$ the corresponding number of measurements at site $i$, as reported by the original study, and $N$ the total number of sites.

$$s_{pooled} = \sqrt{\frac{\sum_{i=1}^{N} (n_i - 1) \cdot s_i^2}{\sum_{i=1}^{N} (n_i - 1)}} \tag{2}$$

where $s_{pooled}$ is the pooled standard deviation and $s_i$ the standard deviation reported for site $i$. If the number of measurements was not provided, $n$ was set at 3 as the minimum number of measurements required to calculate a standard deviation. In case standard deviations were not reported, they were omitted from the calculation.

To assess the effect of season (dry vs. wet season) on the concentration of different nitrogen species, studies were selected that reported dry and wet season values for the same site. The normalised effect size was calculated with Eq. (3):

$$\theta_i = \frac{\overline{x}_{wet,i} - \overline{x}_{dry,i}}{\overline{x}_{dry,i}} \tag{3}$$

where $\theta_i$ is the effect size for site $i$, $\overline{x}_{wet,i}$ is the mean concentration for the wet season and $\overline{x}_{dry,i}$ the mean concentration for the dry season at site $i$. The corresponding standard error of the effect size $se_{\theta_i}$ was calculated with Eq. 4:

$$se_{\theta_i} = \sqrt{\frac{\left(\frac{s_{wet,i}}{\overline{x}_{wet,i}}\right)^2}{n_{wet,i}} + \frac{\left(\frac{s_{dry,i}}{\overline{x}_{dry,i}}\right)^2}{n_{dry,i}}} \tag{4}$$

where $s_{wet,i}$ and $s_{dry,i}$ are the standard deviations for the wet and dry season at site $i$, respectively, and $n_{wet,i}$ and $n_{dry,i}$ the number of measurements for the wet and dry season. The effect sizes were then pooled by land cover type by applying a random effect model. First, a weighted mean effect size was calculated (Eq. (5)):

$$\hat{\theta} = \frac{\sum_{i=1}^{N}(\theta_i \cdot w_i)}{\sum_{i=1}^{N} w_i} \tag{5}$$

where $\hat{\theta}$ is the mean effect size and $w_i$ the weight applied to the effect size of site $i$, which was determined using the inverse variance for random effect models (Eq. (6)):

$$w_i = \frac{1}{s_i^2 + \tau^2} \tag{6}$$

whereby $\tau^2$ is an interstudy variance estimator, which corrects for inter- and intrastudy errors, including variability in measurement methods and conditions among studies (Mikolajewicz and Komarova, 2019). This study used Hedges interstudy variance estimator (Eq. (7)):

$$\tau^2 = \frac{\sum_{i=1}^{N}\left(\theta_i - \left(\frac{\sum \theta_i}{N}\right)\right)^3}{N-1} - \frac{\sum_{i=1}^{N} s_i^2}{N} \tag{7}$$

The standard error for the mean effect size $se_{\hat{\theta}}$ was calculated with Eq. (8) and multiplied the critical value $\nu$=2.78 for a conservative estimate of the 95 % confidence interval:

$$se_{\hat{\theta}} = \frac{1}{\sqrt{\sum_{i=1}^{N} w_i}} \tag{8}$$

Molar N:P ratios were calculated by converting concentrations of total nitrogen and phosphorus from mg N/P $L^{-1}$ to μM.

## 3. Results and discussion

### 3.1. Spatiotemporal data coverage

The strength and representativeness of this synthesis is strongly linked to the spatiotemporal distribution of available studies and data (Fig. 1). There seems to be a strong focus on particular countries (e.g., Nigeria, Ethiopia, Kenya and South Africa; Fig. 1c) and river basins (e.g., the Nile basin and smaller basins in the Rift Valley as well as along the East Central and Indian Ocean coast; Fig. 1b). Such an unequal geographical distribution is not unique to riverine nitrogen data, as similar observations were reported by Dinku (2019) for climate data and by Tramblay et al. (2021) for hydrological information. Data 'hotspots' could be linked to the generally higher scientific publication activity of research institutions in these countries (Cerdeira et al., 2023) and participation in international research collaborations (Adams et al., 2014). The number of measurements follows roughly the same geographical distribution as the number of studies, with many of the regions with >1000 measurements occurring in countries with a high number of studies (Fig. 1b–c). Such high numbers are usually the result of single long-term studies rather than multiple studies having been carried out in the same region. For example, a 3-year study in catchments draining into Lake Kivu (Democratic Republic of the Congo) resulted in 2304 measurements (Bisimwa et al., 2022), and 1200 measurements were accumulated over 5 years of monthly sampling across 20 sites in Edo and Delta states in Nigeria (Edegbene et al., 2022).

Historical data from regular monitoring activities could be a very important source of information, though rarely used in the studies in this review. In fact, the majority of the data used for this review (73 %) has been collected and/or published in the last 15 years (since July 2009), with >50 % of the data having been generated since 2012 (Fig. 1c; excluding Jacobs et al., 2020). Notable studies include a survey of the Zambezi in Mozambique carried out in 1973 and 1974 (Hall et al., 1977), a survey of rivers across Nigeria in 1977 and 1978 (Ajayi and Osibanjo, 1981) and a 1-year study of nutrient and solute transport in the Gambia River in the early 1980s (Lesack et al., 1984). Only South African studies made use of a large amount of available historical data, with records going back to 1965 (Lemley et al., 2014) (Fig. 1c). A big challenge in this context is the limited accessibility to such records, as countries in sub-Saharan Africa perform very poorly in terms of open access data (Van Schalkwyk, 2016).

The longest research-based dataset has been published by Komba et al. (2024) with the associated dataset of Audry et al. (2021). This long-term study (1994–2021) of the hydrochemistry of the Nyong River is an exception, rather than the rule, as the overall median study duration is 9 months (Fig. 1d). These studies of 9 months or less ($n$ = 129) contribute 11 % of the data, whereas 14 studies using datasets of 8 or more years contribute 57 % of the data included in this database, when excluding the contribution of the data collected by Jacobs et al. (2020) in the Sondu basin. The exceptionally high number of measurements ($n$ = 759,123) from the latter study is due to the use of in situ sensors at four sites, recording nitrate ($NO_3$-N) concentration at 10-min intervals for a period of 4 years (Jacobs et al., 2020). Despite technological developments and the decreasing costs of in situ sensors, this is not yet a widely used approach in Africa. The only other studies that report sub-daily information on nitrogen used autosamplers to investigate storm response of various forms of particulate and dissolved nitrogen in the Congo basin (Baumgartner et al., 2022) or manually sampled the same site repeatedly during the day (Yillia et al., 2008) (Fig. S2).

### 3.2. Land cover as driver of spatial patterns

Many drivers of nitrogen concentrations in surface water are linked to human presence, activities and land management (du Plessis, 2022). An analysis of the data extracted from all studies grouped by the dominant land cover type surrounding each study site supports the hypothesis that land cover could be a key driver of spatial patterns in nitrogen concentrations (Fig. 2). Dssolved organic nitrogen (DON) does not show a clear difference among land cover types, although forests have a higher median DON concentration (0.81 mg N $L^{-1}$) than all other land cover types (< 0.22 mg N $L^{-1}$; Fig. 2c). The lack of differences could be related to the low number of sites for which DON concentrations were reported ($n$ = 36), but low sensitivity of DON concentrations to land cover has previously been observed in different parts of the world (Jacobs et al., 2017; Pellerin et al., 2004; Willett et al., 2004). Concentrations of most nitrogen compounds are particularly high at urban sites. The median concentrations of total nitrogen (TN) and $NO_3$-N at these sites (3.9 mg N $L^{-1}$ and 1.2 mg N $L^{-1}$) are, for example, >6 times higher than median concentrations at forested sites (0.44 mg N $L^{-1}$ and 0.20 mg N $L^{-1}$). Urban sites also have high ammonium ($NH_4$-N; 0.45 mg N $L^{-1}$) and nitrite ($NO_2$-N; 0.15 mg N $L^{-1}$) concentrations, which are indicative of poor water treatment and discharge of industrial effluents and sewage.

