

Document Version

Final published version

Licence

CC BY

Citation (APA)

Gani, M. A., Gettel, G. M., van der Kwast, J., Irvine, K. A., & McClain, M. E. (2025). Nitrogen retention dynamics in a large floodplain river: a case study on the Padma River, Bangladesh. *Ecohydrology and Hydrobiology*, 26(1), Article 100724. <https://doi.org/10.1016/j.ecohyd.2025.100724>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

In case the licence states "Dutch Copyright Act (Article 25fa)", this publication was made available Green Open Access via the TU Delft Institutional Repository pursuant to Dutch Copyright Act (Article 25fa, the Taverne amendment). This provision does not affect copyright ownership.
Unless copyright is transferred by contract or statute, it remains with the copyright holder.

Sharing and reuse

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

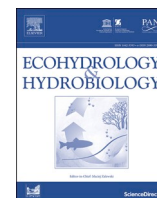
Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.





Contents lists available at ScienceDirect

Ecohydrology & Hydrobiology

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

Nitrogen retention dynamics in a large floodplain river: a case study on the Padma River, Bangladesh

Md Ataul Gani^{a,b,c} , Gretchen M. Gettel^{b,f}, Johannes van der Kwast^d, Kenneth A. Irvine^{a,b}, Michael E. McClain^{b,e,*} 

^a Aquatic Ecology and Water Quality Management Group, Wageningen University and Research, P.O. Box 47, 6700 AA, Wageningen, the Netherlands

^b Department of Water Resources and Ecosystems, IHE Delft Institute for Water Education, P.O. Box 3015, 2601 DA Delft, the Netherlands

^c Department of Botany, Jagannath University, 1100 Dhaka, Bangladesh

^d Department of Land and Water Management, IHE Delft Institute for Water Education, P.O. Box 3015, 2601 DA Delft, the Netherlands

^e Department of Water Management, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, the Netherlands

^f Department of Ecoscience, Freshwater Ecology, University of Aarhus, Aarhus, Denmark

ARTICLE INFO

Keywords:

Retention processes
Seasonal variation
Water retention
Sedimentation
Denitrification
Nitrogen fixation
Padma River

ABSTRACT

Large tropical floodplain rivers act as important pathways of nitrogen transport from land to the sea. In the present study, a mass balance approach was used to evaluate nitrogen retention over a two-year period from a 50 km reach of the Padma River in Bangladesh. The relationship between concentration and discharge was estimated from 58 nitrogen concentration and discharge measurements. Daily nitrogen flux was then calculated from the hydrological inflow and outflows of the reach, and total nitrogen (TN) retention was estimated based on the flux difference of TN inflow and outflows. To validate mass-balance measurements, retention processes of nitrogen loss due to water retention (NLWR), sedimentation, potential denitrification rate (PDR), and nitrogen fixation rate (NFR) were estimated from the water column of the river. Monthly mass-balance measurements revealed substantial seasonal variation in nitrogen retention, indicating river discharge as the main controlling factor. Estimated maximum retention values (tonnes per month) of NLWR, sedimentation, PDR, and NFR were all associated with the monsoons, with 86 % occurring during that period. However, the percentage of PDR and NFR to TN retention was higher in non-monsoon months (post-monsoon, dry/winter and pre-monsoon), suggesting retention mechanisms varied seasonally. TN retention via NLWR accounted for the largest portion of total TN retention, that consistently exceeded 50 %, followed by sedimentation. PDR in submerged geomorphic units was the second-most important retention mechanism in the dry/winter and pre-monsoon seasons. The present research provides a benchmark for nitrogen-budget modelling in tropical rivers, supporting planning for sustainable river management.

1. Introduction

Large floodplain rivers are among the most dynamic and productive ecosystems on Earth, providing drinking water for humans and livestock, and are characterised by seasonal inundation and high biological activity (e.g. Nicole, 2003; Subramanian, 2008; Campbell, 2009; Davidson et al., 2012). These rivers also play an essential role in transforming and retaining nitrogen (N) (Tockner and Stanford, 2002; Junk et al., 1989). Nitrogen is a key nutrient regulating aquatic productivity but can become a pollutant when present in excess, leading to eutrophication, harmful algal blooms, and hypoxia (Vitousek et al., 1997;

Galloway et al., 2008). Nitrogen cycling in riverine ecosystems plays a vital role in regulating water quality, primary productivity, and nutrient export to coastal zones (Seitzinger et al., 2006). Many large rivers in the tropics are under development pressures from anthropogenic activities, including the construction of dams and hydropower stations, and reclamation linked to mining, deforestation, and channelisation (Winemiller et al., 2016; Böck et al., 2018; Best, 2019). In addition, climate change has altered river discharge and floodplain inundation, affecting ecological structure, river functioning, and seasonality (Hamilton, 2010; Eisner et al., 2017).

Large rivers have more potential to retain nitrogen than small rivers

* Corresponding author at: Professor, Department of Water Management, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, the Netherlands.
E-mail address: m.e.mcclain@tudelft.nl (M.E. McClain).

<https://doi.org/10.1016/j.ecohyd.2025.100724>

Received 10 October 2025; Received in revised form 9 December 2025; Accepted 14 December 2025

1642-3593/© 2025 The Authors. Published by Elsevier B.V. on behalf of European Regional Centre for Ecohydrology of the Polish Academy of Sciences. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

because of notably high discharge (Wang et al., 2020), sediment transport (Wang et al., 2022), flow path modification and increasing transport distances (Tanaka et al., 2021; Seitzinger et al., 2002; Wollheim et al., 2006; Mulholland and Webster, 2010). The river water column acts as a zone where removal processes of nitrogen from denitrification and sedimentation occur. However, retention also occurs at the interface between the water column and sediment (Grizzetti et al., 2015). Most tropical rivers have extensive floodplains and deltas that can deliver sediments and nutrients to the oceans (Cotrim et al., 2007). In addition, they exhibit dynamic channel forms, regarded as geomorphic units (GUs), that change their pattern from single- to multi-channel systems (Latrubesse et al., 2005). This can amplify the magnitude of the interaction between sediment and the water column, regulating nitrogen retention in the GUs and the water column and export to the seas. In tropical rivers, this capacity may be amplified by warm temperatures, high biological activity, and prolonged flood periods that promote microbial and biogeochemical transformations (Neill et al., 2001; Forsberg et al., 2017).

Seasonal variation is a distinctive feature of most tropical rivers, manifest in changes in flow, precipitation, and temperature (Hamilton et al., 2010). Large rivers such as the Amazon, Congo, and Mekong exhibit notable seasonal and hydrological variations driven mainly by regional precipitation patterns and monsoonal influences. These seasonal dynamics shape the ecology, biogeochemistry, and socioeconomics of their floodplains (Melack and Forsberg, 2001; Gode et al., 2022; MRC, 2023). In South Asia, high temperatures during the monsoon amplify snow or ice melt in the Himalayas, leading to massive water discharge into the Ganges and Brahmaputra rivers (Islam, 2016). Concurrent high rainfall and storm events accelerate water discharge and sediment loads in the rivers (Syvitski et al., 2014).

Although several studies in temperate basins have quantified nitrogen retention and seasonal variability, it remains poorly quantified in large tropical floodplain systems (e.g., Loken et al., 2018; Ritz and Fischer, 2019; Wang et al., 2020). Available studies show that measuring upstream versus downstream nitrogen fluxes (mass balance) is an empirical approach for estimating nitrogen retention in large rivers (McKee et al., 2000; Chen et al., 2009; Bukaveckas and Isenberg, 2013; Ritz and Fischer, 2019). However, retention measures from mass balance approaches often lack simultaneous quantification of the individual physical and biogeochemical processes that are responsible for the retention, such as water loss to floodplains, sedimentation, and denitrification (Buckaveckas & Isenberg, 2013). These are vital for maintaining downstream water quality and ecosystem functioning (Saunders and Kalf, 2001; Seitzinger et al., 2006). This gap is particularly notable for large tropical rivers, where high hydrological variation and complex geomorphology are expected to create seasonal retention mechanisms. Therefore, understanding different retention mechanisms is crucial for accurate estimates of the nitrogen budget in these river systems.

