frontiers | Frontiers in Water

TYPE Original Research
PUBLISHED 26 November 2025
DOI 10.3389/frwa.2025.1691103

Rewetting as a hot-moment for NO_3^- and NH_4^+ consumption in sediment of non-perennial rivers in the semiarid region

Patricia A. Velasquez-Vottelerd[1], Antonio E. B. Silva[1,2,3]*, Hermano M. Queiroz[3,4], Tamara M. Pereira[1], Gabriel N. Nóbrega[3,5], Maria R. N. Duarte[1], Daniel P. Oliveira[1,6], Carla F. Rezende[1] and Tiago O. Ferreira[2,3]

[1]Postgraduate in Ecology and Natural Resources, Department of Biology, Federal University of Ceará, Fortaleza, Brazil, [2]Department of Soil Science, "Luiz de Queiroz" College of Agriculture, University of São Paulo, Piracicaba, Brazil, [3]Research Centre for Greenhouse Gas Innovation – RCGI, University of São Paulo, Av. Professor Mello Moraes, São Paulo, SP, Brazil, [4]Department of Geography, University of São Paulo, Av. Prof. Lineu Prestes, Cidade Universitária, São Paulo, Brazil, [5]Department of Soil Science, Federal University of Ceará, Fortaleza, Brazil, [6]Research Institute of Meteorology and Water Resources (FUNCEME), Fortaleza, Brazil

Non-perennial rivers (NPRs) occur all over continents, despite more than 50% being located in arid, semi-arid, and tropical regions. NPRs act as biogeochemists hotspots, in which flows drive ecological processes and nutrient cycling (e.g., nitrogen – N). The aim of this study was to investigate how the hydrological regime drives nitrogen concentrations and forms in an NPR located in the semi-arid region of Ceará, Brazil. We hypothesized that the rewetting phase acts as a "hot moment" for nitrogen dynamics, resulting in N depletion followed by increased concentrations during dry periods. We analyzed the physicochemical characteristic, nitrogen forms, organic carbon and sulfur concentrations of sediment samples (129) collected during three hydrological phases (Dry, Rewetting, and Flow). Physicochemical analyses indicated that the sediments were predominantly sandy and exhibited variations in redox potential (Eh), pH, and dissolved oxygen (DO). Regards the hydrological phases, amonium levels ($N{-}NH_4^+$) in sediments differed significantly across them, reaching values approximately four times higher (∼74.9% increase) during the dry phase compared with the rewetting phase (i.e., dry: 3.25 ± 2.9 mg kg^{-1}; flow: 2.49 ± 1.91 mg kg^{-1}; rewetting: 0.72 ± 1.21 mg kg^{-1}). For $N\text{-}NO_3^-$, concentrations in the dry and flow phases dry and flow phases were about 13 times higher than those observed in the rewetting phase, corresponding to 92.1% increase (i.e., dry: 1.34 ± 1.40 mg kg^{-1}; flow: 0.85 ± 1.30 mg kg^{-1}; rewetting: 0.12 ± 0.14 mg kg^{-1}). Our results highlight the role of hydrological dynamics in influencing nutrient availability, suggesting that the rewetting phase should be considered a "hot moment" in NPRs. During this period, there is a rapid response in nitrogen processing driven by the water in the riverbed, which provides information on how drought could act on nutrient cycling. Such as most rivers in semiarid regions are non-perennial, prolonged droughts under climate change scenarios are expected to reduce primary production, impacting biodiversity (i.e., population and community ecology). This is particularly relevant in the context of reduced natural flow due to water abstraction, damming, and climate change.

KEYWORDS

drought, rivers, nitrogen forms, birch effect, nutrient cycling

OPEN ACCESS

EDITED BY
George P. Karatzas,
Technical University of Crete, Greece

REVIEWED BY
Renhua Yan,
Nanjing Institute of Geography and Limnology, China
Maria Pia Gervasio,
University of Ferrara, Italy

*CORRESPONDENCE
Antonio E. B. Silva
✉ daniel.oliveira@funceme.br

RECEIVED 22 August 2025
ACCEPTED 28 October 2025
PUBLISHED 26 November 2025

CITATION
Velasquez-Vottelerd PA, Silva AEB, Queiroz HM, Pereira TM, Nóbrega GN, Duarte MRN, Oliveira DP, Rezende CF and Ferreira TO (2025) Rewetting as a hot-moment for NO_3^- and NH_4^+ consumption in sediment of non-perennial rivers in the semiarid region. *Front. Water* 7:1691103. doi: 10.3389/frwa.2025.1691103

1 Introduction

Non-perennial rivers (NPRs) comprise more than 50 % of the world's river networks (Messager et al., 2021), representing a large proportion of the channels that cease flow or dry periodically (Allen et al., 2020; Sauquet et al., 2021), causing nutrient intermittency driven by the alternation between lentic and lotic phases (von Schiller et al., 2017), and exhibiting temporal, spatial nutrient pulses and acting as biogeochemical reactors (von Schiller et al., 2017; Shumilova et al., 2019). Furthermore, NPRs have been identified as empirical models for future climate change scenarios, which project longer drought phases, providing insights into nutrient biogeochemical cycles in perennial rivers (da Silva et al., 2024).

Biogeochemical dynamics of nutrients in NPRs encompass the processes of input, transformation, and removal/export of these elements for low land ecosystems (von Schiller et al., 2008, 2011; Arce et al., 2018). The knowledge of nutrients dynamics, such as nitrogen (N) and phosphorus (P), is critical to understand processes of ecosystem productivity, and the maintenance of habitats associated with aquatic systems (Peñuelas et al., 2013; Ceulemans et al., 2017; Du et al., 2020; Wu et al., 2022). Nitrogen, in particular, plays a pivotal role and can enter aquatic environments through atmospheric deposition, microbial fixation, discharges from industrial and agricultural activities, and biological transformations involving organic matter (Du et al., 2020). However, nitrogen availability is often constrained by its consumption through processes such as denitrification or its export during the lotic phases of river flow (Austin and Strauss, 2011), thereby limiting its bioavailability within the aquatic system.

Research on nutrient cycles and nutrient processing rates in NPRs remains limited in semiarid tropical regions (da Silva et al., 2024), where hydrological dynamics exhibit greater variability (Soares et al., 2024). Consequently, the temporal and spatial availability of nitrogen may be limited, depending on the hydrological phase. For example, during drier phases, nitrogen inputs from biological processes, sediment fluxes, and primary productivity may be interrupted (Mitchell and Baldwin, 1999; von Schiller et al., 2011; Arce et al., 2014, 2018). Conversely, the rewetting of sediments following prolonged droughts can stimulate nitrogen and carbon (C) mineralization (McIntyre, 2009), increasing nutrient availability. This phenomenon, ecologically recognized as the "Birch effect" (Birch, 1958; Wilson and Baldwin, 2008), is associated with a pulse of microbial mineralization of organic matter in previously dry soils, resulting in the rapid release of nutrients (C and N). Since fluvial discharge plays a critical role by transporting nitrogen to downstream and coastal environments (Bruesewitz et al., 2017), and hydrological cycle (i.e., wetting and drying cycles) alter its behavior and availability (von Schiller et al., 2011).