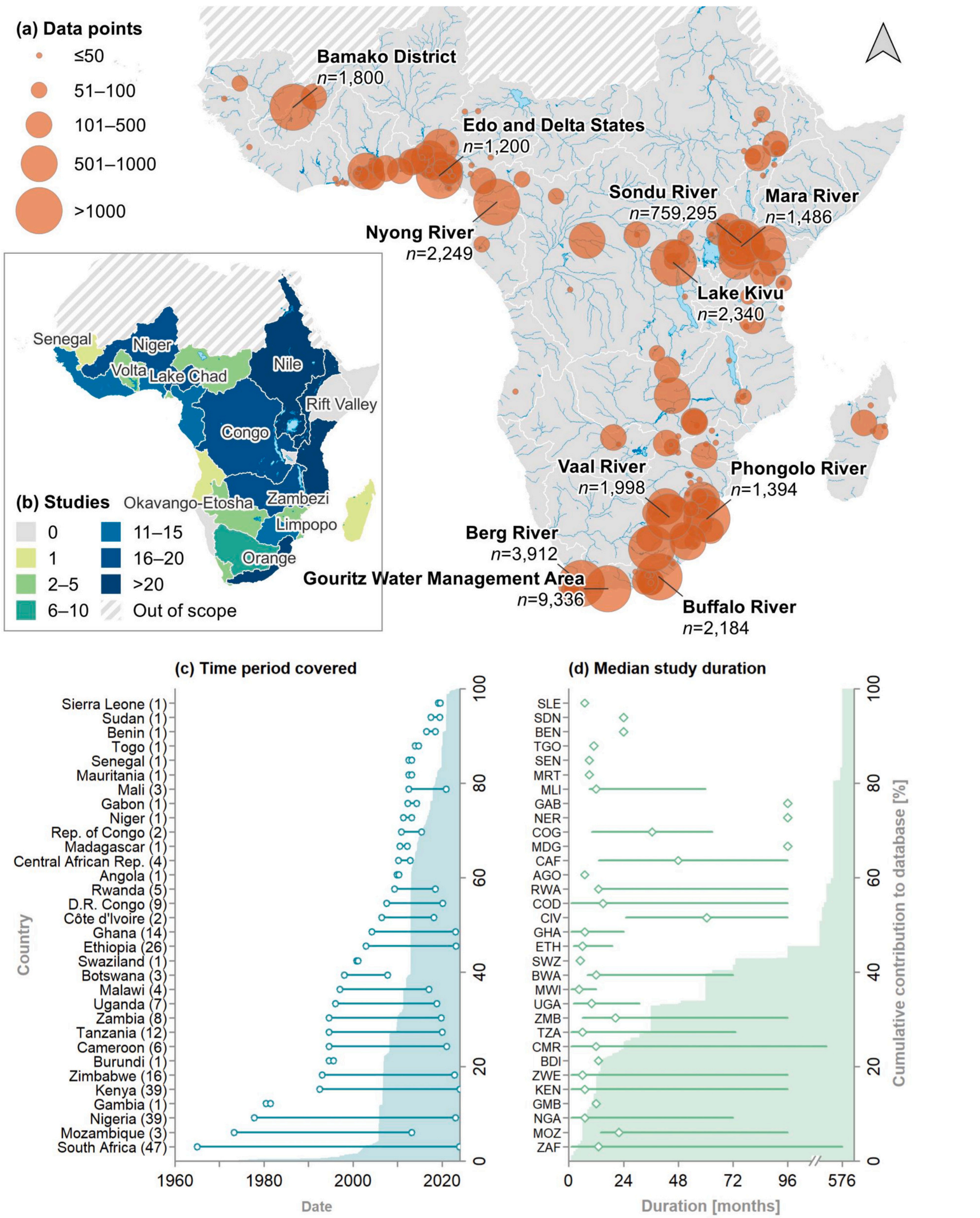



**Fig. 1.** Overview of the availability of data on nitrogen in rivers and streams across sub-Saharan Africa. (a) Geographical distribution of study regions, whereby the size of the bubble indicates the number of measurements (*n*) in the region. Regions with >1000 measurements have been labelled with the name of the region and the total number of measurements. (b) Number of studies per major river basin (based on HydroSheds level 3; Lehner et al., 2008). Darker colours indicate a larger number of studies. (c) Time period covered by datasets for each country (horizontal line) and the cumulative amount of data generated over time (shaded area). The number of studies is indicated in parentheses behind each country. (d) Median (diamond) and range (horizontal line) of study durations in months for each country, as well as cumulative contribution of studies of different duration to the overall database (shaded area). Countries are presented in the same order in (c) and (d), whereby the country codes in (d) correspond to the full names in (c). The study by Jacobs et al. (2020) has been excluded from the calculation of the cumulative contribution, because of the disproportionately large size of the dataset.

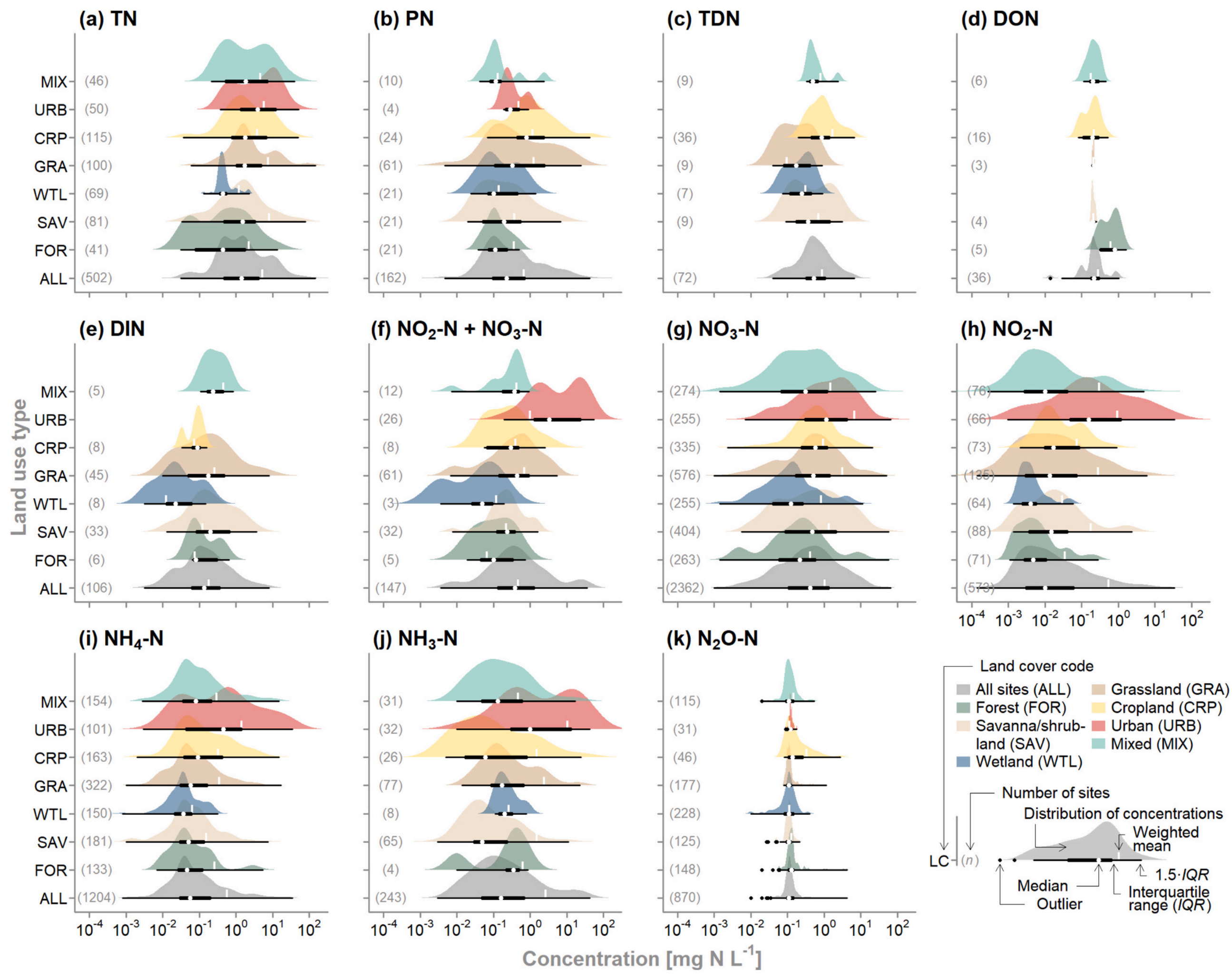



**Fig. 2.** Concentrations of different nitrogen compounds in rivers and stream across sub-Saharan Africa. Distribution of concentrations of (a) total nitrogen TN, (b) particulate nitrogen PN, (c) total dissolved nitrogen TDN, (d) dissolved organic nitrogen DON, (e) dissolved inorganic nitrogen DIN, (f) inorganic nitrogen measured as the sum of nitrite $NO_2$-N and nitrate $NO_3$-N, (g) nitrate $NO_3$-N, (h) nitrite $NO_2$-N, (i) ammonium $NH_4$-N, (j) ammonia $NH_3$-N and (k) nitrous oxide $N_2O$—N. Data is provided for all sites (ALL) and for individual land cover types: forest (FOR), shrubs (SHR), wetland (WTL), rangeland (RGL), cropland (CRP), urban (URB) and mixed (MIX). The number in parentheses indicates the total number of sites of each land cover type for which data is included in the database ($n = 3150$). The median value and interquartile range of each land cover type are represented by white dot and black lines, and the weighted mean is indicated with a white vertical line. A logarithmic scale has been used for the x-axis for better visualisation of the distribution of the wide range of concentrations.

The drinking water guidelines of the World Health Organization (WHO) for $NO_3$-N (50 mg $L^{-1}$ or 11.3 mg N $L^{-1}$) and $NO_2$-N (3 mg $L^{-1}$ or 0.91 mg N $L^{-1}$) (World Health Organization, 2022) are exceeded at 65 and 29 sites (88 unique sites), respectively. This represents 3.7 % of the sites in the database for which data on $NO_3$-N and/or $NO_2$-N concentrations are available ($n = 2390$). In comparison, the guidelines were exceeded at 1.2 % of the sites in a European dataset on $NO_3$-N in rivers in 28 countries (European Environment Agency, 2022), despite the generally higher $NO_3$-N concentrations in European surface waters compared to Africa (He et al., 2011; Sheikholeslami and Hall, 2023). One could argue that the sites in this review are not representative for all rivers in Africa as it could be biased by a stronger research interest in areas with high human impact and low water quality. It nevertheless confirms that especially urbanised sites are prone to eutrophication, as these sites represent more than a third ($n = 31$) of the affected sites.

Savanna, shrubland and grassland sites show generally higher concentrations of nitrogen compounds than forest sites. Grassland sites are particularly associated with high soil and nutrient losses due to (over) grazing (Kiage, 2013), which could explain the higher concentrations of particulate nitrogen (median values of 0.19, 0.33 and 0.11 mg N $L^{-1}$ for savanna/shrubland, grassland and forest sites, respectively). Cropland sites have higher TN, PN and TDN concentrations than natural land cover types. The inclusion of sites characterised by smallholder agriculture with zero or low external nutrient inputs, might have reduced the visibility of the impact of large-scale or commercial agricultural areas with higher fertilizer use and, therefore, also losses to surface water. Low nitrogen concentrations, particularly for $NO_3$-N and $NO_2$-N, at wetland sites are in line with the potential role of wetlands in improving water quality and underlines the importance of conserving and restoring these ecosystems for the continued delivery of this important ecosystem service. Forest, savanna, shrubland and grassland sites with poor water quality (Fig. 3b–c, e) mostly occur in areas with a strong human influence, such as around Addis Abeba and Accra, as well as around Johannesburg.

Nitrogen loads (usually expressed as mass per time) or export (expressed as mass per surface area), estimated by combining nitrogen concentrations with river discharge data, are useful to understand the fate of nitrogen in rivers. They express how much nitrogen is transported downstream and could potentially contribute to the eutrophication of downstream water bodies and eventually coastal waters. Along this pathway, nitrogen can also be removed through in-stream biogeochemical processes, hyporheic zone exchange processes and retention.