The Ganges and Brahmaputra are the largest river basins in Bangladesh, also draining a large area of India, all of Nepal, Bhutan, and a relatively small area of China. Land-use activities and the construction of dams and barrages in the upper reaches of these rivers affect water and sediment supply to downstream areas, altering riverine ecosystems (Bouwman et al., 2013; Weigelhofer et al., 2018; Hauer et al., 2018). Increased nitrogen loads are of concern in the lower river system and the Bay of Bengal, where harmful algal blooms can form, resulting in ecosystem degradation (Sattar et al., 2014; Zinia and Kroeze, 2015; Shaika et al., 2022). A better understanding of the nitrogen retention mechanisms in these rivers is of great importance for implementing river management and restoration programmes. Key research areas are identifying and quantifying nitrogen retention, the processes involved, and how these are affected by river discharge and geomorphology. The present study focuses on a large tropical floodplain, the Padma River, one of the world's largest and most populated downstream areas of the Ganges and Brahmaputra basins (Metcalf, 2003). The overall research objective was to determine how variations in discharge, water retention,

and biogeochemical processes (sedimentation, denitrification and N_2 fixation) influence nitrogen retention in a large tropical floodplain river. Specific research objectives were to:

- estimate the nitrogen retention of a 50 km reach of the Padma River, Bangladesh, including monsoon, post-monsoon, dry/winter, and post-monsoon seasons;
- show the contribution of water losses to floodplains and aquifers, sedimentation, and potential denitrification rate (PDR) to the nitrogen retention estimation; and
- determine how discharge, water retention, and denitrification control the nitrogen retention capacity of the reach.

2. Materials and methods

2.1. Description of the study reach

The study reach is the downstream of the confluence of the Ganges and the Brahmaputra rivers, known as the Padma River in Bangladesh. The reach is about 50 km long, with a maximum width of 20 km. The inflow station, known as Baruria, is located near Aricha, Manikganj. One of the outflow stations, Mawa, is situated in Munshiganj, and another, Arial Khan, is near Sadarpur in Faridpur. After the main outflow of Mawa, the river flows southeast, merging with the Meghna River and finally empties into the Bay of Bengal (Fig. 1). The mean annual discharge is $30,000 \text{ m}^3\text{s}^{-1}$, whereas, in the dry season, discharge can drop to $3500 \text{ m}^3\text{s}^{-1}$; in the monsoon season, it exceeds $90,000 \text{ m}^3\text{s}^{-1}$. The mean annual sediment load is $900 \text{ (Mtyear}^{-1}\text{)}$ (Sarker and Thorne, 2006). Seasonal variation can be considerable based on the hydrograph; March – May is considered pre-monsoon, June – September is monsoon, October – November is post-monsoon, and December – February is dry/winter.

Seasonal variations in discharge are a frequent feature of the reach, resulting in complex geomorphic structures, including primary and secondary channels, islands, bars, unvegetated banks, backwaters, and water depressions (Gani et al., 2022). Extensive in-channel geomorphic units (GUs) and high discharge and sediment loads make the study reach very hydrologically dynamic for sediment transport (NASA Earth Observatory, 2019) and, thus, nitrogen transport.

2.2. Overall approach

The sampling stations were located strategically to capture the water and nutrient budgets of the entire system. The study reach does not have any significant tributaries, so samplings for the measurement of upstream-downstream transport of total nitrogen (TN) were carried out from an inflow (Baruria), a main outflow (Mawa) and a relatively small outflow (Arial Khan) (Fig. 1). These points ensured that all major pathways of water and nitrogen export were accounted for in the mass balance.

Monthly samplings for water quality were conducted in collaboration with the Bangladesh Water Development Board (BWDB) to align with their regular monitoring programmes for discharge measurements. Samplings for total dissolved nitrogen (TDN) and total suspended solids (TSS) were carried out from August 2019 to September 2020 at all three stations. Monthly water samples from Baruria (inflow) and Mawa (main outflow) were collected at 20 % and 80 % of channel depth, mainly from three sampling points across the river using a Binkley sampler. Additional samples were collected from three sampling points across the river channel of Arial Khan. The downstream (Mawa) station is considered tidal for seven months of the year. So, more samples were collected during the tidal periods. Overall, 70 samples from Baruria, 107 from Mawa, and 13 from Arial Khan were collected for nitrogen concentration analysis over the 14 months of sampling. Additional field campaigns were conducted from March 2021 to August 2021 to assess the influence of extreme storm events and the relationship between discharge and