In this context, the aim of this research is to characterize nitrogen dynamics in a semiarid NPR in Brazil, thereby contributing to a deeper understanding of ecosystem functioning and nutrient cycling in regions marked by high temperatures and prolonged dry periods lasting up to 9 months per year. The study gains further relevance in the context of the Anthropocene, as understanding how the hydrological cycle influences NPRs is essential for predicting nutrient dynamics under future scenarios marked by increased drought in river networks. Drying is intensifying globally due to climate change, water abstraction, dam construction, and land-use changes. Thus, we hypothesized that the rewetting phase of the hydroperiod would result in the depletion of N forms, with concentrations increasing during the subsequent dry phase. Therefore, the rewetting hydrological phases is expected to act as a "hot moment" in the nitrogen dynamics of semiarid NPRs. To test this hypothesis, we analyzed nitrogen concentrations and forms to evaluate the influence of hydrological dynamics on nutrient cycling in semiarid NPR systems.

2 Material and methods

2.1 Study site

Localized in State of Ceará, the Cruxati basin (3.1888° S, 39.5774° W) has an area of approximately 77 km^2 flowing into another significant river (i.e., Mundaú River; Figure 1). It comprises a naturally intermittent catchment that drains into the Litoral Basin, which subsequently discharges into the Atlantic Ocean (Duarte et al., 2021) (Figure 1). Cruxati River flows for4 months a year (from March to June). When the flow ceases, the river breaks up into isolated pools of different sizes distributed along the dry riverbed. Some of these pools (approximately 40 %) remain with water during the rest of the year. They reconnect after rainy events in the following year. The hydrological cycle of Cruxati NPR is divided into three hydrological phases: (i) Flow- river flows after torrential rains (ii) Dry- the flow of water ceases and riverbed is fragmented into isolated pools; this is the longest phase of the hydrological cycle; it can last up to 6 or 9 months (iii) Rewetting – the remaining pools starts to fill again in the beginning of the rain season. Rainfall in the region is torrential and concentrated (Porto et al., 2004), preventing any gradual change among hydrological phrases. According to da Silva et al. (2024) during the dry period, surface water completely dries up and disconnects from the groundwater. In the intermediate phase (i.e., rewetting), the river has no flow and fragments into pools along the riverbed. Due to the concentrated rainfall, the watercourse quickly stabilizes, and the river resumes a continuous flow.

Cruxati River has a diversity neotropical fauna and a high ecological value of biodiversity (e.g., fish species; Teixeira F. K et al., 2017; Gonçalves-Silva et al., 2022, 2025), and it contributes as nutrient source into estuaries (da Silva et al., 2024). This region is situated in a semi-arid climate with most of the annual precipitation concentrated in the months of January to June (Duarte et al., 2021; FUNCEME, 2018; Porto et al., 2004). The region has a predominantly hot tropical semi-arid climate (Aw, according to the Köppen climate classification; IPECE, 2007), with an annual precipitation of 954 mm and average temperatures ranging between 24.2 °C and 35.3 °C. The annual precipitation is around 1,100 mm, with an evaporation rate of 1,400 mm (FUNCEME, 2018). The vegetation is characterized by typical vegetation of the local coastal zone, which is composed of heterogeneous vegetation types ranging from sub-deciduous tropical rainforest (dry forest), tropical sub-evergreen rain-cloud forest (humid forest), dense shrub caatinga, and open shrub caatinga under metamorphic and sedimentary

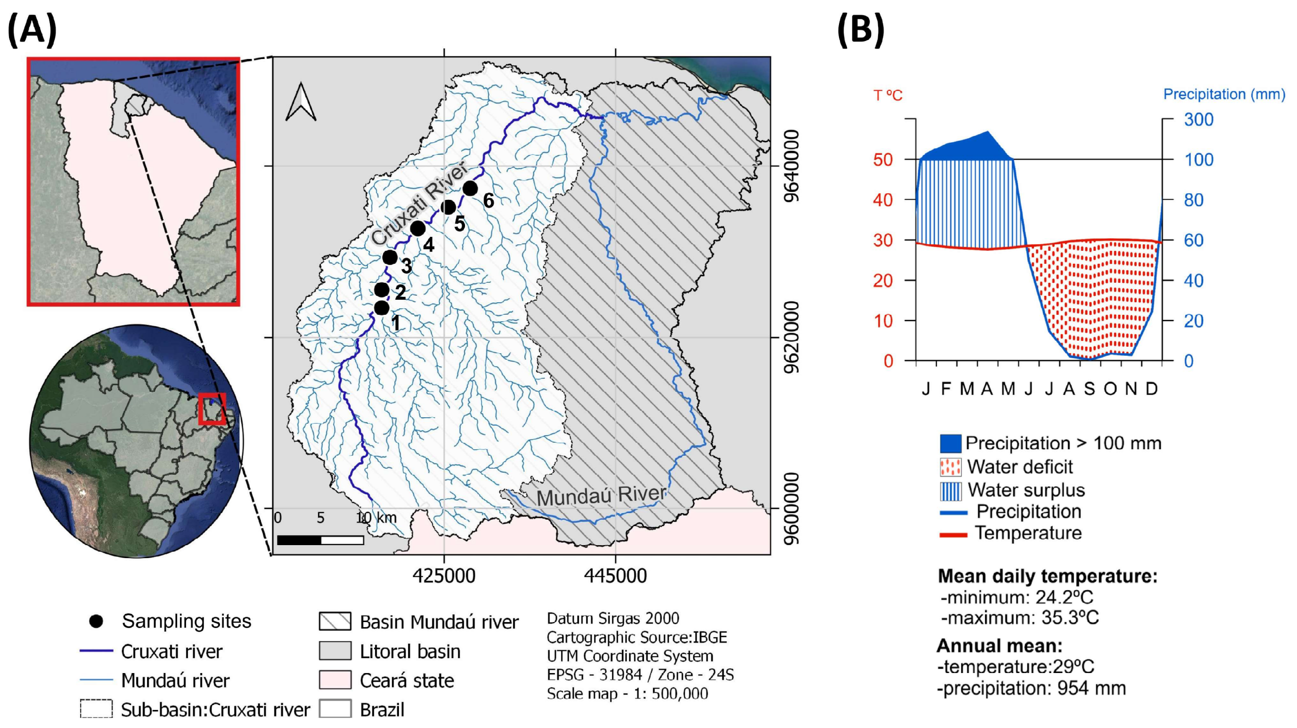

FIGURE 1
Study Area. **(A)** Map of the study area. The Cruxati River basin highlights its drainage network and sampling sites along the main course. Mundaú Basin (hatched area). **(B)** Walter & Lieth diagram showing the climatic dynamics of the region. The climatic variables were obtained from (FUNCEME, 2022) and the diagram was built using the *climatol* R package (Guijarro, 2024).

rocks. The soils are classified as Luxisols, Luvisols, Fluvisols, Planosols, and Regosols (Moro et al., 2016; FUNCEME, 2018).

2.2 Sampling

Sediments were collected during dry (September 2018), flow (June 2019) and rewetting (January 2020) hydrological phases. We collected sediment at six sites along the riverbed, spaced 3 km apart along a longitudinal gradient (Figure 1). Each transect was divided into three sections (0, 100 and 200 m). In each transect, we randomly collected three samples at a depth of 0–9 cm from the left bank, right bank, and center of the river channel, totalizing 129 samples. Sediment collection was performed using polyvinyl chloride tubes (0.05 m internal diameter and 0.5 m length) attached to a sediment sampler (Trado Josefina). The tubes were hermetically sealed, kept refrigerated, and translated to the laboratory in a vertical position.

In each section, the river width and depth (bathymetry) was measured, as well as the physical-chemical properties of the water using a multimeter probe YSI 7,000 (temperature, pH, conductivity, Eh, dissolved oxygen). To measure depth, we recorded the width and six depth points per transect from one bank to the other, using a tape measure and a graduated ruler, respectively. Based on these measurements, we calculated cross-sectional areas of each transect using the trapezoidal rule and estimated total water volume by integrating these areas along the 200 m stretch of river or the pools extent, following the hydraulic criterion based on channel geometry described by Gordon et al. (2004) and Godinho et al. (2014).