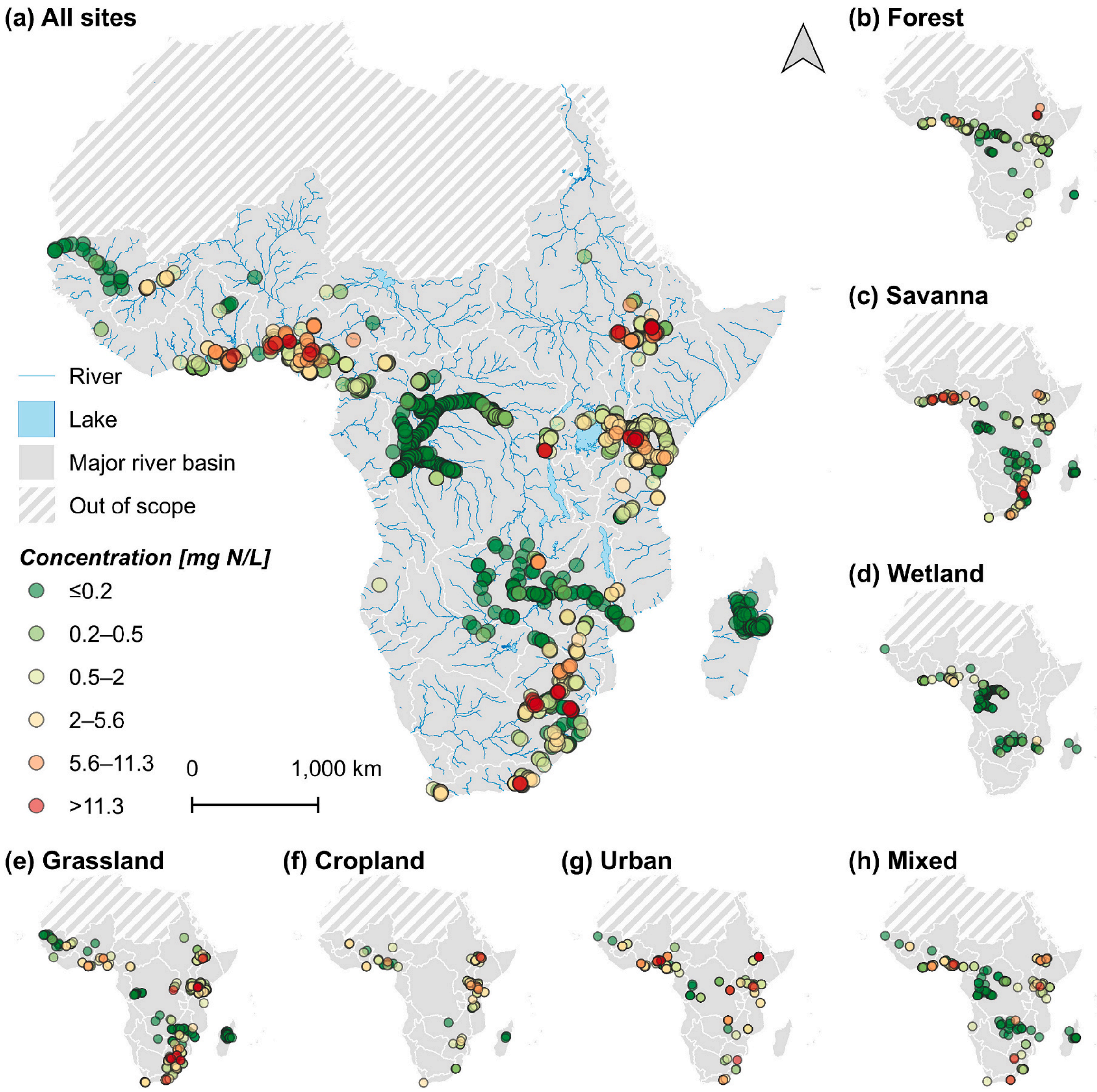



**Fig. 3.** Spatial distribution of nitrate ($NO_3$-N) concentrations in rivers and streams across sub-Saharan Africa. $NO_3$-N concentrations are indicated in colour with dark green representing very low concentrations of $\leq$0.2 mg N $L^{-1}$ and red very high concentrations of >11.3 mg N $L^{-1}$ (World Health Organization drinking water guidelines for $NO_3$-N (World Health Organization, 2022)) for (a) all sites ($n$ = 1704), (b–g) sites characterised by a single dominant land cover type, and (h) sites characterised by a mixture of natural and/or managed land cover types.

Nitrogen export is also an indicator for nitrogen losses from upstream areas through surface runoff, soil erosion and leaching. For a reliable estimate of annual nitrogen export of a given nitrogen compound, regular measurements of nitrogen concentrations and discharge are required for a full hydrological year. The logistical challenges associated with this, especially when sites are located in remote areas, have probably contributed to the low number of studies reporting annual nitrogen export ($n$ = 20). These studies cover 127 sites (4.0 %). Based on these data, DIN and $NO_3$-N exports are higher from agricultural and urban sites, with a median annual DIN export of 1.1 and 1.4 kg N $ha^{-1}$ $y^{-1}$ at cropland and urban sites, respectively, compared to 0.25 kg N $ha^{-1}$ $y^{-1}$ for forested sites (Fig. S3). This supports the hypothesis that inorganic nitrogen losses are higher from agricultural compared to forested sites, whereas forests export more DON (2.1 kg N $ha^{-1}$ $y^{-1}$ for forested sites vs. 0.56 kg N $ha^{-1}$ $y^{-1}$ for cropland sites). Wetlands export the least amount of nitrogen, although sites with $NO_3$-N + $NO_2$-N data were ranked higher than sites from other land cover classes (Fig. S3). Extremely high export values (49.3 to 158.6 kg N $ha^{-1}$ $y^{-1}$) were observed for $NO_3$-N at five sites draining highly urbanised areas of Bukavu on the banks of Lake Kivu (Democratic Republic of the Congo) (Bisimwa et al., 2022).

### 3.3. From seasonal patterns to long-term trends

Climates across sub-Saharan Africa are generally driven by precipitation patterns, which in turn regulate discharge of rivers and streams. This seasonality influences hydro-biogeochemical processes, such as the occurrence of surface runoff, the connectivity of soil and groundwater to streams, biogeochemical transformation processes and leaching. Almost a third of the studies in this synthesis ($n$ = 76, 31 %) purposively conducted sampling campaigns covering the dry and wet seasons to investigate seasonal differences (Fig. S2). In total, 116 studies (48 %) report values specifically for the dry and/or wet season, whereas 73 studies (30 %) report nitrogen concentrations for the same site for both seasons. The latter set of studies was used to investigate seasonal patterns by calculating the effect size representing the difference between wet and dry season concentrations (Fig. 4).

Due to different mobilization and transport processes, different

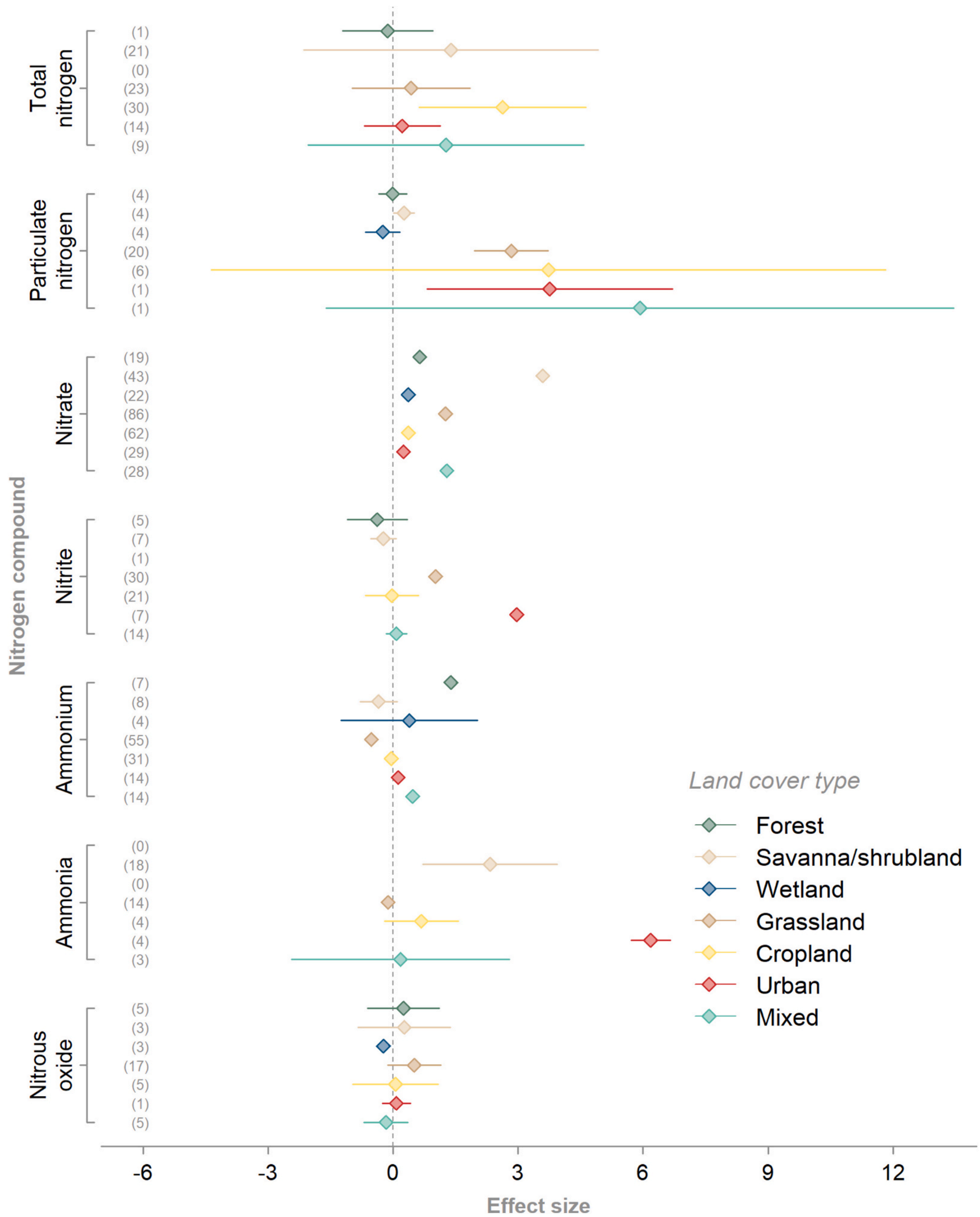



**Fig. 4.** The effect of seasonality on the concentration of different nitrogen compounds in rivers and streams across sub-Saharan Africa. Effect size was calculated using concentrations for the wet and dry seasons for the same site ($n = 381$), whereby higher concentrations during the wet season are represented by positive effect sizes. The number in brackets indicates the number of sites over which the pooled mean effect size (diamond) and standard deviation (line) were calculated.

nitrogen compounds show different behaviour in wet and dry seasons. Runoff-associated nitrogen concentrations, such as PN, are likely to increase during the wet season due to increased surface runoff and associated soil erosion. The highest positive effect sizes, indicating higher concentrations during the wet season are, therefore, also observed for TN and PN, especially at cropland sites (Fig. 4). $NO_2$-N and $NH_4$-N show the highest tendency towards dilution during the wet season, resulting in negative effect sizes for forest and savanna/shrubland sites and for savanna/shrubland and grassland sites, respectively. (Fig. 4). In contrast, $NO_3$-N, and $NH_3$-N tend to get mobilised and increase in concentration in most land cover types. Increased concentrations of dissolved solutes during the wet season are often related to the increased occurrence of leaching and inflow of nitrogen-rich soil or groundwater. Lower concentrations are usually attributed to dilution by a larger volume of water with a low nitrogen content, which is usually the case with precipitation.