EPSG:32465-WGS 84/UTM zone 45 N

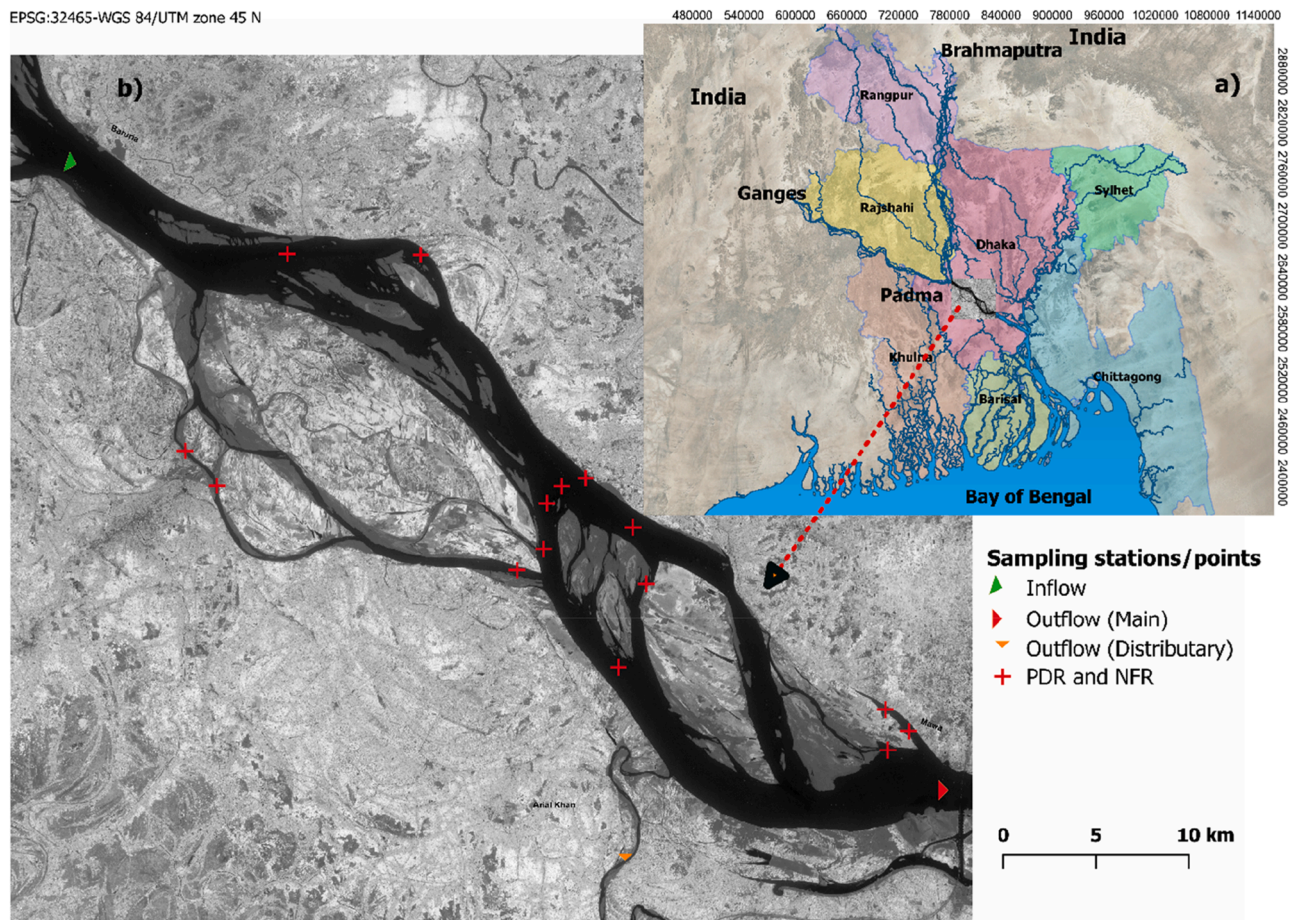


Fig. 1. a). Location of the study reach of the Padma River in Bangladesh. b) Enlarged view of the reach showing sampling stations of Baruria (inflow), Mawa (outflow) and Arial Khan (outflow). The red cross marks represent sampling points in the river for PDR (Potential denitrification rate) and NFR (Nitrogen fixation rate) estimation during the dry/winter season (Source: GeoDASH, Bing Satellite and Copernicus Open Access Hub (<https://scihub.copernicus.eu/dhus/#/home>, accessed on 25 January 2022).

nitrogen concentrations. During that period, 12 samples were collected from Baruria, 11 from Mawa, and 3 from Arial Khan.

For PDR and nitrogen fixation rate (NFR), field campaigns were carried out during February 2020 (dry/winter season). Water samples were collected from 15 sampling points along the mid-river reach in triplicate, with separate samples taken for PDR and NFR. Immediately after collection, all samples were transported in an icebox to the research laboratory in the Department of Botany at Jagannath University, Bangladesh. In addition, sediment sampling points for PDR and NFR were distributed across key geomorphic units (mid-channel bars, secondary channels) identified in a prior geomorphic classification (Gani et al., 2022) to capture the spatial heterogeneity of biogeochemical activity within the river corridor as described by Gani et al. (2025).

After field samplings (i) TN (TDN+PN), (ii) PDR, and (iii) NFR were measured in the laboratory, and (iv) discharge (Q), (v) water retention, and (vi) flux calculations were done separately. Finally, (vii) retention calculation and partitioning and (viii) net N losses via gaseous phases were estimated.

(i) Total nitrogen (TN)

Total nitrogen (TN) is the sum of TDN and PN. The measurements or estimation procedures for these were:

Total dissolved nitrogen (TDN)

For total dissolved nitrogen (TDN), water samples were filtered on site through Whatman GF/F filter paper and stored in high-density polyethylene (HDPE) bottles in a cool ice box for transportation to the

IHE Delft Institute for Water Education, The Netherlands, for analysis. In the laboratory of IHE Delft, TDN was measured by high-temperature combustion (680 °C) using a Shimadzu TOC-L analyser.

Particulate nitrogen (PN)

To determine the particulate nitrogen (PN), TSS data were used. A volume of 60 mL was passed through dry, pre-weighed Whatman GF/F glass fibre filters for TSS measurement. The filter was dried at 105 °C, reweighed, and TSS was calculated (APHA, 2005). According to Balakrishna and Probst (2005), the carbon-to-nitrogen ratio of a large tropical river exhibited seasonal variation, mainly dependent on sediment fluxes during the monsoon and in-channel phytoplankton density during other seasons. In the present study, a comparatively higher TSS was observed during the monsoon, and higher phytoplankton densities were recorded in non-monsoon months (SF1 and SF2). Therefore, PN was calculated using the regression equations as modified by Balakrishna and Probst (2005).

$$PC = \left(\frac{71.04 \text{ mg}}{\text{TSS}} \frac{\text{mg}}{\text{L}} \right) + 1.6068$$

$$\frac{PC}{PN} = 0.0354 \times \text{TSS mg L}^{-1} + 5.5041$$

PC is the concentration of the particulate carbon, and PN is the concentration of the total particulate nitrogen (mg L^{-1}).

(ii) Potential denitrification rate (PDR)

The potential denitrification rate (PDR) was measured by the acetylene inhibition method (Groffman et al., 1999). First, samples for PDR were processed in the research laboratory of the Department of Botany, Jagannath University, Dhaka. Here, water samples of 10, 25, and 50 mL were used for incubation. The gas samples were stored in evacuated exetainers with vacuum grease applied and then shipped to IHE Delft, Netherlands. In the laboratory of IHE Delft, gas samples for N_2O were quantified by gas chromatography (Sciion 456-GC) using an electron capture detector (ECD) at 250 °C. Finally, the PDR was calculated as $mg\ N_2O-N\ L^{-1}\ h^{-1}$.

(iii) Nitrogen fixation rate (NFR)

The nitrogen fixation rate (NFR) was measured using the acetylene inhibition method (Grimm and Petrone, 1997), in which acetylene was introduced to a sample and reduced to ethylene by the nitrogenase enzyme. Water samples were placed in gas-tight flasks, and purified acetylene was added by bubbling it through 10 % acid (H_2SO_4) to protenate (and dissolve) any NH_3 from the acetylene tank (98.5 % acetylene), which could affect microbial activity in the jar. After that, the flasks were placed on a rotary shaker at 125 rpm for 4 h of incubation. Gas accumulated in the flask was removed by hand inserting a syringe, then injected into evacuated gas vials (15 mL), which were sealed and stored for later analysis of ethylene. All vials were transported to IHE Delft, the Netherlands. In the GC (Bruker GC-456), ethylene was quantified using a flame ionisation detector (FID) at 175 °C, with a runtime of 2.5 min. Finally, the NFR was calculated as $mg\ N_2\ L^{-1}\ h^{-1}$.

(iv) Discharge (Q)

Monthly observed discharge data, along with flow velocity measurements from 2019 to 2021, were collected from the BWDB for the Baruria, Mawa, and Arial Khan stations. Three hourly water level data were also collected from the BWDB during that period. Daily mean rainfall data from 2019 to 2020 from the eight rainfall stations close to the study area were collected from the BWDB.

The outflow station at Mawa was tidal from November to May, according to BWDB. So, for measuring the daily discharge of this station, first, the monthly mean discharge of monsoon months (June to October) between Baruria and Mawa was compared, and regression analysis was used to estimate the discharge in Mawa during tidal months, calculated from the discharge in Baruria (Fig. 2). For each station using observed

monthly discharge data, rating curves were produced, and 3 hourly discharges (Q) were calculated from water level (WL) data.

(v) Water retention

Water retention was observed in the study reach throughout the study period, regardless of the season. Monthly outflow discharges were subtracted from the inflow discharges to calculate water retention as:

$$\text{Water retention (m}^3\ \text{month}^{-1}) = \text{Inflow Q (m}^3\ \text{month}^{-1}) - \text{Outflow Q (m}^3\ \text{month}^{-1})$$

(vi) Flux calculations

To calculate the nitrogen flux from the inflow (Baruria) and the outflows (Mawa and Arial Khan), the relationship between discharge and nitrogen concentration (TDN and PN) was first estimated. The relationship between observed discharge and measured nitrogen concentrations is presented in Fig. 3. Observed discharge and measured total dissolved nitrogen (TDN) showed no significant relationship for all the sampling stations (Baruria, Mawa and Arial Khan). Significant relationships were found between discharge and PN data for all stations (Fig. 3). So, linear regression equations were used for the PN concentration to estimate the three hourly PN values from the discharges, whereas, for TDN, only a mean value was used. Finally, three hourly discharges were multiplied by concentration values to obtain three hourly PN and TDN fluxes. From 3 h, first daily and then monthly fluxes were calculated. Finally, TN flux was obtained from PN and TDN, expressed in tonnes per month.