We previously analyzed the data spatially and found differences in nitrogen content only at one site, located further downstream. This result was expected, as nutrients are typically transported from upstream to downstream and tend to accumulate in lower areas (Baldwin et al., 2005). The spatial increase toward lower zones can be attributed to water heterogeneity (von Schiller et al., 2011). We also previously measured organic carbon (upstream: 4.5 ± 1.9 g kg^{-1}; midstream: 5.5 ± 1.9 g kg^{-1}; downstream: 4.9 ± 2.0 g kg^{-1}) and dissolved oxygen (upstream: 7.5 ± 0.6 mg L^{-1}; midstream: 8.2 ± 1.0 mg L^{-1}; downstream: 8.2 ± 1.0 mg L^{-1}) along the river, but found no significant variation among the sampling points. These results suggest that nitrogen is being transported rather than released from organic matter. Based on this and on our focus on discussing the importance of the hot moment, we assumed spatial homogeneity in subsequent analyses.

2.3 Physical-chemical characterization of sediments

The pH values were measured *in situ* using a glass electrode previously calibrated with pH standards of 4.0 and 7.0. Eh values were recorded using a platinum electrode (Hanna Instrument), and the measured values were corrected by adding a reference electrode potential (calomel; +244 mV). In the laboratory, sediment samples were homogenized sieved through a 2 mm mesh for the analysis of particle size according to the method proposed by Gee and Bauder (1986). We dried sub-samples at 60 °C until constant mass to determine gravimetric moisture (GM; Teixeira P. C. et al., 2017):

$$GM = \frac{[(wet\ sample\ mass\ -\ dry\ sample\ mass) * 100}{dry\ sample\ mass} \tag{1}$$

2.4 Ammonium (NH_4^+), Nitrate (NO_3^-), Total Organic Carbon (TOC), and Sulfur (S) concentrations

The inorganic N forms ($N\text{-}NH_4^+$ and $N\text{-}NO_3^-$) in sediment samples were determined using the Kjeldahl method (Silva et al., 2010). Most nitrogen analysis methods (for total N or mineral N) require the transformation of all nitrogen forms into ammonium, and most techniques involve gas diffusion steps (Silva et al., 2010). Consequently, these procedures demand more complex laboratory infrastructure and higher costs. The Kjeldahl digestion method, developed in 1883, has been widely applied and recommended (e.g., by the Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA) due to its simplicity, speed, and low cost (Silva et al., 2010).

We weighed 50 g of the sediment and added 150 mL of 2 mol L^{-1} KCl solution. After stirring for 1 h at 200 rpm and resting for 30 mins, the extract was filtered through filter paper quantitative (diameter: 12.5 cm) and transferred 20 mL aliquot to a distillation flask (Silva et al., 2010). The N was determined using the steam distillation method in the presence of 0.2 g MgO (for ammonium) and 0.2 g Devarda's alloy (for nitrate). The distillation with MgO releases ammoniacal nitrogen, which was collected in 2% boric acid for subsequent titration with sulfuric acid.

In the second stage, the addition of Devarda's alloy reduces nitrate to ammonium, which was collected in an Erlenmeyer flask containing 2% boric acid. We conducted the distillation for about 5 mins, collecting approximately 50 mL of distillate. We performed the titration using a sulfuric acid solution (0.005 mol L^{-1}) and the methyl red/bromocresol green indicator underwent a color change. The concentrations of $N\text{-}NO_3^-$ and $N\text{-}NH_4^+$ were expressed in mg kg^{-1} of dry sediment mass. Inorganic N was estimated considering the sum of $N\text{-}NO_3^-$ and $N\text{-}NH_4^+$. The TOC and S were analyzed using the combustion method with an elemental analyzer (LECO SE 144-DR).

2.5 Statistics Analysis

Due to the non-normal distribution of the variables (i.e., Nitrate, $N\text{-}NO_3^-$; Ammonium, $N\text{-}NH_4^+$; Pool volume, V; Moisture; Temperature, T; Conductivity, Con; Dissolved oxygen, DO; Soil and Water pH, pH_s and pH_w; Redox potential; Eh_s; Sulfur, S; Total organic carbon, TOC) we assessed differences between hydrological phases with the Kruskal-Wallis test - a non-parametric alternative chosen for its robustness to violations of normality and fewer assumptions - followed by Dunn's *post hoc* test, both at a 5% significance level (Zar, 2010). Additionally, we conducted a principal component analysis (PCA; Favero et al., 2024; Reimann et al., 2008) to visualize the distribution of variables across the hydrological phases. For this Analyse, we did not include the $N\text{-}NH_4^+$ because it is collinear with $N\text{-}NO_3^-$. All analyses were performed using R Studio version 4.5.0 software (The R Core Team, 2025).

3 Results

3.1 Grain size distribution and physicochemical sediment parameters

The sediments were collected from six sites across different hydrological phases, in which a predominance of sandy was observed, with a sand content of 93 ± 7.1 %, 2.64 ± 2.93 % silt and 4.36 ± 4.69% clay. The pH values were significantly higher during the dry phase ($K = 128.8$; $df = 2$; $p < 0.05$; Figure 2A; Supplementary Table 1). In contrast, Eh values decreased during the flow hydrological phases in water and sediment ($K = 34.8$; $df = 2$; p-value < 0.05; Figure 2B; Supplementary Table 1).

Sediment moisture was higher during the rewetting phase (50.8 ± 8.1 %), whereas flow (18.7 ± 16.6 %) and dry phases (17.8 ± 3.9 %) were more than 50 % lower ($K = 56.9$, $df = 2$, p-value < 0.00; Supplementary Table 1).

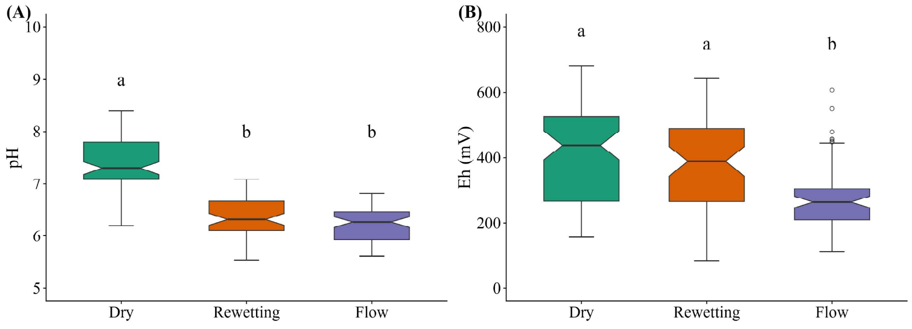

FIGURE 2
pH **(A)** and Eh **(B)** sediment values from the dry, rewetting, and flow hydrological phases of the Cruxati river, Brazil. Different lowercase letters above the bars indicate mean (± SD) differ statistically between the studied hydrological phases at the 0.05 level of the Kruskal–Wallis test.