The difference in concentrations between the dry and wet season can vary up to several orders of magnitude. Very strong seasonal variations were observed for $NH_4$-N in long-term studies in South Africa (Bird and Scholes, 2012; de Villiers, 2007). A similar phenomenon resulted in the extremely large effect size for urban and mixed land cover sites in KwaZulu-Natal in South Africa (Moodley et al., 2015). This study was excluded from the effect size calculation, as the effect size of the study skewed to mean effect size to >100. High nutrient inputs from surrounding settlements and industry during the rainy season likely caused concentrations that were up to 400 times larger in the wet season than in the dry season (Moodley et al., 2015). In contrast, Bird and Scholes (2012) report lower $NH_4$-N concentrations during the wet season due to dilution, most likely due low nitrogen inputs and dilution from grasslands. Similar strong dilution effects and large negative effect sizes were found for mixed land cover, grassland and cropland sites in the Awash River in Ethiopia, where $NH_4$-N concentrations were around 10 times lower during the wet season (Eliku and Leta, 2018).

The potential large seasonal differences underline the limitations of studies based on single snapshots of nitrogen concentrations in rivers and streams, as the timing of sample collection might render the results more or less representative for the overall nitrogen status of the water body. Although samples collected over a hydrological year provide a better representation than single sampling campaigns, it does not capture potential effects of interannual variability in precipitation and streamflow. Phenomena like El Niño/La Niña, as well as climate change can result in significant differences in rainfall quantities and patterns across years. Also changes in land cover and management can contribute to gradual changes in nitrogen concentrations, which are not captured by studies of short duration. Only 15 % of the studies included in this synthesis use measurements collected for >2 years, mostly based on monthly measurements (16 out of 37 studies; Fig. S2). The historical data from South Africa demonstrates the importance of long-term data, as various authors have been able to link changes in nutrient concentrations to changes in agricultural activity and fertilizer use (de Villiers, 2007; Lemley et al., 2014; Petersen et al., 2017; van der Laan et al., 2012). De Villiers and Thiart (2007), for example, found an increasing trend for dissolved inorganic nitrogen (DIN) concentrations (measured as the sum of $NO_3$-N and $NO_2$-N) in catchments with increased agricultural activity, whereas reduced fertilizer use led to lower concentrations in seven other catchments. De Necker et al. (2020) used long-term data to assess changes along a reach of the Phongolo River, which is regulated by the Pongolapoort Dam, and found that water quality in general had decreased in the lower reaches. The absence of similar data for the majority of sub-Saharan Africa hinders an assessment of how water quality across the content is developing and the identification of basins where interventions are critical to reverse the deterioration of surface water bodies. Only few studies revisit sites that were previously sampled (e.g. Tamooh et al. (2013) and Borges et al. (2015) in the Tana River basin in Kenya or Viers et al. (2000) and Komba et al. (2024) in the Nyong River basin in Cameroon), or compile data from multiple studies to infer on drivers of water quality (Borges et al., 2015; Wanderi et al., 2022).

### 3.4. *The role of hydro-biogeochemical processes*

Behind the spatiotemporal patterns related to land cover and seasonality, there is a multitude of hydrological and biogeochemical processes that affect nitrogen concentrations and stream ecosystems in the short and long term, including legacy effects of past land cover types (Maloney and Weller, 2011). Significant work on understanding seasonal nitrogen cycling was carried out by Marwick et al. (2014) in the Athi-Galana-Sabaki River in Kenya. Using nitrogen concentrations and the stable isotope $^{15}$N in samples collected along the river network during dry and wet seasons, they were able to identify sources, transit and transformation processes of $NO_3$-N, $NH_4$-N and $N_2O$, as well as PN and developed a conceptual understanding of nitrogen cycling in this river. They highlighted that particularly (untreated) wastewater discharge results in significantly higher DIN concentrations, whereas long retention times during the dry season cause substantial DIN removal through denitrification (for $NO_3$–N) and nitrification ($NH_4$–N). The use of $^{15}$N is a relatively recent development, but has been successfully been applied in sub-Saharan Africa to identify sources of nitrogen in surface water (Motitsoe et al., 2020; Nyilitya et al., 2020, 2021; Saka et al., 2023) and understand nitrogen loss pathways (Rütting et al., 2015), thus demonstrating its potential to identify which sources and transport pathways should be addressed to reduce nitrogen pollution.

Other authors used ancillary variables, such as dissolved organic carbon, oxygen and carbon dioxide concentrations to study in-stream biogeochemical processes related to $N_2O$ concentrations and fluxes (Borges et al., 2019; Bouillon et al., 2012; Mwanake et al., 2019; Upstill-Goddard et al., 2017) (also see Box 1). Such ancillary variables are recorded in many studies, particularly those quantifying water quality indices, which usually include of a wide range of parameters. In-depth analysis of the relationship between ancillary variables and different nitrogen species could be useful to predict nitrogen concentrations in rivers and streams where no nitrogen data are available. In the case of $N_2O$, availability of $NO_3$-N and dissolved oxygen seemed to enhance $N_2O$ fluxes due to nitrification, whereas conditions with low dissolved oxygen and high $NH_4$-N concentrations resulted in $N_2O$ removal through denitrification (Borges et al., 2019; Mwanake et al., 2019). Bouillon et al. (2012) related peaks in $N_2O$ concentrations at the onset of the rainy season to the release of large quantities of $NO_3$-N, stimulating denitrification and the production of nitrous oxide. In a similar manner, Jacobs et al. (2018) linked peaks in $NO_3$-N concentrations in tropical montane streams in Kenya at the onset of the rainy season to flushing out of nutrients accumulated in the soil during the dry season. By analysing response to storm events (i.e., hysteresis analysis; Evans and Davies, 1998) and the general relationship between $NO_3$-N and discharge, they were able to infer on processes responsible for $NO_3$-N inputs, such as an increased contribution of nitrate-rich groundwater during the wet season in agricultural catchments. The identification of so-called ‘hot moments’ in nitrogen export and the analysis of short-term responses to rainfall events was made possible by the availability of sub-daily data. Such sub-daily data also allows for the investigation of diurnal patterns in nutrient concentrations, which can be indicative for biogeochemical processes related to stream ecosystem metabolism (Jacobs et al., 2020). Yillia et al. (2008) used sub-daily data to investigate the potential effect of human activities on diurnal variations in water quality. They did not observe any effects on TN concentrations, although dissolved oxygen levels decreased and turbidity and suspended sediment concentrations increased (Yillia et al., 2008).

Stream ecosystem metabolism (gross primary productivity and ecosystem respiration) is considered a key indicator of nutrient and organic matter cycling in aquatic ecosystems and both influences and is influenced by the nutrient status of the stream (Bernot et al., 2010). On one hand different forms of nitrogen provide important substrates to support primary productivity, but the processes related to stream metabolism also determine nitrogen retention and transformation in the river system (Grimm et al., 2005). Maintaining or enhancing the retention capacity of streams was identified as a crucial mechanism to reduce downstream eutrophication in streams affected by sewage discharge in South Africa (Dalu et al., 2019). Other studies investigated the impact of nutrient inputs on ecosystem metabolism and found that enhanced nutrient inputs from agriculture and wildlife enhanced both gross primary productivity and ecosystem respiration (Masese et al., 2017; Subalusky et al., 2018).

### 3.5. *Linking the phosphorus cycle*

Similar to nitrogen, phosphorus is a macronutrient, which is essential for all organisms and closely linked to the carbon cycle through primary production and mineralization of organic matter in aquatic ecosystems. Dissolved inorganic phosphorus, also referred to as soluble reactive phosphorus or SRP, is available for primary producers and microorganisms. SRP is not as soluble as, for example, $NO_3$-N and instead attaches easily to soil particles, meaning that its primary pathway from terrestrial to aquatic ecosystems is through soil erosion (Weigelhofer et al., 2018). The ratio in which nitrogen and phosphorus occur (the N:P ratio) is relevant for primary producers, consumers and decomposers, as their demand for nutrient is controlled by the C:N:P ratio of their bodies compared to their food (Cross et al., 2005). Changes in nutrient load, composition and stoichiometry interact with aquatic food web dynamics and alter the food web structure through different feedbacks (Glibert, 2012), which in turn can affect in-stream nutrient cycling.

The median molar N:P ratio of all sites for which concentrations of

**Box 1**
Riverine nitrous oxide emissions.

Early studies estimated that rivers contribute an equivalent of 10 % of the global anthropogenic nitrous oxide ($N_2O$) emissions through the nitrification and denitrification of anthropogenic dissolved inorganic nitrogen inputs to rivers and streams (Beaulieu et al., 2011). The magnitude of this contribution is still uncertain due to the low number of measurements, particularly in the tropics. The earliest data from sub-Saharan Africa were obtained in April 2009 in the rivers of the Lake Kivu basin (Borges et al., 2015). The studies included here mainly focused on large river systems, such as the Congo and Zambezi (Borges et al., 2019; Teodoru et al., 2015; Upstill-Goddard et al., 2017) with more recent efforts in the Mara river (Mwanake et al., 2019, 2022) and Athi-Galana-Sabaki river (Marwick et al., 2018) in Kenya. The majority of the data is from natural land cover types, particularly forest and savanna/shrubland, as well as grassland, with fewer measurements at sites characterised by cropland or settlement (Table 2), even though rivers experiencing elevated nutrient loads are expected to be larger sources of $N_2O$ (Beaulieu et al., 2011). This is supported by the positive correlation between nitrate and $N_2O$ observed by Bouillon et al. (2012) in the Oubangui river (Congo basin) and by higher $N_2O$ fluxes from agricultural and grassland sites in the Mara river in Kenya (Mwanake et al., 2019, 2022), but contradicts the overall higher $N_2O$ concentrations at sites characterised by high tree cover ($0.64 \pm 0.24$ μg N $L^{-1}$; Table 2). Current evidence suggests that $N_2O$ fluxes from rivers in sub-Saharan Africa are still lower than from rivers in Europe or North America, and that the relative contribution of $N_2O$ to overall greenhouse gas emissions from water bodies is relatively small compared to the contribution of $CO_2$ (Borges et al., 2015; Bouillon et al., 2012).