(vii) Retention calculations and partitioning

Overall retention

The mass balance approach used discharge and nitrogen concentration to calculate the difference between loads at the inflow and outflow points that define the study reach. In the nitrogen retention calculation, the lateral input due to anthropogenic activity – e.g., from wastewater input and runoff - was assumed to be trivial compared with upstream input to the study reach. Therefore, lateral inputs were ignored. The mass balance was calculated as:

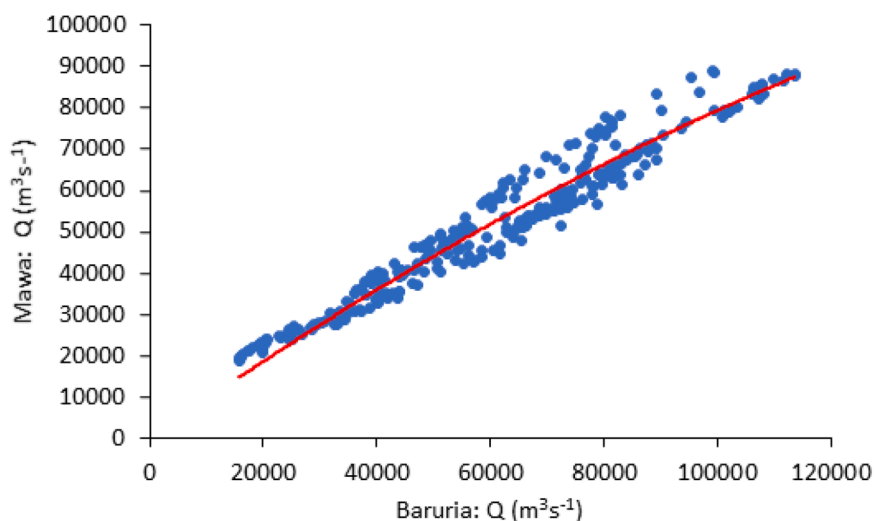


Fig. 2. Regression analysis between Q (discharges) of Baruria (inflow) and Mawa (outflow) during monsoon months (June-October), showing the determination of coefficient ($R^2 = 0.95$) and regression equation ($y = -2 \times 10^{-6} \times 2 + 0.9724x$) that was used to derive the discharges during non-monsoon months in Mawa.

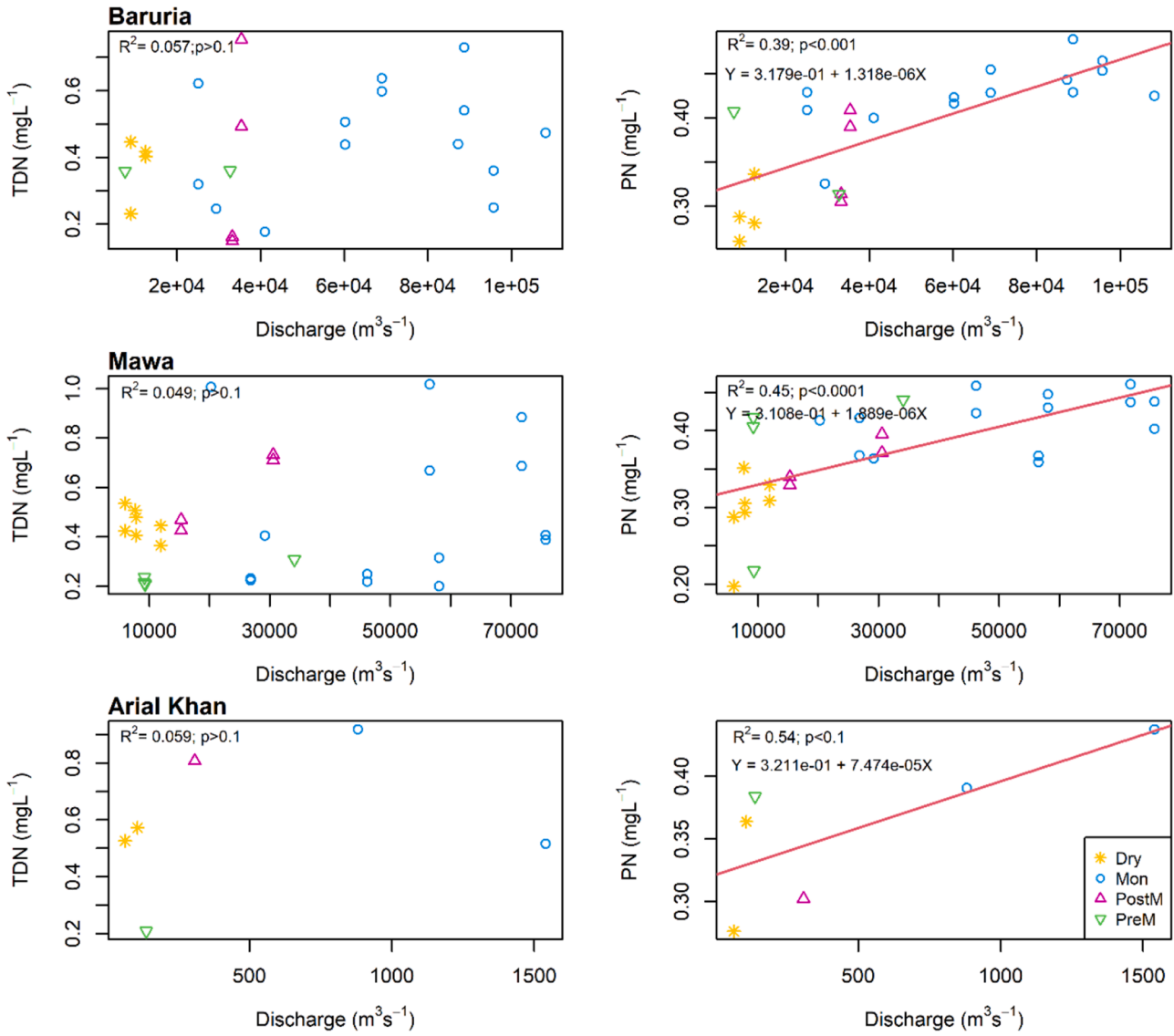


Fig. 3. Relationships between discharge (Q) and total dissolved nitrogen (TDN) and particulate nitrogen (PN). In case of PN, regressions were significant at least at $p < 0.1$ in the Baruria (inflow), Mawa (outflow 1), and Arial Khan (outflow 2) of the Padma River, Bangladesh.

$$\text{Nitrogen retention (t month}^{-1}\text{)} = \text{Input (inflow) (t month}^{-1}\text{)} - \text{Output (outflows) (t month}^{-1}\text{)}$$

Nitrogen loss due to water retention

To estimate the nitrogen loss due to water retention (NLWR) through the reach, water retention for every month was multiplied by the inflow TN concentration to quantify monthly N losses. So, N loss due to water retention (NLWR) was calculated as:

$$\text{NLWR (t month}^{-1}\text{)} = \text{Water retention (m}^3\text{month}^{-1}\text{)} \times \text{Inflow TN Conc. (t m}^{-3}\text{)}$$