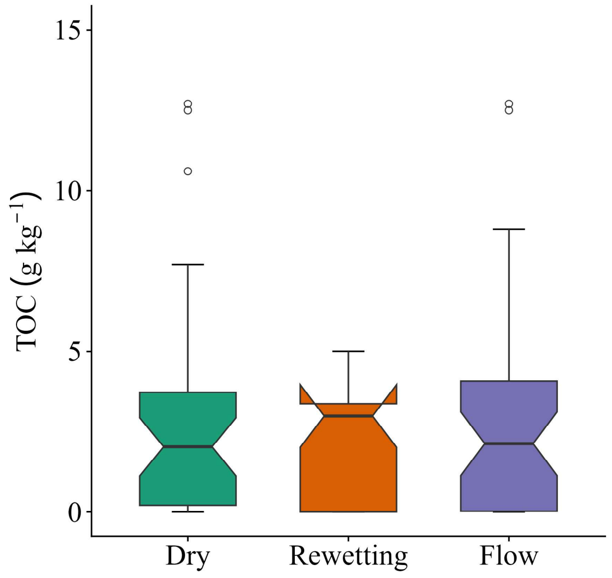

FIGURE 3
Total organic carbon - TOC (g kg^{-1}) content from the dry, rewetting, and flow hydrological phases of the Cruxati river, Brazil. Different lowercase letters above the bars indicate mean (± SD) differ statistically between the studied hydrological phases at the 0.05 level of the Kruskal–Wallis test.

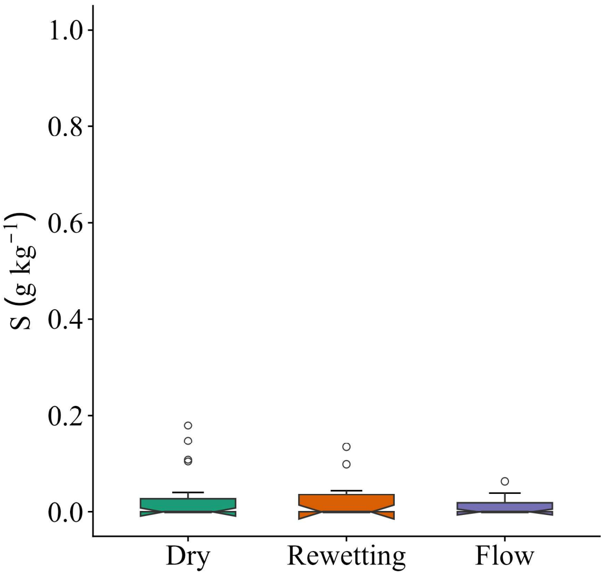

FIGURE 4
Sulfur - S (g kg^{-1}) contents from the dry, rewetting, and flow hydrological phases of the Cruxati river, Brazil. Different lowercase letters above the bars indicate mean (± SD) differ statistically between the studied hydrological phases at the 0.05 level of the Kruskal–Wallis test.

3.2 TOC and S levels

TOC contents were not different among hydrological phases (K = 1.8; df = 2; p-value = 0.4), being 3.4 ± 4.7 g kg^{-1}, 1.9 ± 1.7 g kg^{-1}, 3.0 ± 3.3 g kg^{-1} during dry, flow and rewetting phases, respectively (Figure 3; Supplementary Table 2). Similarly, S levels did not differ among phases (K = 0.3; df = 2; p-value = 0.8), being 0.028 ± 0.05 g kg^{-1}, 0.025 ± 0.04 g kg^{-1}, and 0.012 ± 0.02 g kg^{-1} during dry, rewetting, and flow phases, respectively (Figure 4; Supplementary Table 2). Although statistical differences were not observed, total organic carbon (TOC) concentrations were approximately ∼2-fold higher during the dry phase than on the flow phase. Sulfur (S) contents exhibited a similar pattern, with the highest values observed during the dry phase.

3.3 Nitrogen forms

The N-NH$_4^+$ contents were different among hydrological phases (K = 22.94; df = 2; p-value < 0.05), being higher during the flow (2.49 ± 1.91 mg kg^{-1}) and dry (3.25 ± 2.9 mg kg^{-1}), than rewetting phase (mean ± SD: 0.72 ± 1.21 mg kg^{-1}), reaching means 4-fold higher (∼74.9 % increase). Similarly, N-NO$_3^-$ contents were higher (K = 22.98; df = 2; p-value < 0.05) during the flow (0.85 ± 1.30 mg kg^{-1}) and dry (1.34 ± 1.40 mg kg^{-1}) than to the rewetting phase (0.12 ± 0.14 mg kg^{-1}; Figure 5B); with mean values 13-fold higher (92.1 % increase) than rewetting.

Inorganic nitrogen (N) had significantly differences among phases (K = 22.63; df = 2; p < 0.05), with lower values during rewetting (0.85 ± 1.29 mg kg^{-1}) compared to the dry (4.58 ± 3.93 mg kg^{-1}) and flow phases (3.34 ± 2.79 mg kg^{-1}; Figure 5C).

3.4 Principal Component Analysis (PCA)

The two principal components of the PCA explained 58.2% of the total variability, with PC1 accounting for 35.2 % and PC2 for 23 % of the total variance (Figure 6). PC1 was primarily associated with N–NO$_3^-$, pH, and Eh (eigenvalue = 3.87), whereas PC2 was mainly composed by moisture, temperature, and dissolved oxygen (eigenvalue = 2.53). The eigenvectors for N–NO$_3^-$, pH, and Eh were located in the positive quadrant of PC1, clustering the dry phase, while the vectors for moisture and DO grouped the rewetting and flow phases (Figure 6).

4 Discussion

4.1 Geological settings of the sediments

The studied site is located within the "Barreiras geological formation". This unit is characterized by the presence of sedimentary rocks with low iron (Fe) content (Nunes et al., 2011). In addition to small amounts of Fe (Melo et al., 2002a,b; Correa et al., 2008), this clay-poor formation is mainly composed of kaolinite. Indeed, previous studies (e.g., da Silva et al., 2024) conducted in the same river identified a predominance of kaolinite and low Fe contents throughout its extent, confirming the homogeneity of the mineralogical matrix in this environment.

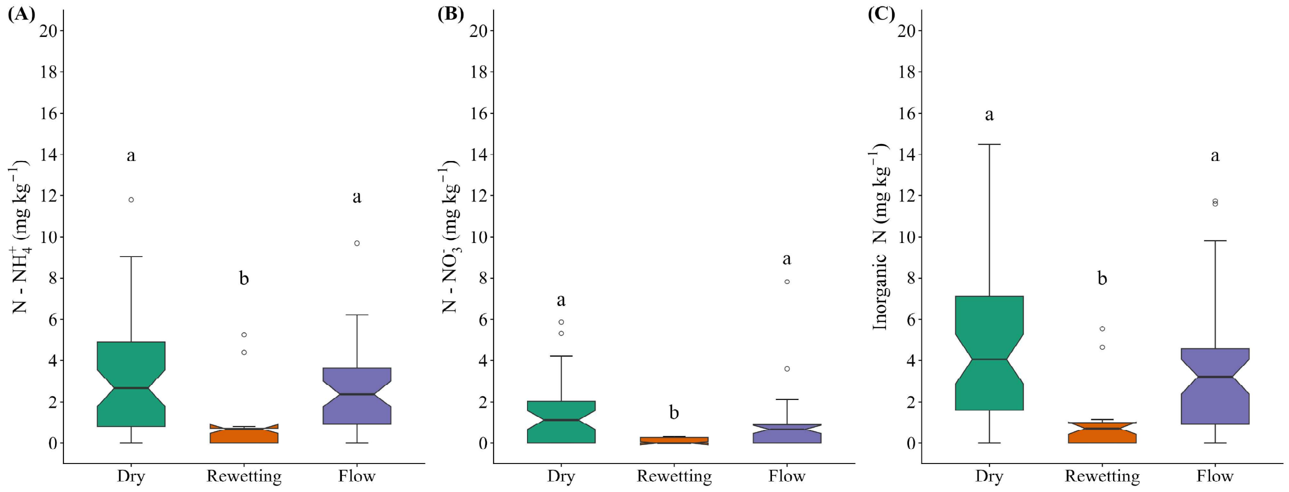

FIGURE 5
N-NH_4^+ **(A)**, N-NO_3^- **(B)** and Inorganic N **(C)** contents from the dry, rewetting, and flow hydrological phases of the Cruxati river, Brazil. Different lowercase letters above the bars indicate mean (± SD) differ statistically between the studied hydrological phases at the 0.05 level of the Kruskal–Wallis test.