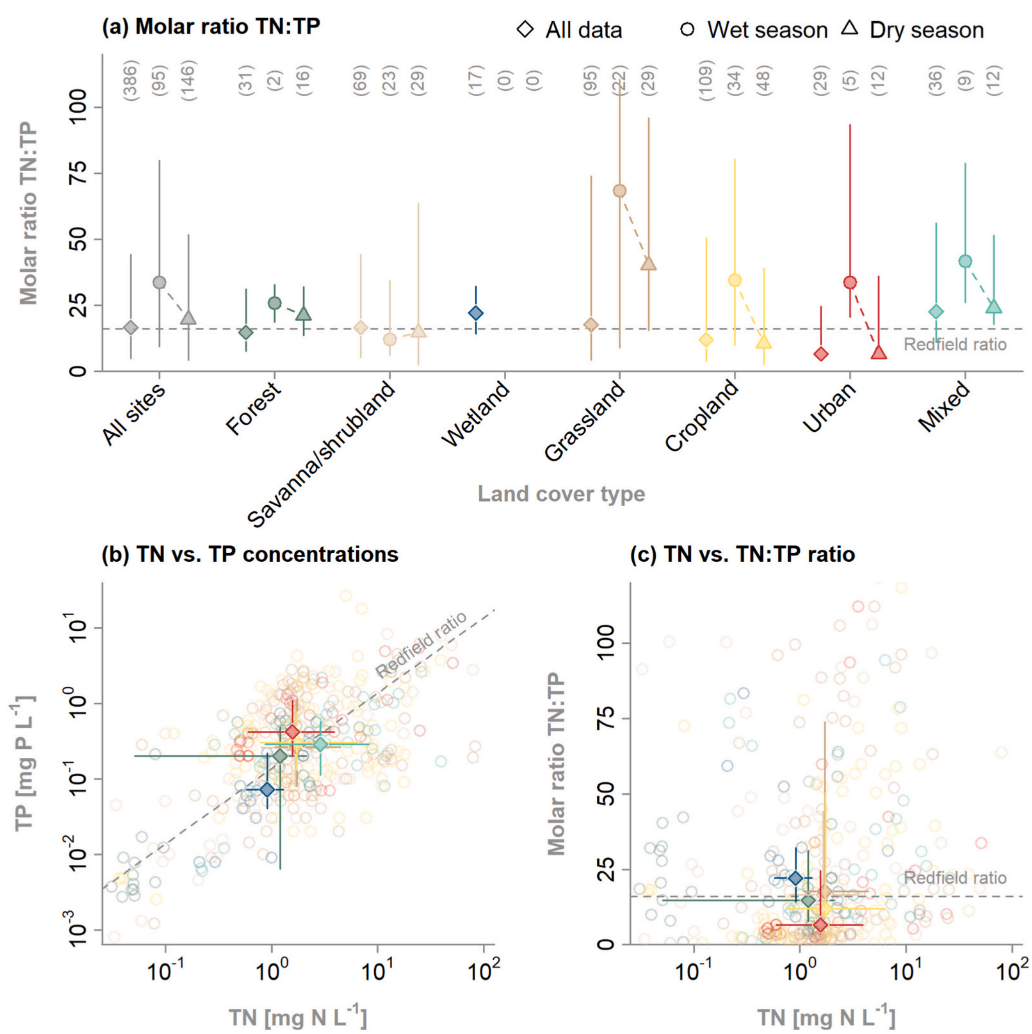



**Fig. 5.** Relationship between total nitrogen (TN) and total phosphorus (TP). (a) Median (symbol) and interquartile range (line) of molar TN to TP ratios at all sites (diamonds), during the wet season (circles) and during the dry season (triangle) for each land cover type. Numbers in brackets indicate the number of sites for which data is available. (b) TN and TP concentrations at all sites (open circles), as well as the median (diamonds) and interquartile range (line) for each land cover type. (c) TN concentrations and molar TN to TP ratios for all sites (open symbols), as well as median (diamonds) and interquartile range (lines) for each land cover type. The dashed line in all plots indicates the Redfield ratio of 16:1. Please note the logaritmic scale for TN and TP concentrations.

both total nitrogen (TN) and total phosphorus (TP) were reported ($n$ = 386, 12 %) is 16.6:1 (interquartile range IQR: 4.8–44.2), which is very close to the 'Redfield ratio' of 16:1 that was observed for phytoplankton in marine environments (Redfield, 1958). N:P ratios in rivers and streams in the United States were reported to be 24.7:1 (IQR: 13.6–44.6) (Maranger et al., 2018). These higher N:P ratios could be related to stronger agricultural impact (high fertilizer use) and subsequent legacy effects in the United States compared to many parts of Africa. Another study in the United States found a median N:P ratio of 31:1 (IQR: 18–64), with forested watersheds generally showing N:P ratios below the Redfield ratio and agricultural and urban watersheds above (Manning et al., 2020). Although the median N:P ratio for forest sites falls below the Redfield ratio (14.6, IQR: 7.7–31.1), median N:P ratios across sub-Saharan Africa are generally higher in natural ecosystems than in managed land cover types. This could be related to nutrient depletion, particularly for nitrogen, of agricultural soils (Stenfert Kroese et al., 2021; Stoorvogel et al., 1993) and overall differences in nutrient limitations and cycling between tropical and temperate ecosystems (Augusto et al., 2017) and warrants further investigation. Sites characterised by settlement and industry have lower N:P ratios than cropland sites (median values of 6.6:1 and 12.0:1, respectively), probably related to enhanced P pollution from sewage systems and poor water treatment. Interestingly, sites characterised by a mixture of land cover types, typically cropland with settlements, have the highest N:P ratios with a median of 22.6:1 (IQR: 11.0–56.2), which cannot be explained by a cumulative effect of the different land cover types.

Most land cover types show a tendency towards a higher N:P ratio during the wet season, whereas savanna and shrubland sites generally have higher N:P ratios during the dry season (Fig. 5a). Greater nitrogen availability during the wet season, as suggested by the positive effect size for many nitrogen compounds (Fig. 4) in combination with increased N:P ratios indicate higher mobility of nitrogen compared to phosphorus. This particularly applies in land cover types where surface runoff and leaching increase nitrogen inputs, such as in urban areas. However, Manning et al. (2020) argue that this usually leads to enrichment of both N and P and, therefore, not necessarily to changes in the N:P ratio. The availability of discharge data could provide further insights in the relationship between land cover, seasonality and N:P ratios, but very few studies reported discharge data alongside nutrient concentrations ($n = 25$, 10 %). Catchment area and stream length could also play a role, as biogeochemical processes along the pathway from headwaters to the ocean likely affect the N:P ratio. Respiratory N losses and gaseous emissions could lower N:P ratios, whereas effective P burial in streams and lakes with high residence times could result in substantial increases in the N:P ratio (Maranger et al., 2018).

Management interventions to reduce phosphorus inputs from point source pollution has led to shifts in the N:P ratio in many rivers worldwide, as the N loading has often not been reduced to the same extent (Westphal et al., 2020). Studies using long-term datasets from South Africa, however, report the opposite (de Villiers, 2007; de Villiers and Thiart, 2007). Nevertheless, these studies were carried out >15 years ago and the general lack of historical data for the African continent hinders the assessment of current trends in phosphorus pollution and N:P ratios. The weak log-linear relationship ($p < 0.001$, $R^2 = 0.367$) between TN and TP concentrations suggests, however, that there is no major nutrient imbalance due to excessive nitrogen inputs. With the exception of urban sites, almost all land cover types plot close to the Redfield ratio of 16:1 (Fig. 5b). This is confirmed by the absence of a clear relationship between TN concentrations and the N:P ratio (Fig. 5c). The highest N:P ratios are generally observed for sites with TN concentrations between 1 and 10 mg N $L^{-1}$.

### 3.6. Updating Africa's research agenda

Africa is a vast continent with a wide range of ecosystems, soil types, climates and population densities. This is reflected in the large variability in nitrogen concentrations in rivers and streams across the continent, even between sites characterised by similar land cover types. The generally lower concentrations at sites in natural land cover types, such as forests and savanna, compared to cropland and, particularly, urban sites, highlight the potential human impact on aquatic ecosystems and riverine nutrient cycling. The extent of this impact in space and time is, however, still uncertain. For example, increased atmospheric nitrogen deposition from biomass burning could already be affecting natural river systems. In absence of long-term data, such trends are practically impossible to investigate. The relatively short funding period of most research projects inhibits the collection of long-term datasets and therefore, research might not be the key solution to this problem. Projects could, however, be used to develop and test monitoring approaches that are suited for the challenging conditions in many sub-Saharan African countries. Such approaches could include community-based participatory monitoring, which would also contribute to increasing the environmental awareness and empowerment of local communities (Njue et al., 2019). Finally, research projects could also play an important role in the capacity building of local stakeholders in water management, including local communities, and equipping relevant institutions with the facilities and skills required to run monitoring schemes.

Regular, long-term monitoring should be complemented by in-depth studies of nitrogen sources and processes. The comparison of median values and effect sizes for different nitrogen compounds, land cover types and seasons in this synthesis allowed for the identification of general spatiotemporal patterns in nitrogen concentrations, but it is clear that we still lack a thorough understanding of underlying drivers and processes. Several studies have demonstrated the use of various tools, such as stable isotopes, high-frequency data from in situ sensors and ancillary parameters, to advance our knowledge of nutrient cycling and ecosystem metabolism in different land cover types and river systems. The results of such studies are extremely valuable, but they cover a relatively small portion of the large continent. Fig. 1a–b highlights that parts of sub-Saharan Africa are virtually black holes when it comes to scientific data regarding nitrogen in rivers and streams. Particularly underrepresented are arid regions, such as the Okavango-Etosha basin and the South West and Atlantic Coast, the Lake Chad basin, the Senegal basin and the North East Coast (Figs. 1b and S4). Although these regions might be less populated and, as a consequence, experience fewer water quality issues, this does not mean that these areas can simply be ignored. In fact, these might be excellent regions to study less disturbed aquatic ecosystems. The more processed-based knowledge we gain, the better we will be able to understand the conditions under which specific processes occur and the potential consequences these have for nutrient cycling. Key aspects that should be considered for more comprehensive studies include covering different flow conditions and the measurements of multiple forms of nitrogen, as each nitrogen compound might behave differently. Previous studies have mostly focused on the analysis of one or two nitrogen compounds, particularly dissolved inorganic forms like nitrate and ammonium, but these are not representative of the total amount of nitrogen in surface water (Dodds, 2003).

Finally, the availability of data alone is not sufficient to improve water management and policy-making (Giest and Samuels, 2020; PARIS21 and Mo Ibrahim Foundation, 2021), even though it is a first step in the right direction. Scientific results should be translated into meaningful outputs that can be used by stakeholders, such as tools for the identification of pollution sources and hotspots for targeted interventions. Process understanding should support the development of sustainable and effective measures to reduce nutrient losses and eutrophication. As such, a whole suite of research approaches is required, from basic research to applied research and innovation projects, to contribute to clean water and healthy aquatic ecosystems for a sustainable future.