Sedimentation

The difference in PN concentration from the inflow to outflows is attributed to sedimentation in the study reach. So, sedimentation of particulate N in the study reach was estimated by :

(viii) Net N losses via gaseous phases

Upscaling of the measured PDR and NFR in the water column

Measured PDR and NFR in the water column were upscaled using the monthly observed flow velocity, discharges in outflows and estimated water travel time in the study reach. Only the amount of water in the outflows was considered for PDR and NFR up-scaling. A travel time factor was used to estimate water travel time from inflow to outflows, using the flow velocity and total distance (50 km) of the reach. Finally, the amount of water from each month was multiplied by the measured average PDR or NFR to obtain an estimate for the entire reach. So, the upscaling of PDR and NFR is:

$$\text{N Sedimentation (t month}^{-1}\text{)} = [\text{Conc. of inflow PN (t m}^{-3}\text{)} \times \text{inflow Q (m}^3\text{ month}^{-1}\text{)} - \text{Conc. of outflows PN (t m}^{-3}\text{)} \times \text{Outflow Q (m}^3\text{ month}^{-1}\text{)}]$$

$$PDR (t\ month^{-1}) = [(Outflow1\ Q1 + Outflow2\ Q2) (L\ month^{-1})] \\ \times k_t (d) \times Mean\ PDR (tL^{-1}\ d^{-1})$$

$$NFR (t\ month^{-1}) = [(Q1 + Q2) (L\ month^{-1})] \times k_t (d) \\ \times Mean\ NFR (tL^{-1}\ d^{-1})$$

$$kt (d) = \frac{\text{reach distance (m)}}{\text{Outflow1 weighted average velocity (m d}^{-1}) + \text{Outflow2 weighted average velocity (m d}^{-1})}$$

Q1 and Q2 are the discharges of outflow₁ (Mawa) and outflow₂ (Arial Khan), respectively. k_t was the travel time factor derived from the monthly water velocities. Mean PDR and NFR were calculated from the measured PDR and NFR at different sampling points.

Estimation and upscaling of PDR in submerged GUs

To estimate PDR in submerged GUs, the submerged area of GUs was first calculated for each season using the surface area of GUs described in Gani et al. (2022) (ST1). After that, the mean PDR of each GU was calculated from the measured PDR in GUs during the dry/winter season (Gani et al., 2025) (SF3). Finally, the area of submerged GUs was multiplied by the mean PDR for each GU to obtain seasonal estimates, which were then converted to monthly estimates:

$$PDR\ in\ Submerged\ GUs (t\ month^{-1}) = \text{Area of submerged GUs (m}^2) \times \text{Mean measured PDR in GUs (t m}^{-2}\ month^{-1})$$

3. Results

3.1. River hydrology

The highest discharge was found in July 2020 (Baruria: 2.67×10^{11} m³ month⁻¹, Mawa: 2.35×10^{11} m³ month⁻¹ and Arial Khan: 5.46×10^9 m³ month⁻¹) for all the sampling locations, and the lowest discharge

was in March 2020 for Baruria (1.18×10^{10} m³ month⁻¹) and February 2020 for Mawa (1.12×10^{10} m³ month⁻¹) and Arial Khan (3.9×10^8 m³ month⁻¹) (Fig. 4). Water retention, i.e. the difference in discharge between inflow and outflows, showed that during monsoon months, the retention was higher than in other months. The highest water retention occurred during September 2019 (3.17×10^{10} m³ month⁻¹), and the lowest in March 2020 (3.59×10^7 m³ month⁻¹) (Fig. 5). During the monsoon, river discharge is mostly driven by rains, and therefore closely related to precipitation patterns (SF4).

3.2. Nitrogen concentration and flux

Monthly average TN concentrations were higher in the inflow and

outflows during the monsoon than in the other months. The TN concentrations were consistently higher in the inflow (Baruria) than in the main outflow (Mawa). However, the TN concentration of the distributary was the highest (Arial Khan) (Fig. 6). TN fluxes through Baruria, Mawa, and Arial Khan ranged from 6950 – 301,777, 6144 – 173,805 and 214 – 5696 t month⁻¹, respectively (Fig. 7). Like the rainfall,

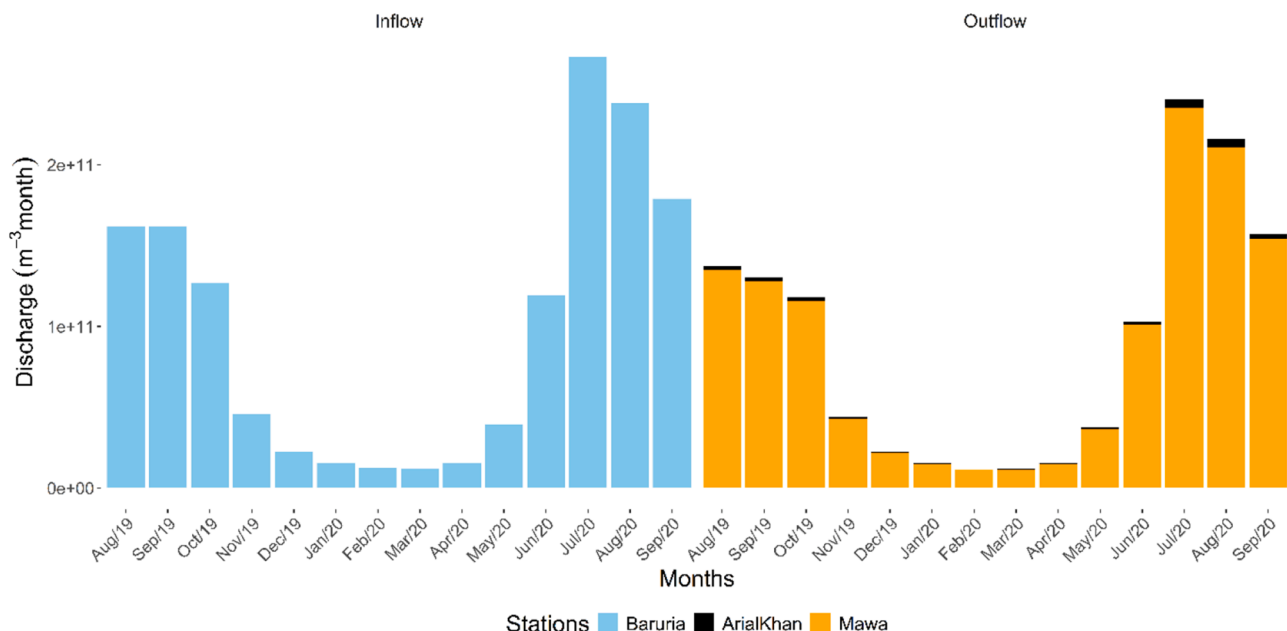


Fig. 4. Monthly variation of calculated discharge in the study area of the Padma River, Bangladesh, from August 2019 to September 2020.