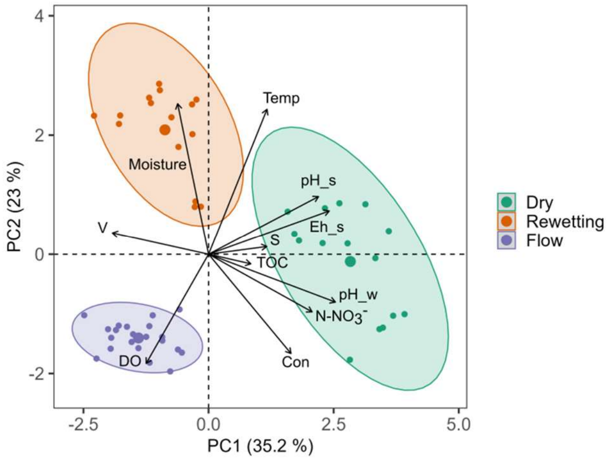

FIGURE 6
Principal component analysis of measured variables across hydrological phases of Cruxati river. **(A)** Scatter plot of the observed point for hydrological phases (Flow, Rewetting and Dry phases). **(B)** Plot of the variables used on PCA analysis. DO: dissolved oxygen (mg L^{-1}). N-NO_3^- : nitrate levels in sediments. TOC: total organic carbon (g kg^{-1}). S: sulfur content in sediment (g kg^{-1}). pH_w: pH in the water. pH_s: pH in the sediments. Eh_s: Eh in the sediments (mV). Moisture: sediment moisture (%). Temp.: water temperature (°C). Con: water conductivity (µS.cm^{-1}) V: water volume (m^3). Ammonium content was excluded from the PCA analysis because of its strong correlation with nitrate.

4.2 N forms in NPR cruxati

N-NH_4^+ was a dominant form in all hydrological phases. This form tends to be favored in both aerobic and anaerobic environments (Andreote et al., 2012; Yan et al., 2022) since this form is the first product in the transformation of organic N into inorganic form (Lin et al., 2016; Li et al., 2021). In conditions that experience phases of re-flooding, the slight decrease in oxygen between the cycles (Supplementary Table 1) could favor denitrification processes in agriculture semiarid rivers (Arce et al., 2015). While in flow conditions, ammonium content may be influenced by external inputs that increase nutrient flux during the rainy phase (von Schiller et al., 2017; da Silva et al., 2024). During dry phases, N-NH_4^+ tends to accumulate, likely due to desiccation-induced microbial cell lysis and the mineralization of organic matter (Qiu and Mccomb, 1996; Austin and Strauss, 2011; Merbt et al., 2016). Due to N-limitation being common in low-precipitation ecosystems (Yahdjian et al., 2011), the N dynamic observed in this NPR is particularly important for N processing and fluxes in semiarid environments. Sediments during the dry season act as NH_4^+ font for the subsequent rewetting phase (Arce et al., 2015), ensuring N movement in semiarid watershed. However, extreme drought in future scenarios could lead to an unbalance in N cycle and compromise nutrients availability in rivers and estuaries.

4.3 Ammonium (N-NH_{4+}) and Nitrate (N-NO_3^-) distribution across hydrological phases

We demonstrated that the accumulation patterns of N–NH_4^+ and N–NO_3^- differ across nitrogen forms and hydrological phases, reflecting the biogeochemical conditions of the sediment. Specifically, a depletion of N forms was observed during the rewetting phase, supporting our hypothesis that this phase represents a "hot moment" in the hydrological cycle of NPRs.

During the dry phase, we observed that both N-NH_4^+ and N-NO_3^- accumulated. The increase in ammonia levels was expected probably because of bacterial lysis and organic matter mineralization (Merbt et al., 2016). While the increased nitrate content indicates: (i) nitrate accumulation due denitrification depletion caused by oxygenic conditions in sediment (Arce et al., 2015) or (ii) nitrate formation derived from ammonia oxidation (nitrification) in dry sediments (Koschorreck, 2005; Gómez et al., 2012; von Schiller et al., 2017). After the start of rewetting, N-NH_4^+ and N-NO_3^- accumulated are immediately microbially processed (Gómez et al., 2012). In this phase, NH_4 $^+$ and O_2 were used (via nitrification) for N-NO_3^- production (Austin and Strauss, 2011). Saturated sediment, as in soils, promotes oxygen depletion and undergoes denitrification under inundated conditions (Supplementary Table 1; Vepraskas et al., 2016; Vepraskas and Faulkner, 2001; Zhang and Furman, 2021; Maria Isabel Arce et al., 2015). Previous studies in non-perennial streams reported that NO_3^- can be consumed via denitrification in rewetted sediments rather than being completely released into the water column (Arce et al., 2015). The microbial community in non-perennial rivers exposed to drought conditions, such as those in semiarid or Mediterranean regions, may undergo rapid adjustments to water availability (Schimel et al., 2007; Arce et al., 2013). Additionally, the presence of extracellular enzymes (Marxsen et al., 2010), for example, may represent a mechanism that contributes to sediment processing after rewetting in NPRs (Arce et al., 2013).

In fluvial systems, denitrification may be driven by multiple electron donors such as organic carbon and iron minerals (Rivett et al., 2008; Kreiling et al., 2011; Tomasek et al., 2017). The low levels of N-NH_4^+ and N-NO_3^- observed during the rewetting phase should be considered a critical moment in the NPRs cycle (Gómez et al., 2012), where water content increases in the sediments (Supplementary Table 1) and a stimulation of nutrient mineralization occurs (Austin and Strauss, 2011; Gómez et al., 2012; Arce et al., 2015; von Schiller et al., 2017). This ecological effect, called the "Birch effect," has been described in semi-arid soils (Birch, 1958; Wilson and Baldwin, 2008; Lado-Montserrat et al., 2014), and it is defined as the release of inorganic N from dried soil on re-wetting, caused by mineralization of N by soil bacteria stimulation (Birch, 1958; Wilson and Baldwin, 2008). In stream, a great quantity of microbial metabolic pathways tends to recover after rewetting and causes a pulse of nutrient and OM mineralization (Wilson and Baldwin, 2008; McIntyre, 2009; Sabater et al., 2016; von Schiller et al., 2017; Coulson et al., 2022).

Water content directly or indirectly regulates N flux and is influenced by environmental forcing (Vepraskas et al., 2016; Zhang and Furman, 2021). Our findings indicate that the immobilization and mineralization of N forms generally depend on redox potential (Eh), which is governed by the hydrological dynamics of dry–rewetting cycles in semiarid non-perennial rivers (NPRs) (Zhang and Furman, 2021). Furthermore, drought stress can lead to the accumulation of specific N forms (Austin and Strauss, 2011).