## 4. Conclusion

This review of particulate and dissolved nitrogen in rivers and streams across sub-Saharan Africa shows that the availability of data is unevenly distributed across the continent with an underrepresentation of (semi-)arid, sparsely populated areas. From the available data, general patterns in nitrogen concentrations across land cover types could be discerned. Higher concentrations of total nitrogen and different forms of dissolved inorganic nitrogen at sites characterised by cropland and urban land cover types emphasise the important role that humans play. Seasonal differences in concentrations, driven by rainfall, were observed for all nitrogen compounds, with the responses of the different compounds varying in direction and magnitude with land cover. However, the review also demonstrates that we do not have sufficient understanding of the hydro-biogeochemical processes underlying the observed spatiotemporal variations as the majority of the studies simply report nitrogen concentrations without investigating the drivers behind their observations. Addressing data and knowledge gaps following recommendations based on the findings of this review will help to improve our understanding of nitrogen cycling in aquatic ecosystems and their interaction with surrounding terrestrial ecosystems in sub-Saharan Africa and increase the availability of data and knowledge across the subcontinent.

## CRediT authorship contribution statement

**Suzanne R. Jacobs:** Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Lutz Breuer:** Writing – review & editing, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The dataset used for this analysis is compiled from data obtained from originally published manuscripts and, where applicable, their supplementary material, and is provided in an open access online repository (Jacobs and Breuer, 2024).

*Acknowledgements*

This work was enabled through “Integrated Nitrogen Studies in Africa (INSA)”, funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 871944, and “The role of nature for human well-being in the Kilimanjaro Social Ecological System (Kili-SES)” (FOR 5064), subproject “SP 1: Biodiversity and the supply of regulating NCP”, funded by the German Research Foundation (DFG), grant number BR2238/35-1.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.176611.

## References

Adams, J., Gurney, K., Hook, D., Leydesdorff, L., 2014. International collaboration clusters in Africa. Scientometrics 98, 547–556. https://doi.org/10.1007/s11192-013-1060-2.

Ajayi, S.O., Osibanjo, O., 1981. Pollution studies on Nigerian rivers, II: water quality of some Nigerian rivers. Environ. Pollut. B. 2, 87–95. https://doi.org/10.1016/0143-148X(81)90044-6.

Anas, M., Liao, F., Verma, K.K., Sarwar, M.A., Mahmood, A., Chen, Z.-L., Li, Q., Zeng, X.-P., Liu, Y., Li, Y.-R., 2020. Fate of nitrogen in agriculture and environment: agronomic, eco-physiological and molecular approaches to improve nitrogen use efficiency. Biol. Res. 53, 1–20. https://doi.org/10.1186/s40659-020-00312-4.

Audry, S., Ateba Bessa, H., Bedimo Bedimo, J.-P., Boeglin, J.-L., Boithias, L., Braun, J.-J., Dupré, B., Faucheux, M., Lagane, C., Maréchal, J.-C., Ndam-Ngoupayou, J.R., Nka Nnomo, B., Nlozoa, J., Ntonga, J.-C., Ribolzi, O., Riotte, J., Rochelle-Newall, E., Ruiz, L., 2021. The Multiscale TROPIcal CatchmentS critical zone observatory M-TROPICS dataset I: the Nyong River Basin. Cameroon. Hydrol. Process. 35, e14138. https://doi.org/10.1002/hyp.14138.

Augusto, L., Achat, D.L., Jonard, M., Vidal, D., Ringeval, B., 2017. Soil parent material—a major driver of plant nutrient limitations in terrestrial ecosystems. Glob. Chang. Biol. 23, 3808–3824. https://doi.org/10.1111/gcb.13691.

Bakayoko, A., Galy-Lacaux, C., Yoboué, V., Hickman, J.E., Roux, F., Gardrat, E., Julien, F., Delon, C., 2021. Dominant contribution of nitrogen compounds in precipitation chemistry in the Lake Victoria catchment (East Africa). Environ. Res. Lett. 16, 045013. https://doi.org/10.1088/1748-9326/abe25c.

Baumgartner, S., Bauters, M., Drake, T.W., Barthel, M., Alebadwa, S., Bahizire, N., Bazirake, B.M., Six, J., Boeckx, P., Van Oost, K., 2022. Substantial organic and particulate nitrogen and phosphorus export from geomorphologically stable African tropical forest landscapes. Ecosystems 26, 553–567. https://doi.org/10.1007/s10021-022-00773-6.

Beaulieu, J.J., Tank, J.L., Hamilton, S.K., Wollheim, W.M., Jr., R.O.H., Mulholland, P.J., Peterson, B.J., Ashkenas, L.R., Cooper, L.W., Dahm, C.N., Dodds, W.K., Grimm, N.B., Johnson, S.L., McDowell, W.H., Poole, G.C., Valett, H.M., Arango, C.P., Bernot, M.J., Burgin, A.J., Crenshaw, C.L., Helton, A.M., Johnson, L.T., O'Brien, J.M., Potter, J.D., Sheibley, R.W., Sobota, D.J., Thomas, S.M., Schlesinger, W.H., 2011. Nitrous oxide emission from denitrification in stream and river networks. PNAS 108, 214–219.

Bernot, M.J., Sobota, D.J., Hall Jr, R.O., Mulholland, P.J., Dodds, W.K., Webster, J.R., Tank, J.L., Ashkenas, L.R., Cooper, L.W., Dahm, C.N., Gregory, S.V., Grimm, N.B., Hamilton, S.K., Johnson, S.L., Mcdowell, W.H., Meyer, J.L., Peterson, B., Poole, G.C., Valett, H.M., Arango, C., Beaulieu, J.J., Burgin, A.J., Crenshaw, C., Helton, A.M., Johnson, L., Merriam, J., Niederlehner, B.R., O'brien, J.M., Potter, J.D., Sheibley, R. W., Thomas, S.M., Wilson, K., 2010. Inter-regional comparison of land-use effects on stream metabolism. Freshw. Biol. 55, 1874–1890. doi:https://doi.org/10.1111/j.1365-2427.2010.02422.x.

Bird, T.L., Scholes, M.C., 2012. Using multivariate statistical analysis to assess changes in water chemistry in sections of the Vaal Dam catchment between 1991 and 2008. Water SA 38, 647–654. https://doi.org/10.4314/wsa.v38i5.1.

Bisimwa, A.M., Amisi, F.M., Bamawa, C.M., Muhaya, B.B., Kankonda, A.B., 2022. Water quality assessment and pollution source analysis in Bukavu urban rivers of the Lake Kivu basin (Eastern Democratic Republic of Congo). Environ. Sustain. Indic. 14, 100183. https://doi.org/10.1016/j.indic.2022.100183.

Borges, A.V., Darchambeau, F., Teodoru, C.R., Marwick, T.R., Tamooh, F., Geeraert, N., Omengo, F.O., Guérin, F., Lambert, T., Morana, C., Okuku, E., Bouillon, S., 2015. Globally significant greenhouse-gas emissions from African inland waters. Nat. Geosci. 8, 637. https://doi.org/10.1038/ngeo2486.

Borges, A.V., Darchambeau, F., Lambert, T., Morana, C., Allen, G.H., Tambwe, E., Toengaho Sembaito, A., Mambo, T., Nlandu Wabakhangazi, J., Descy, J.-P., Teodoru, C.R., Bouillon, S., 2019. Variations in dissolved greenhouse gases ($CO_2$, $CH_4$, $N_2O$) in the Congo River network overwhelmingly driven by fluvial-wetland connectivity. Biogeosciences 16, 3801–3834. https://doi.org/10.5194/bg-16-3801-2019.

Bouillon, S., Yambélé, A., Spencer, R.G.M., Gillikin, D.P., Hernes, P.J., Six, J., Merckx, R., Borges, A.V., 2012. Organic matter sources, fluxes and greenhouse gas exchange in the Oubangui River (Congo River basin). Biogeosciences 9, 2045–2062. https://doi.org/10.5194/bg-9-2045-2012.

Breitburg, D., Levin, L.A., Oschlies, A., Grégoire, M., Chavez, F.P., Conley, D.J., Garçon, V., Gilbert, D., Gutiérrez, D., Isensee, K., Jacinto, G.S., Limburg, K.E., Montes, I., Naqvi, S.W.A., Pitcher, G.C., Rabalais, N.N., Roman, M.R., Rose, K.A., Seibel, B.A., Telszewski, M., Yasuhara, M., Zhang, J., 2018. Declining oxygen in the global ocean and coastal waters. Science 359, eaam7240. https://doi.org/10.1126/science.aam7240.

Cerdeira, J., Mesquita, J., Vieira, E.S., 2023. International research collaboration: is Africa different? A cross-country panel data analysis. Scientometrics 128, 2145–2174. https://doi.org/10.1007/s11192-023-04659-9.

Coetzee, J.A., Hill, M.P., 2012. The role of eutrophication in the biological control of water hyacinth, *Eichhornia crassipes*, in South Africa. BioControl 57, 247–261. https://doi.org/10.1007/s10526-011-9426-y.

Cross, W.F., Benstead, J.P., Frost, P.C., Thomas, S.A., 2005. Ecological stoichiometry in freshwater benthic systems: recent progress and perspectives. Freshw. Biol. 50, 1895–1912. https://doi.org/10.1111/j.1365-2427.2005.01458.x.

Dalu, T., Wasserman, R.J., Magoro, M.L., Froneman, P.W., Weyl, O.L.F., 2019. River nutrient water and sediment measurements inform on nutrient retention, with implications for eutrophication. Sci. Total Environ. 684, 296–302. https://doi.org/10.1016/j.scitotenv.2019.05.167.

Dinku, T., 2019. Chapter 7 - challenges with availability and quality of climate data in Africa. In: Melesse, A.M., Abtew, W., Senay, G. (Eds.), Extreme Hydrology and Climate Variability. Elsevier, pp. 71–80. https://doi.org/10.1016/B978-0-12-815998-9.00007-5.

Dodds, W.K., 2003. Misuse of inorganic N and soluble reactive P concentrations to indicate nutrient status of surface waters. J. N. Am. Benthol. Soc. 22, 171–181. https://doi.org/10.2307/1467990.

Doney, S.C., 2010. The growing human footprint on coastal and open-ocean biogeochemistry. Science 328, 1512–1516. https://doi.org/10.1126/science.1185198.

Edegbene, A.O., Akamagwuna, F.C., Odume, O.N., Arimoro, F.O., Edegbene Ovie, T.T., Akumabor, E.C., Ogidiaka, E., Kaine, E.A., Nwaka, K.H., 2022. A macroinvertebrate-based multimetric index for assessing ecological condition of forested stream sites draining Nigerian urbanizing landscapes. Sustainability 14, 11289. https://doi.org/10.3390/su141811289.