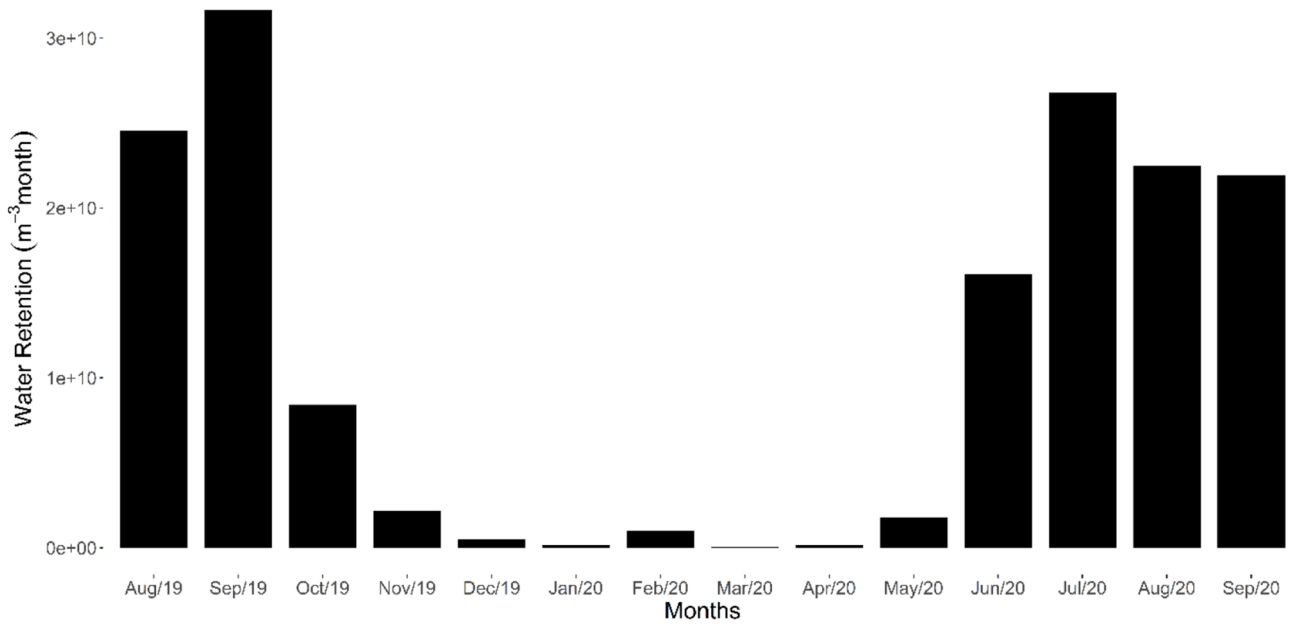


Fig. 5. Monthly variation of water retention in the study area of the Padma River, Bangladesh, from August 2019 to September 2020.

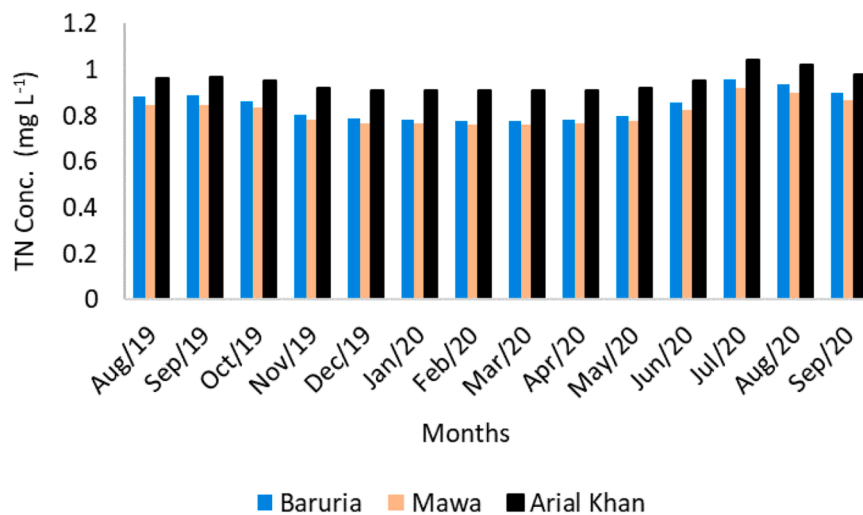


Fig. 6. Monthly variation of TN (TDN+TPN) concentration (mg L^{-1}) in the study area of the Padma River, Bangladesh.

discharge and average TN concentration, the highest TN flux was estimated in the monsoon months. The highest value was found in July 2020. However, the TN flux pattern during monsoon months differed in both outflows. In Mawa, the highest value was found in July 2020; in Arial Khan, the highest was found in August 2020; and the lowest was in June 2020. More TPN was transported through Mawa during July 2020 and August 2020, and less during August 2019 and September 2019 (Fig. 7). The two monsoon periods showed a distinct feature of nitrogen flux in Mawa, which is the main outflow of the river.

3.3. Measured retention through a mass balance

The monthly mass balance measurement showed that the maximum TN retention occurred in July 2020 ($120,000 \text{ t month}^{-1}$). Retention occurred mainly during the monsoon season, except in September 2019, when the inflow flux exceeded the outflow fluxes. In post-monsoon 2019, retention was comparatively lower, as more TN was transported through Mawa than through Baruria during October 2019. A similar scenario was found in dry/winter 2020 and pre-monsoon 2020, where

more TN was transported through Mawa than Baruria, resulting in net TN export during those periods (January 2020, February 2020, April 2020 and May 2020) (Fig. 8). From October 2019 to September 2020 (hereafter annual) TN retention of the reach was 121,715 t which was 11 % of the total inflow to the river. Seasonal variation showed that measured TN retention in the post-monsoon, dry/winter, pre-monsoon and monsoon seasons were 12,928 t (10.6 % of annual TN retention), 1946 t (1.6 % of annual TN retention), 2493 t (2.1 % of annual TN retention) and 104,347 t (85.7 % of annual TN retention), respectively (ST2).

3.4. Estimated retention through retention processes

3.4.1. Variation of estimated nitrogen loss due to water retention (NLWR) and sedimentation

In the study area, TN was lost due to water retention (NLWR) to the floodplains and aquifers throughout the study period, but it was comparatively higher in monsoon months. The maximum TN transport as floodplain and aquifer loss occurred during July 2020 (30,135 T/