On the other hand, we observed an increase of N-NH_4^+ and N-NO_3^- forms contents in flow rather than rewetting season. This may be caused by the transport of nitrogen in the rainy season. In NPRs, high nitrate export can occur by ammonia oxidation in dry streambeds during flush events following flow reconnection (Merbt et al., 2016). The Mundaú River (Cruxati River is a principal tributary) has a mean estimated flow of 15 m^3 s^{-1} during the rainy season (Molisani et al., 2006) and could transport important sources of N that sustained levels of N forms in the flow phase (147 days $year^{-1}$; Lacerda et al., 2008). Therefore, the flow phase may represent the input of nitrogen sources (Lacerda et al., 2008) and the output that supplies nutrients to lowland ecosystems (da Silva et al., 2024). In a similar direction, our results are consistent with other studies in NPRs (Austin and Strauss, 2011; von Schiller et al., 2011; Arce et al., 2015, 2018), which reinforce that these intermittent rivers represent cycles of accumulation, transport, and export of organic matter (von Schiller et al., 2017).

5 Conclusion

The hydrological cycle of the Cruxati non-perennial river (NPR) influences both the quantity and form of ammonium (N–NH_4^+) and nitrate (N–NO_3^-). Reduced nutrient levels observed during the rewetting phase suggest intense nitrogen transformations, indicating a biogeochemical pulse in nitrogen cycling within semiarid NPRs. However, if intensity and duration of drought increases in semiarid regions, greater amounts of nitrogen are likely to become immobilized. Due to the critical role of nitrogen in biogeochemical processes, and considering that most rivers in semiarid regions are non-perennial, prolonged droughts under climate change scenarios are expected to reduce primary production, impacting biodiversity. Future research should prioritize integrated studies that combine biogeochemical analyses with microbial investigations to advance our understanding of the biogeochemical functioning of semiarid NPRs.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

PV-V: Writing – original draft, Software, Formal analysis, Project administration, Conceptualization, Methodology, Writing – review & editing, Validation, Data curation, Investigation. AS: Data curation, Formal analysis, Writing – original draft, Conceptualization, Software, Writing – review & editing, Investigation, Methodology. HQ: Writing – original draft, Data curation, Software, Methodology, Investigation, Conceptualization, Writing – review & editing, Formal analysis. TP: Methodology, Conceptualization, Investigation, Writing – review & editing, Writing – original draft. GN: Writing – review & editing, Writing – original draft, Methodology, Conceptualization, Investigation, Data curation. MD: Conceptualization, Writing – review & editing, Methodology, Writing – original draft, Data curation, Investigation. DO: Software, Investigation, Conceptualization, Writing – review & editing, Formal analysis, Writing – original draft, Data curation, Methodology. CR: Formal analysis, Resources, Writing – original draft, Project administration, Data curation, Visualization, Conceptualization, Investigation, Writing – review & editing, Validation, Funding acquisition, Methodology, Supervision. TF: Visualization, Project administration, Formal analysis, Validation, Data curation, Resources, Supervision, Methodology, Writing – review & editing, Investigation, Conceptualization, Writing – original draft, Funding acquisition.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This study received partial funding from Brazilian Federal Foundation for Support and Evaluation of Graduate Education (CAPES) code 001, and the Cearense Foundation for Support of Scientific and Technological Development (FUNCAP) through the PRONEM announcement (process 0112-00026.01.00/16).

Acknowledgments

This study was part of the first-second and fourth author's studies in Postgraduate in Ecology and Natural Resources, Department of Biology, Federal University of Ceará, Fortaleza, Brazil.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2025.1691103/full#supplementary-material

References

Allen, D., Datry, T., Boersma, K. S., Bogan, M. T., Boulton, A. J., Bruno, D., et al. (2020). River ecosystem conceptual models and non-perennial rivers: A critical review. *Wiley Interdiscip. Rev. Water* 7:1473. doi: 10.1002/wat2.1473

Andreote, F. D., Jiménez, D. J., Chaves, D., Dias, A. C. F., Luvizotto, D. M., Dini-Andreote, F., et al. (2012). The microbiome of Brazilian mangrove sediments as revealed by metagenomics. *PLoS ONE* 7:e38600. doi: 10.1371/journal.pone.0038600

Arce, M. I., Gómez, R., Suárez, M. L., and Vidal-Abarca, M. R. (2013). Denitrification rates and controlling factors in two agriculturally influenced temporary Mediterranean saline streams. *Hydrobiologia* 700, 169–185. doi: 10.1007/s10750-012-1228-4

Arce, M. I., Sánchez-Montoya, M., del, M., and Gómez, R. (2015). Nitrogen processing following experimental sediment rewetting in isolated pools in an agricultural stream of a semiarid region. *Ecol. EngEcol. Eng.* 77, 233–241. doi: 10.1016/j.ecoleng.2015.01.035

Arce, M. I., Sánchez-Montoya, M., del, M., Vidal-Abarca, M. R., Suárez, M. L., and Gómez, R. (2014). Implications of flow intermittency on sediment nitrogen availability and processing rates in a Mediterranean headwater stream. *Aquat. SciAquat. Sci.* 76, 173–186. doi: 10.1007/s00027-013-0327-2

Arce, M. I., Von Schiller, D., Bengtsson, M. M., Hinze, C., Jung, H., Alves, R. J. E., et al. (2018). Drying and rainfall shape the structure and functioning of nitrifying microbial communities in riverbed sediments. *Front. Microbiol.* 9:02794. doi: 10.3389/fmicb.2018.02794

Austin, B. J., and Strauss, E. A. (2011). Nitrification and denitrification response to varying periods of desiccation and inundation in a western Kansas stream. *Hydrobiologia* 658, 183–195. doi: 10.1007/s10750-010-0462-x

Baldwin, D. S., Rees, G. N., Mitchell, A. M., and Watson, G. (2005). Spatial and temporal variability of nitrogen dynamics in an upland stream before and after a drought. *Mar. Freshwater Res.* 56, 457–464. doi: 10.1071/MF04189

Birch, H. F. (1958). The effect of soil drying on humus decomposition and nitrogen availability. *Plant Soil* 1, 9–31. doi: 10.1007/BF01343734

Bruesewitz, D. A., Hoellein, T. J., Mooney, R. F., Gardner, W. S., and Buskey, E. J. (2017). Wastewater influences nitrogen dynamics in a coastal catchment during a prolonged drought. *Limnol. OceanogrLimnol. Oceanogr.* 62, S239–S257. doi: 10.1002/lno.10576

Ceulemans, T., Bodé, S., Bollyn, J., Harpole, S., Coorevits, K., Peeters, G., et al. (2017). Phosphorus resource partitioning shapes phosphorus acquisition and plant species abundance in grasslands. *Nat. Plants* 3:224. doi: 10.1038/nplants.2016.224

Correa, M. M., Ker, J. C., Barrón, V., Fontes, M. P., Torrent, J., and Curi, N. (2008). Characterizing iron oxides from coastal and central plain soils. *Rev. Brasileira de Ciência do Solo.* 32, 1017–1031. doi: 10.1590/S0100-06832008000300011

Coulson, L. E., Weigelhofer, G., Gill, S., Hein, T., Griebler, C., and Schelker, J. (2022). Small rain events during drought alter sediment dissolved organic carbon leaching and respiration in intermittent stream sediments. *Biogeochemistry* 159, 159–178. doi: 10.1007/s10533-022-00919-7

da Silva, A. E. B., Queiroz, H. M., de Oliveira, D. P., Nóbrega, G. N., Pereira, T. M., de Freitas Lima, P., et al. (2024). Effects of hydrological dynamics in controlling phosphorus bioavailability in intermittent rivers and implications for estuaries. *Front. Water* 6:1286968. doi: 10.3389/frwa.2024.1286968