Eliku, T., Leta, S., 2018. Spatial and seasonal variation in physicochemical parameters and heavy metals in Awash River, Ethiopia. Appl Water Sci 8, 177. https://doi.org/10.1007/s13201-018-0803-x.

European Environment Agency, 2022. Status of nitrates in rivers in European countries [WWW Document]. URL. https://www.eea.europa.eu/data-and-maps/daviz/nitrate-in-rivers-4/#tab-chart_2 (accessed 8.11.23).

Evans, C., Davies, T.D., 1998. Causes of concentration/discharge hysteresis and its potential as a tool for analysis of episode hydrochemistry. Water Resour. Res. 34, 129–137. https://doi.org/10.1029/97WR01881.

Fetahi, T., 2019. Eutrophication of Ethiopian water bodies: a serious threat to water quality, biodiversity and public health. Afr. J. Aquat. Sci. 44, 303–312. https://doi.org/10.2989/16085914.2019.1663722.

Galy-Lacaux, C., Delon, C., 2014. Nitrogen emission and deposition budget in West and Central Africa. Environ. Res. Lett. 9, 125002. https://doi.org/10.1088/1748-9326/9/12/125002.

Gichuki, J., Omondi, R., Boera, P., Okorut, T., Matano, A.S., Jembe, T., Ofulla, A., 2012. Water hyacinth *Eichhornia crassipes* (Mart.) Solms-Laubach dynamics and succession in the Nyanza Gulf of Lake Victoria (East Africa): implications for water quality and biodiversity conservation. Sci. World J. 2012, e106429. https://doi.org/10.1100/2012/106429.

Giest, S., Samuels, A., 2020. 'For good measure': data gaps in a big data world. Policy. Sci. 53, 559–569. https://doi.org/10.1007/s11077-020-09384-1.

Glibert, P.M., 2012. Ecological stoichiometry and its implications for aquatic ecosystem sustainability. Curr. Opin. Environ. Sustain. 4, 272–277. https://doi.org/10.1016/j.cosust.2012.05.009.

Grimm, N.B., Sheibley, R.W., Crenshaw, C.L., Dahm, C.N., Roach, W.J., Zeglin, L.H., 2005. N retention and transformation in urban streams. J. N. Am. Benthol. Soc. 24, 626–642. https://doi.org/10.1899/04-027.1.

Gumbricht, T., Román-Cuesta, R.M., Verchot, L.V., Herold, M., Wittmann, F., Householder, E., Herold, N., Murdiyarso, D., 2024. Tropical and subtropical wetlands distribution [dataset]. Dataverse v7.1. https://doi.org/10.17528/CIFOR/DATA.00058.

Hall, A., Valente, I.M.C.B.S., Davies, B.R., 1977. The Zambezi River in Moçambique: the physico-chemical status of the Middle and Lower Zambezi prior to the closure of the Cabora Bassa Dam. Freshw. Biol. 7, 187–206. https://doi.org/10.1111/j.1365-2427.1977.tb01668.x.

He, B., Kanae, S., Oki, T., Hirabayashi, Y., Yamashiki, Y., Takara, K., 2011. Assessment of global nitrogen pollution in rivers using an integrated biogeochemical modeling framework. Water Res. 45, 2573–2586. https://doi.org/10.1016/j.watres.2011.02.011.

Jacobs, S.R., Breuer, L., 2024. Dataset of nitrogen in rivers and streams in sub-Saharan Africa [dataset]. Zenodo v2. https://doi.org/10.5281/zenodo.13252417.

Jacobs, S.R., Breuer, L., Butterbach-Bahl, K., Pelster, D.E., Rufino, M.C., 2017. Land use affects total dissolved nitrogen and nitrate concentrations in tropical montane streams in Kenya. Sci. Total Environ. 603–604, 519–532. https://doi.org/10.1016/j.scitotenv.2017.06.100.

Jacobs, S.R., Weeser, B., Guzha, A.C., Rufino, M.C., Butterbach-Bahl, K., Windhorst, D., Breuer, L., 2018. Using high-resolution data to assess land use impact on nitrate dynamics in East African tropical montane catchments. Water Resour. Res. 54, 1812–1830. https://doi.org/10.1002/2017WR021592.

Jacobs, S.R., Weeser, B., Rufino, M.C., Breuer, L., 2020. Diurnal patterns in solute concentrations measured with *in situ* UV-vis sensors: natural fluctuations or artefacts? Sensors 20, 859. https://doi.org/10.3390/s20030859.

Kiage, L.M., 2013. Perspectives on the assumed causes of land degradation in the rangelands of Sub-Saharan Africa. Prog. Phys. Geog. Earth Environ. 37, 664–684. https://doi.org/10.1177/0309133313492543.

Komba, D.E., Nlend, B., Braun, J.J., Boum-Nkot, S.N., Audry, S., Nkoue Ndondo, G.R., Riotte, J., Nnomo, B.N., Ntamak-Nida, M.J., Etame, J., Fongoh, E.J., Bessa, H.A., Lagane, C., Ngoupayou, J.R.N., 2024. Chemical weathering and $CO_2$ consumption in the upper Nyong Basin rivers (Central Africa): insights on climatic and anthropogenic forcing in humid tropical environments. Sci. Total Environ. 937, 173405. https://doi.org/10.1016/j.scitotenv.2024.173405.

van der Laan, M., van Antwerpen, R., Bristow, K.L., 2012. River water quality in the northern sugarcane-producing regions of South Africa and implications for irrigation: a scoping study. Water SA 38, 87–96. https://doi.org/10.4314/wsa.v38i1.11.

Le Moal, M., Gascuel-Odoux, C., Ménesguen, A., Souchon, Y., Étrillard, C., Levain, A., Moatar, F., Pannard, A., Souchu, P., Lefebvre, A., Pinay, G., 2019. Eutrophication: a new wine in an old bottle? Sci. Total Environ. 651, 1–11. https://doi.org/10.1016/j.scitotenv.2018.09.139.

Lehner, B., Verdin, K., Jarvis, A., 2008. New global hydrography derived from spaceborne elevation data. Eos 89, 93–94. https://doi.org/10.1029/2008EO100001.

Lemley, D.A., Taljaard, S., Adams, J.B., Strydom, N., 2014. Nutrient characterisation of river inflow into the estuaries of the Gouritz Water Management Area, South Africa. Water SA 40, 687–698. https://doi.org/10.4314/wsa.v40i4.14.

Lesack, L.F.W., Hecky, R.E., Melack, J.M., 1984. Transport of carbon, nitrogen, phosphorus, and major solutes in the Gambia River, West Africa. Limnol. Oceanogr. 29, 816–830. https://doi.org/10.4319/lo.1984.29.4.0816.

Liu, J., You, L., Amini, M., Obersteiner, M., Herrero, M., Zehnder, A.J.B., Yang, H., 2010. A high-resolution assessment on global nitrogen flows in cropland. PNAS 107, 8035–8040. https://doi.org/10.1073/pnas.0913658107.

Maloney, K.O., Weller, D.E., 2011. Anthropogenic disturbance and streams: land use and land-use change affect stream ecosystems via multiple pathways. Freshw. Biol. 56, 611–626. https://doi.org/10.1111/j.1365-2427.2010.02522.x.

Manning, D.W.P., Rosemond, A.D., Benstead, J.P., Bumpers, P.M., Kominoski, J.S., 2020. Transport of N and P in U.S. streams and rivers differs with land use and between dissolved and particulate forms. Ecol. Appl. 30, e02130. https://doi.org/10.1002/eap.2130.

Maranger, R., Jones, S.E., Cotner, J.B., 2018. Stoichiometry of carbon, nitrogen, and phosphorus through the freshwater pipe. Limnol. Oceanogr. Lett. 3, 89–101. https://doi.org/10.1002/lol2.10080.

Marconcini, M., Metz-Marconcini, A., Üreyen, S., Palacios-Lopez, D., Hanke, W., Bachofer, F., Zeidler, J., Esch, T., Gorelick, N., Kakarla, A., Paganini, M., Strano, E., 2020. Outlining where humans live, the world settlement footprint 2015. Sci. Data 7, 242. https://doi.org/10.1038/s41597-020-00580-5.

Marwick, T.R., Tamooh, F., Ogwoka, B., Teodoru, C., Borges, A.V., Darchambeau, F., Bouillon, S., 2014. Dynamic seasonal nitrogen cycling in response to anthropogenic N loading in a tropical catchment, Athi–Galana–Sabaki River, Kenya. Biogeosciences 11, 443–460. https://doi.org/10.5194/bg-11-443-2014.

Marwick, T.R., Tamooh, F., Ogwoka, B., Borges, A.V., Darchambeau, F., Bouillon, S., 2018. A comprehensive biogeochemical record and annual flux estimates for the Sabaki River (Kenya). Biogeosciences 15, 1683–1700. https://doi.org/10.5194/bg-15-1683-2018.

Masese, F.O., Salcedo-Borda, J.S., Gettel, G.M., Irvine, K., McClain, M.E., 2017. Influence of catchment land use and seasonality on dissolved organic matter composition and ecosystem metabolism in headwater streams of a Kenyan river. Biogeochemistry 132, 1–22. https://doi.org/10.1007/s10533-016-0269-6.

Masso, C., Baijukya, F., Ebanyat, P., Bouaziz, S., Wendt, J., Bekunda, M., Vanlauwe, B., 2017. Dilemma of nitrogen management for future food security in sub-Saharan Africa – a review. Soil Res. 55, 425–434. https://doi.org/10.1071/SR16332.

McDowell, R.W., Noble, A., Pletnyakov, P., Mosley, L.M., 2021. Global database of diffuse riverine nitrogen and phosphorus loads and yields. Geosci. Data J. 8, 132–143. https://doi.org/10.1002/gdj3.111.

Mikolajewicz, N., Komarova, S.V., 2019. Meta-analytic methodology for basic research: a practical guide. Front. Physiol. 10, 203. https://doi.org/10.3389/fphys.2019.00203.

Moodley, K., Pillay, S., Pather, K., 2015. Spatiotemporal characterization of water chemistry and pollution sources of the Umhlatuzana, Umbilo and Amanzimnyama River catchments of Durban, KwaZulu-Natal, South Africa. Environ. Earth Sci. 74, 1273–1289. https://doi.org/10.1007/s12665-015-4118-z.

Motitsoe, S.N., Hill, M.P., Avery, T.S., Hill, J.M., 2020. A new approach to the biological monitoring of freshwater systems: mapping nutrient loading in two South African rivers, a case study. Water Res. 171, 115391. https://doi.org/10.1016/j.watres.2019.115391.