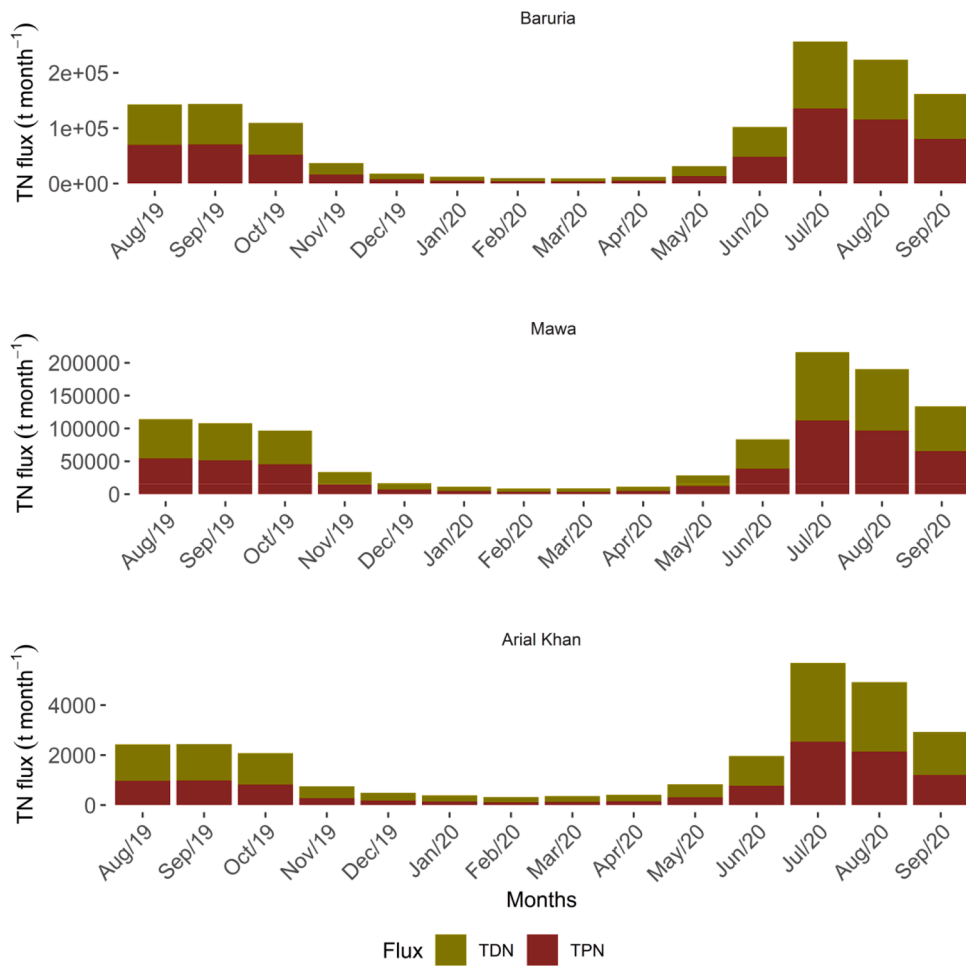


Fig. 7. Monthly variation of TN (total nitrogen) flux (t month⁻¹) in the Baruria (inflow), Mawa (outflow) and Arial Khan (outflow) of the study area of the Padma River, Bangladesh.

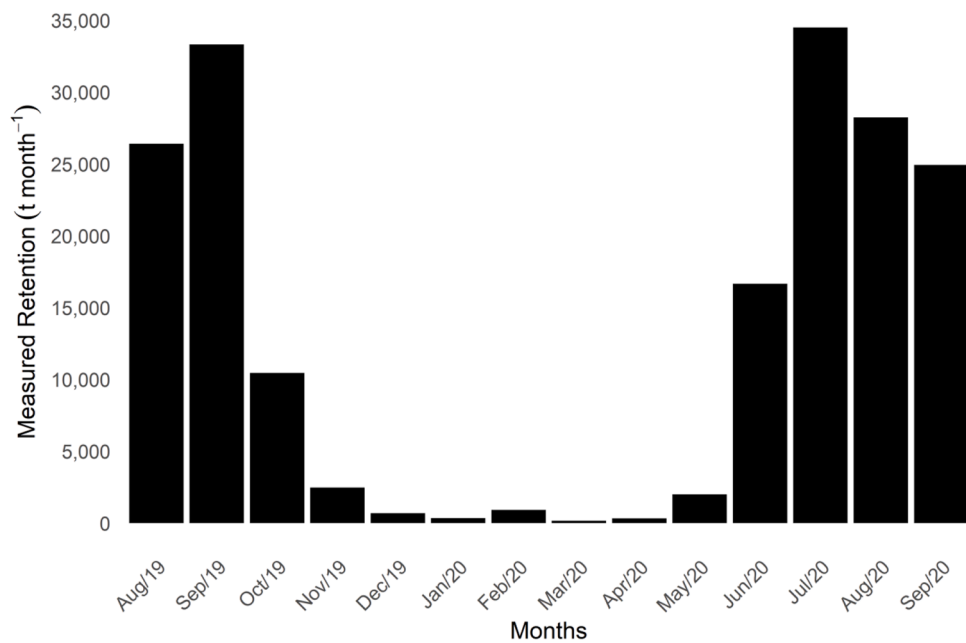


Fig. 8. Monthly variation of measured TN (total nitrogen) retention in the study reach of the Padma River during August 2019-September 2020.

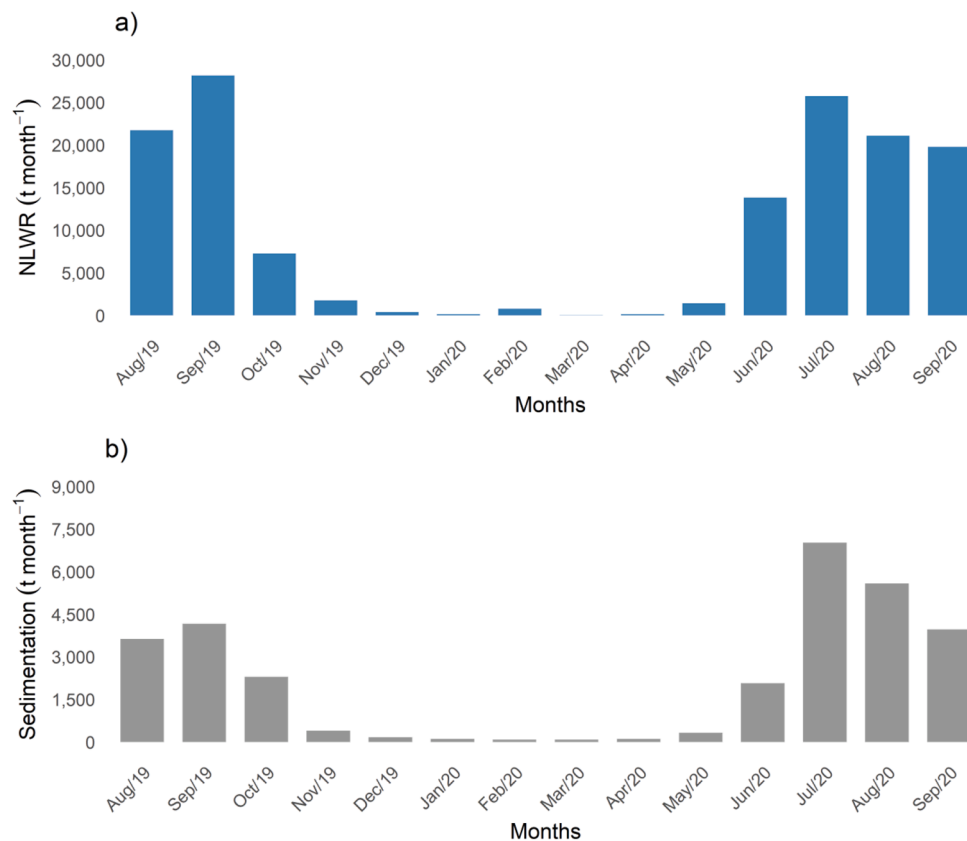


Fig. 9. Monthly variation of estimated a) NLWR (N loss due to water retention) and b) sedimentation in the study reach of Padma River during August 2019–September 2020.

month). Some amount of N loss occurred during post-monsoon 2019 (1889 – 7630 t month⁻¹) and pre-monsoon (103 – 1169 t month⁻¹), while in the dry/winter 2020, it was a minimum (21 – 617 t month⁻¹). TN losses also occurred due to sedimentation, and the highest was during the monsoon. Among monsoon months, the maximum sedimentation was found in July 2020 (7014 t month⁻¹) and the minimum was in June 2020 (2066 t month⁻¹), which was 5 times higher than the lowest value during non-monsoon (80 t month⁻¹) (Fig. 9). Estimated annual TN retention as NLWR was 92,289 t (77 % of total measured retention) and estimated annual TN retention via sedimentation was 22,176 t (18 % of total measured retention) (ST2).

3.4.2. Variation of estimated potential denitrification rate (PDR) in the water column and submerged GUs and nitrogen fixation rate (NFR)

Most of the nitrogen loss by denitrification (PDR) in the water column and submerged GUs occurred during the monsoon months, while nitrogen was added through nitrogen fixation (NFR) at the same time. PDR in submerged GUs was higher than in the water column during non-monsoon months. The highest PDR and NFR values in the water column were found in July 2020 (PDR: 542 t month⁻¹, NFR: 7.34 t month⁻¹), and the lowest values were in March 2020 (PDR: 27 t month⁻¹, NFR: 0.36 t month⁻¹) during monsoon months. In non-monsoon months, the values were higher in October 2019 (PDR: 213 t month⁻¹, NFR: 2.89 t month⁻¹) (Fig. 10). Estimated annual PDR in submerged GUs was 2795 t (2.3 % of total measured retention) and estimated annual water column PDR was 2152 t (1.8 % of total measured retention) (ST2).