Du, E., Terrer, C., Pellegrini, A. F. A., Ahlström, A., van Lissa, C. J., Zhao, X., et al. (2020). Global patterns of terrestrial nitrogen and phosphorus limitation. *Nat. GeosciNat. Geosci.* 13, 221–226. doi: 10.1038/s41561-019-0530-4

Duarte, M., Pereira, T., Lima, P., Braga, E., Lopes, F., and Rezende, C. (2021). Limnological dynamics in an artificial reservoir and intermittent river in the semi-arid region as a function of land use and occupation. *Rev. Ciencia Agronomica.* 52:e20207181. doi: 10.5935/1806-6690.20210010

Favero, M., Carlucci, S., Chinazzo, G., Møller, J. K., Schweiker, M., Vellei, M., et al. (2024). Ten questions concerning statistical data analysis in human-centric buildings research: a focus on thermal comfort investigations. *Build EnvironBuild. Environ.* 264:111903. doi: 10.1016/j.buildenv.2024.111903

FUNCEME (2018). *Projetos e mapas*. Fortaleza: Funceme. Available online at: http://www.funceme.br/?page_id=2807(Accessed May 19, 2025).

FUNCEME (2022). *Postos Pluviométricos*. Funceme, 1. Available online at: www.funceme.br/?page_id=2694 (Accessed January 5, 2024).

Gee, G. W., and Bauder, J. W. (1986). "Particle-size analysis," in Methods of soil analysis: Part 1—Physical and mineralogical methods, ed. *Am. Soc. Agron. (American Society of Agronomy)* 383–411. doi: 10.2136/sssabookser5.1.2ed.c15

Godinho, F., Costa, S., Pinheiro, P., Reis, F., and Pinheiro, A. (2014). Integrated procedure for environmental flow assessment in rivers. *Environ. Process.* 1, 137–147. doi: 10.1007/s40710-014-0012-z

Gómez, R., Arce, M. I., Sánchez, J. J., and del Mar Sánchez-Montoya, M. (2012). The effects of drying on sediment nitrogen content in a Mediterranean intermittent stream: a microcosms study. *Hydrobiologia* 679, 43–59. doi: 10.1007/s10750-011-0854-6

Gonçalves-Silva, M., D'Bastiani, E., Datry, T., and Rezende, C. F. (2025). Hydrological fluctuations determine predator–prey interactions in a semi-arid non-perennial river. *Hydrobiologia* doi: 10.1007/s10750-025-05968-1

Gonçalves-Silva, M., Manna, L. R., Rodrigues-Filho, C. A. S., Teixeira, F. K., and Rezende, C. F. (2022). Effect of drying dynamics on the functional structure of a fish assemblage from an intermittent river network. *Front. Environ. Sci.* 10:903974. doi: 10.3389/fenvs.2022.903974

Gordon, N. D., McMahon, T. A., Finlayson, B. L., Gippel, C. J., and Nathan, R. J. (2004). *Stream Hydrology: An Introduction for Ecologists*, *2nd Edn. Ch 5*. Chichester: John Wiley and Sons.

Guijarro, J. (2024). *Package "climatol" Title Climate Tools (Series Homogenization and Derived Products)*. Available online at: https://climatol.eu (Accessed February 2, 2025).

IPECE (2007). *Ceará em Números*. Fortaleza: IPECE.

Koschorreck, M. (2005). Nitrogen turnover in drying sediments of an Amazon floodplain lake. *Microb. Ecol.* 49, 567–577. doi: 10.1007/s00248-004-0087-6

Kreiling, R. M., Richardson, W. B., Cavanaugh, J. C., and Bartsch, L. A. (2011). Summer nitrate uptake and denitrification in an upper Mississippi river backwater lake: the role of rooted aquatic vegetation. *Biogeochemistry* 104, 309–324. doi: 10.1007/s10533-010-9503-9

Lacerda, L. D., Molisani, M. M., Sena, D., and Maia, L. P. (2008). Estimating the importance of natural and anthropogenic sources on N and P emission to estuaries along the Ceará State Coast NE Brazil. *Environ. Monit. Assess.* 141, 149–164. doi: 10.1007/s10661-007-9884-y

Lado-Montserrat, L., Lull, C., Bautista, I., Lidón, A., and Herrera, R. (2014). Soil moisture increment as a controlling variable of the "Birch effect". interactions with the pre-wetting soil moisture *and litter addition. Plant Soil* 379, 21–34. doi: 10.1007/s11104-014-2037-5

Li, C., Zhong, Z., Wang, W., Wang, H., Yan, G., Dong, W., et al. (2021). Distribution characteristics of nitrogen and the related microbial community in the surface sediments of the Songhua River. *RSC AdvRSC Adv.* 11, 26721–26731. doi: 10.1039/D1RA04903H

Lin, X., Hou, L., Liu, M., Li, X., Zheng, Y., Yin, G., et al. (2016). Nitrogen mineralization and immobilization in sediments of the East China Sea: Spatiotemporal variations and environmental implications. *J. Geophys. Res. Biogeosci.* 121, 2842–2855. doi: 10.1002/2016JG003499

Marxsen, J., Zoppini, A., and Wilczek, S. (2010). Microbial communities in streambed sediments recovering from desiccation. *FEMS Microbiol. Ecol.* 71, 374–386. doi: 10.1111/j.1574-6941.2009.00819.x

McIntyre, R. E. (2009). *Soil Biogeochemistry and Flooding in Intermittent Streams of the Semi-Arid Pilbara Region*. Pilbara: University of Western Australia.

Melo, V. F., Novais, R. F., Schaefer, C. E. G. R., Fontes, M. P. F., and Singh, B. (2002a). Chemical and crystal properties of kaolinite and iron oxides in the Barreiras group sediments in Aracruz, Espírito Santo state, Brazil. *Rev. Brasileira de Ciência do Solo* 26, 53–64. doi: 10.1590/S0100-06832002000100006

Melo, V. F., Novais, R. F., Schaefer, C. E. G. R., Fontes, M. P. F., and Singh, B. (2002b). Mineralogy of the sand, silt and clay fractions of Barreiras group sediments in Aracruz, Espírito Santo state, Brazil. *Rev. Brasileira de Ciência do Solo* 26, 29–41. doi: 10.1590/S0100-06832002000100004

Merbt, S. N., Proia, L., Prosser, J. I., Marti, E., Casamayor, E. O., and Von Schiller, D. (2016). Stream drying drives microbial ammonia oxidation and first-flush nitrate export. *Ecology* 97, 2192–2198. doi: 10.1002/ecy.1486

Messager, M. L., Lehner, B., Cockburn, C., Lamouroux, N., Pella, H., Snelder, T., et al. (2021). Global prevalence of non-perennial rivers and streams. *Nature* 594, 391–397. doi: 10.1038/s41586-021-03565-5

Mitchell, A. M., and Baldwin, D. S. (1999). The effects of sediment desiccation on the potential for nitrification, denitrification, and methanogenesis in an Australian reservoir. *Hydrobiologia* 392, 3–11. doi: 10.1023/A:1003589805914

Molisani, M., Cruz, A., and Maia, L. (2006). Estimation of the freshwater river discharge to estuaries in Ceará State, Brazil. *Arquivos de Ciências do Mar.* 39, 53–60. doi: 10.32360/acmar.v39i1-2.6173

Moro, M. F., Nic Lughadha, E., de Araújo, F. S., and Martins, F. R. (2016). A Phytogeographical metaanalysis of the semiarid Caatinga domain in Brazil. *Bot. Rev.* 82, 91–148. doi: 10.1007/s12229-016-9164-z

Nunes, F. C., Silva, E. F., and Vilas Boas, G. S. (2011). *Grupo Barreiras: Características, Gênese e Evidências de Neotectonismo*. Rio de Janeiro: Embrapa Solos, 31.