Mwanake, R.M., Gettel, G.M., Aho, K.S., Namwaya, D.W., Masese, F.O., Butterbach-Bahl, K., Raymond, P.A., 2019. Land use, not stream order, controls $N_2O$ concentration and flux in the upper Mara River basin, Kenya. J. Geophys. Res.-Biogeo. 124, 3491–3506. https://doi.org/10.1029/2019JG005063.

Mwanake, R.M., Gettel, G.M., Ishimwe, C., Wangari, E.G., Butterbach-Bahl, K., Kiese, R., 2022. Basin-scale estimates of greenhouse gas emissions from the Mara River, Kenya: importance of discharge, stream size, and land use/land cover. Limnol. Oceanogr. 67, 1776–1793. https://doi.org/10.1002/lno.12166.

de Necker, L., Neswiswi, T., Greenfield, R., van Vuren, J., Brendonck, L., Wepener, V., Smit, N., 2020. Long-term water quality patterns of a flow regulated tropical lowland river. Water 12, 37. https://doi.org/10.3390/w12010037.

Njue, N., Stenfert Kroese, J., Gräf, J., Jacobs, S.R., Weeser, B., Breuer, L., Rufino, M.C., 2019. Citizen science in hydrological monitoring and ecosystem services management: state of the art and future prospects. Sci. Total Environ. 693, 133531. https://doi.org/10.1016/j.scitotenv.2019.07.337.

Nyenje, P.M., Foppen, J.W., Uhlenbrook, S., Kulabako, R., Muwanga, A., 2010. Eutrophication and nutrient release in urban areas of sub-Saharan Africa — a review. Sci. Total Environ. 408, 447–455. https://doi.org/10.1016/j.scitotenv.2009.10.020.

Nyilitya, B., Mureithi, S., Boeckx, P., 2020. Land use controls Kenyan riverine nitrate discharge into Lake Victoria – evidence from Nyando, Nzoia and Sondu Miriu river catchments. Isot. Environ. Healt. S. 56, 170–192. https://doi.org/10.1080/10256016.2020.1724999.

Nyilitya, B., Mureithi, S., Bauters, M., Boeckx, P., 2021. Nitrate source apportionment in the complex Nyando tropical river basin in Kenya. J. Hydrol. 594, 125926. https://doi.org/10.1016/j.jhydrol.2020.125926.

Otu, M.K., Ramlal, P., Wilkinson, P., Hall, R.I., Hecky, R.E., 2011. Paleolimnological evidence of the effects of recent cultural eutrophication during the last 200 years in Lake Malawi, East Africa. J. Great Lakes Res. 37, 61–74. https://doi.org/10.1016/j.jglr.2010.09.009.

PARIS21, Mo Ibrahim Foundation, 2021. Bridging the Data-policy Gap in Africa. Recommendations to National Statistical Offices and Governments to Enhance the Production and Use of Data for Evidence-based Policymaking. PARIS21 & MIF.

Pellerin, B.A., Wollheim, W.M., Hopkinson, C.S., McDowell, W.H., Williams, M.R., Vörösmarty, C.J., Daley, M.L., 2004. Role of wetlands and developed land use on dissolved organic nitrogen concentrations and DON/TDN in northeastern U.S. rivers and streams. Limnol. Oceanogr. 49, 910–918. https://doi.org/10.4319/lo.2004.49.4.0910.

Petersen, C.R., Jovanovic, N.Z., Maitre, D.L., Grenfell, M.C., 2017. Effects of land use change on streamflow and stream water quality of a coastal catchment. Water SA 43, 139–152. https://doi.org/10.4314/wsa.v43i1.16.

du Plessis, A., 2022. Persistent degradation: global water quality challenges and required actions. One Earth. 5, 129–131. https://doi.org/10.1016/j.oneear.2022.01.005.

Potapov, P., Turubanova, S., Hansen, M.C., Tyukavina, A., Zalles, V., Khan, A., Song, X.-P., Pickens, A., Shen, Q., Cortez, J., 2022. Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. Nat. Food. 3, 19–28. https://doi.org/10.1038/s43016-021-00429-z.

Redfield, A.C., 1958. The biological control of chemical factors in the environment. Am. Sci. 46, 230A–221.

Reiner, F., Brandt, M., Tong, X., Skole, D., Kariryaa, A., Ciais, P., Davies, A., Hiernaux, P., Chave, J., Mugabowindekwe, M., Igel, C., Oehmcke, S., Gieseke, F., Li, S., Liu, S., Saatchi, S., Boucher, P., Singh, J., Taugourdeau, S., Dendoncker, M., Song, X.-P., Mertz, O., Tucker, C.J., Fensholt, R., 2023. Africa tree cover map [dataset]. Zenodo v1. https://doi.org/10.5281/zenodo.7764460.

Rütting, T., Cizungu Ntaboba, L., Roobroeck, D., Bauters, M., Huygens, D., Boeckx, P., 2015. Leaky nitrogen cycle in pristine African montane rainforest soil. Glob. Biogeochem. Cy. 29, 1754–1762. https://doi.org/10.1002/2015GB005144.

Saka, D., Adu-Gyamfi, J., Skrzypek, G., Antwi, E.O., Heng, L., Torres- Martínez, J.A., 2023. Disentangling nitrate pollution sources and apportionment in a tropical agricultural ecosystem using a multi-stable isotope model. Environ. Pollut. 328, 121589. https://doi.org/10.1016/j.envpol.2023.121589.

Sheikholeslami, R., Hall, J.W., 2023. Global patterns and key drivers of stream nitrogen concentration: a machine learning approach. Sci. Total Environ. 868, 161623. https://doi.org/10.1016/j.scitotenv.2023.161623.

Stenfert Kroese, J., Quinton, J.N., Jacobs, S.R., Breuer, L., Rufino, M.C., 2021. Particulate macronutrient exports from tropical African montane catchments point to the impoverishment of agricultural soils. SOIL 7, 53–70. https://doi.org/10.5194/soil-7-53-2021.

Stoorvogel, J.J., Smaling, E.M.A., Janssen, B.H., 1993. Calculating soil nutrient balances in Africa at different scales. Fert. Res. 35, 227–235. https://doi.org/10.1007/BF00750641.

Subalusky, A.L., Dutton, C.L., Njoroge, L., Rosi, E.J., Post, D.M., 2018. Organic matter and nutrient inputs from large wildlife influence ecosystem function in the Mara River, Africa. Ecology 99, 2558–2574. https://doi.org/10.1002/ecy.2509.

Tamooh, F., Borges, A.V., Meysman, F.J.R., Van Den Meersche, K., Dehairs, F., Merckx, R., Bouillon, S., 2013. Dynamics of dissolved inorganic carbon and aquatic metabolism in the Tana River basin, Kenya. Biogeosciences 10, 6911–6928. https://doi.org/10.5194/bg-10-6911-2013.

Teodoru, C.R., Nyoni, F.C., Borges, A.V., Darchambeau, F., Nyambe, I., Bouillon, S., 2015. Dynamics of greenhouse gases ($CO_2$, $CH_4$, $N_2O$) along the Zambezi River and major tributaries, and their importance in the riverine carbon budget. Biogeosciences 12, 2431–2453. https://doi.org/10.5194/bg-12-2431-2015.

Tramblay, Y., Rouché, N., Paturel, J.-E., Mahé, G., Boyer, J.-F., Amoussou, E., Bodian, A., Dacosta, H., Dakhlaoui, H., Dezetter, A., Hughes, D., Hanich, L., Peugeot, C., Tshimanga, R., Lachassagne, P., 2021. ADHI: the African database of hydrometric indices (1950–2018). Earth Syst. Sci. Data. 13, 1547–1560. https://doi.org/10.5194/essd-13-1547-2021.

Upstill-Goddard, R.C., Salter, M.E., Mann, P.J., Barnes, J., Poulsen, J., Dinga, B., Fiske, G. J., Holmes, R.M., 2017. The riverine source of $CH_4$ and $N_2O$ from the republic of Congo, western Congo Basin. Biogeosciences 14, 2267–2281. https://doi.org/10.5194/bg-14-2267-2017.

Van Drecht, G., Bouwman, A.F., Harrison, J., Knoop, J.M., 2009. Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050. Glob. Biogeochem. Cy. 23, GB0A03. https://doi.org/10.1029/2009GB003458.

Van Schalkwyk, F., 2016. Open Data Barometer, Third edition. Africa. World Wide Web Foundation, Regional Report.

Viers, J., Dupré, B., Braun, J.-J., Deberdt, S., Angeletti, B., Ngoupayou, J.N., Michard, A., 2000. Major and trace element abundances, and strontium isotopes in the Nyong basin rivers (Cameroon): constraints on chemical weathering processes and elements transport mechanisms in humid tropical environments. Chem. Geol. 169, 211–241. https://doi.org/10.1016/S0009-2541(00)00298-9.

de Villiers, S., 2007. The deteriorating nutrient status of the Berg River, South Africa. Water SA 33, 659–664. https://doi.org/10.4314/wsa.v33i5.

de Villiers, S., Thiart, C., 2007. The nutrient status of South African rivers: concentrations, trends and fluxes from the 1970s to 2005. S. Afr. J. Sci. 103, 343–349.

Wanderi, E.W., Gettel, G.M., Singer, G.A., Masese, F.O., 2022. Drivers of water quality in Afromontane-savanna rivers. Front. Environ. Sci. 10, 972153. https://doi.org/10.3389/fenvs.2022.972153.

Weigelhofer, G., Hein, T., Bondar-Kunze, E., 2018. Phosphorus and nitrogen dynamics in riverine systems: Human impacts and management options. In: Schmutz, S., Sendzimir, J. (Eds.), Riverine Ecosystem Management: Science for Governing Towards a Sustainable Future, Aquatic Ecology Series. Springer International Publishing, Cham, pp. 187–202. https://doi.org/10.1007/978-3-319-73250-3_10.

Westphal, K., Musolff, A., Graeber, D., Borchardt, D., 2020. Controls of point and diffuse sources lowered riverine nutrient concentrations asynchronously, thereby warping molar N:P ratios. Environ. Res. Lett. 15, 104009. https://doi.org/10.1088/1748-9326/ab98b6.

Willett, V.B., Reynolds, B.A., Stevens, P.A., Ormerod, S.J., Jones, D.L., 2004. Dissolved organic nitrogen regulation in freshwaters. J. Environ. Qual. 33, 201–209. https://doi.org/10.2134/jeq2004.2010.

World Health Organization, 2022. Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First and Second Addenda. World Health Organization, Geneva, Switzerland.

Yillia, P.T., Kreuzinger, N., Mathooko, J.M., 2008. The effect of in-stream activities on the Njoro River, Kenya. Part I: stream flow and chemical water quality. Phys. Chem. Earth 33, 722–728. https://doi.org/10.1016/j.pce.2008.06.041.