Peñuelas, J., Poulter, B., Sardans, J., Ciais, P., Van Der Velde, M., Bopp, L., et al. (2013). Human-induced nitrogen-phosphorus imbalances alter natural and managed ecosystems across the globe. *Nat. Commun.* 4:3934. doi: 10.1038/ncomms3934

Porto, M. M., Andrade, E. M., Costa, R. N. T., Lemos Filho, L. C. A., and Meireles, M. (2004). Identification of homogeneous groups of watersheds in Ceará state, Brazil. *Revista Ciência Agronômica* 35, 17–25.

Qiu, S., and Mccomb, A. J. (1996). Drying induced stimulation of ammonium release and nitrification in reflooded lake sediment. *Mar. Freshwater Res.* 47, 531–537. doi: 10.1071/MF9960531

Reimann, C., Filzmoser, P., Garrett, R. G., and Dutter, R. (2008). "Front Matter," in *Statistical Data Analysis Explained*, *(Wiley)* doi: 10.1002/9780470987605

Rivett, M. O., Buss, S. R., Morgan, P., Smith, J. W. N., and Bemment, C. D. (2008). Nitrate attenuation in groundwater: a review of biogeochemical controlling processes. *Water Res.* 42, 4215–4232. doi: 10.1016/j.watres.2008.07.020

Sabater, S., Timoner, X., Borrego, C., and Acuña, V. (2016). Stream biofilm responses to flow intermittency: From cells to ecosystems. *Front. Environ. Sci.* 4:00014. doi: 10.3389/fenvs.2016.00014

Sauquet, E., Shanafield, M., Hammond, J. C., Sefton, C., Leigh, C., and Datry, T. (2021). Classification and trends in intermittent river flow regimes in Australia, northwestern Europe and USA: a global perspective. *J. Hydrol. (Amst)* 597, 1–17. doi: 10.1016/j.jhydrol.2021.126170

Schimel, J., Balser, T. C., and Wallenstein, M. (2007). Microbial stress-response physiology and its implications for ecosystem function. *Ecology* 88, 1386–1394. doi: 10.1890/06-0219

Shumilova, O., Zak, D., Datry, T., von Schiller, D., Corti, R., Foulquier, A., et al. (2019). Simulating rewetting events in intermittent rivers and ephemeral streams: A global analysis of leached nutrients and organic matter. *Glob. Chang. Biol.* 25, 1591–1611. doi: 10.1111/gcb.14537

Silva, D., de Andrade, C., Simeone, M., Amaral, T., Castro, L., and Moura, B. (2010). *Análise de Nitrato e Amônio em Solo e Água*. Sete Lagoas: Embrapa. Available online at: www.cnpms.embrapa.br (Accessed April 2, 2024).

Soares, N. S., Costa, C. A. G., Carneiro de Lima, J. B., Francke, T., and de Araújo, J. C. (2024). Method for identification of hydrological seasons in the semi-arid Caatinga biome, Brazil. *Hydrol. Sci. J.* 69, 309–320. doi: 10.1080/02626667.2024.2311758

Teixeira, F. K., Ramos, T. P. A., De Paiva, R. E. C., Távora, M. A., Lima, S. M. Q., and Rezende, C. F. (2017). Ichthyofauna of Mundaú river basin, Ceará State, Northeastern Brazil. *Biota. Neotrop.* 17:e20160174. doi: 10.1590/1676-0611-bn-2016-0174

Teixeira, P. C., Donagemma, G. K., Fontana, A., and Teixeira, W. G. (Eds.) (2017). Manual de métodos de análise de solo. Brasília: Embrapa.

The R Core Team (2025). *R: A Language and Environment for Statistical Computing*. Geneva: The R Core Team. Available online at: https://www.gnu.org/copyleft/gpl.html (Accessed May 3, 2025).

Tomasek, A., Kozarek, J. L., Hondzo, M., Lurndahl, N., Sadowsky, M. J., Wang, P., et al. (2017). Environmental drivers of denitrification rates and denitrifying gene abundances in channels and riparian areas. *Water Resour. Res.* 53, 6523–6538. doi: 10.1002/2016WR019566

Vepraskas, M. J., and Faulkner, S. P. (2001). "Redox chemistry of hydric soils," *in Wetland Soils: Genesis, Hydrology, Landscapes, and Classification, Richardson, eds. J.L. and M. J. Vepraskas (Boca Raton: CRC Press, Taylor and Francis Group),* 85–105. doi: 10.1201/9781420026238.ch4

Vepraskas, M. J., Polizzotto, M., and Faulkner, S. P. (2016). "Redox Chemistry of Hydric Soils," in *Wetland Soils*, eds. *M. J. Vepraskas and C. B. Craft (Boca Raton: CRC Press)*, 105:b18996. doi: 10.1201/b18996

von Schiller, D., Acuña, V., Graeber, D., Martí, E., Ribot, M., Sabater, S., et al. (2011). Contraction, fragmentation and expansion dynamics determine nutrient availability in a Mediterranean forest stream. *Aquat. Sci.* 73, 485–497. doi: 10.1007/s00027-011-0195-6

von Schiller, D., Bernal, S., Dahm, C. N., and Martí, E. (2017). "Nutrient and organic matter dynamics in intermittent rivers and ephemeral streams," in *Intermittent Rivers and Ephemeral Streams: Ecology and Management*, eds. *T. Datry, N. Bonada, and A.* Boulton (London: Elsevier Inc*)*, 135–160. doi: 10.1016/B978-0-12-803835-2.00006-1

von Schiller, D., Martí, E., Riera, J. L., Ribot, M., Argerich, A., Fonollà, P., et al. (2008). Inter-annual, annual, and seasonal variation of P and N retention in a perennial and an intermittent stream. *Ecosystems* 11, 670–687. doi: 10.1007/s10021-008-9150-3

Wilson, J. S., and Baldwin, D. S. (2008). Exploring the 'Birch effect' in reservoir sediments: Influence of inundation history on aerobic nutrient release. *Chem. Ecol.* 24, 379–386. doi: 10.1080/02757540802497582

Wu, Z., Li, J., Sun, Y., Peñuelas, J., Huang, J., Sardans, J., et al. (2022). Imbalance of global nutrient cycles exacerbated by the greater retention of phosphorus over nitrogen in lakes. *Nat. Geosci.* 15, 464–468. doi: 10.1038/s41561-022-00958-7

Yahdjian, L., Gherardi, L., and Sala, O. E. (2011). Nitrogen limitation in arid-subhumid ecosystems: A meta-analysis of fertilization studies. *J. Arid. Environ.* 75, 675–680. doi: 10.1016/j.jaridenv.2011.03.003

Yan, A., Guo, X., Hu, D., and Chen, X. (2022). Reactive transport of NH4+ in the hyporheic zone from the ground water to the surface water. *Water (Switzerland)* 14, 1–9. doi: 10.3390/w14081237

Zar, J. (2010). *Biostatistical Analysis.*, *5th Edn.* New Jersey: Prentice Hall Pearson.

Zhang, Z., and Furman, A. (2021). Soil redox dynamics under dynamic hydrologic regimes - a review. *Sci. Total Environ.* 763, 143026. doi: 10.1016/j.scitotenv.2020.143026