3.5. Comparison between measured and estimated retention

The sum of estimated annual retention was 119,412 t, which is 98 % of the measured value. Estimated TN retention in the post-monsoon, dry/winter, pre-monsoon, and monsoon seasons was 12,500 t, 2380 t,

2904 t, and 101,629 t, respectively, which corresponds to 97 %, 122 %, 116 %, and 97 % of the measured retention in those seasons, respectively (Fig. 11 and ST2).

A comparison of measured retention and the sum of estimated retention processes is shown in Fig. 12. During the monsoon months, measured retention was higher than estimated retention, whereas during non-monsoon months, except for October 2019, measured retention was lower than estimated retention (Fig. 12). The monthly estimated retention through NLWR, sedimentation, and PDR showed the same pattern as measured retention. Comparatively, the percentage of NLWR was higher during the monsoon months. In case of sedimentation, the highest percentage was found in March 2020, and the lowest was in February 2020. The percentage of PDR both in the water column and submerged GUs showed a higher value in non-monsoon months (Fig. 13). Fig. 13 also shows that the difference between the measured and estimated retention was negative during non-monsoon periods.

4. Discussion

To our knowledge, this is the first study that has looked at monthly time steps for nitrogen retention in a monsoon-dominated large tropical river. Studies in temperate rivers have, however, shown monthly variation in nitrogen retention (de Klein and Koelmans, 2011; Natho et al., 2013). Considering the mean width of the reach, the measured annual mean TN retention during the present study was 556 mg m⁻² d⁻¹, which can be comparable to the large lowland Elbe River, where the estimated annual mean retention was 408 mg m⁻² d⁻¹ (Ritz and Fischer, 2019). All nitrogen retention processes were influenced by discharge, which varied significantly across seasons. Moreover, in all seasons, the studied reach was found to be losing water, as downstream discharge was less than upstream discharge. The annual retention of the Padma River (representing 11 % of the total input to the river) was similar to that reported

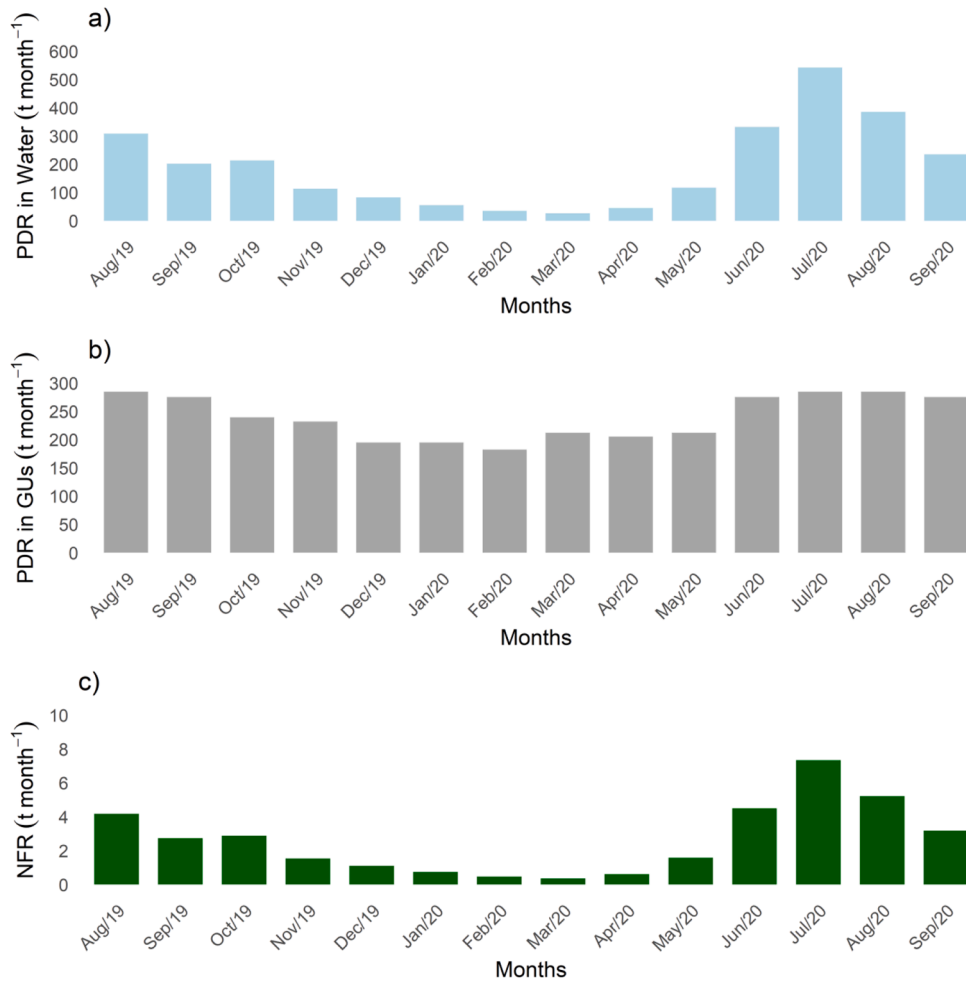


Fig. 10. Monthly variation of estimated PDR (potential denitrification rate) in a) water column, b) submerged GUs, and c) NFR (nitrogen fixation rate) in the study area of Padma River, Bangladesh.

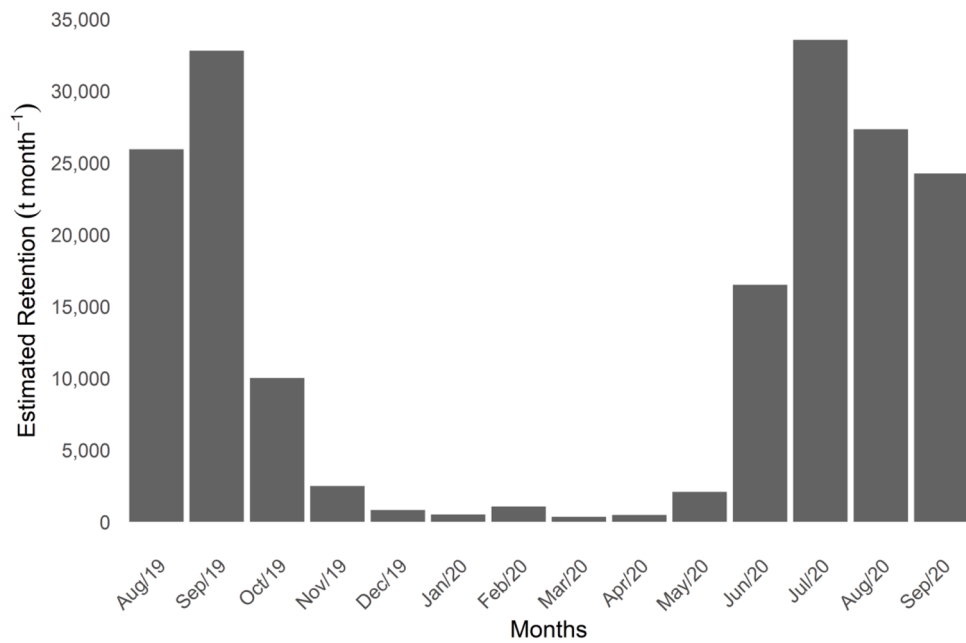


Fig. 11. Monthly variation of estimated TN (total nitrogen) retention in the study reach of Padma River during August 2019-September 2020.

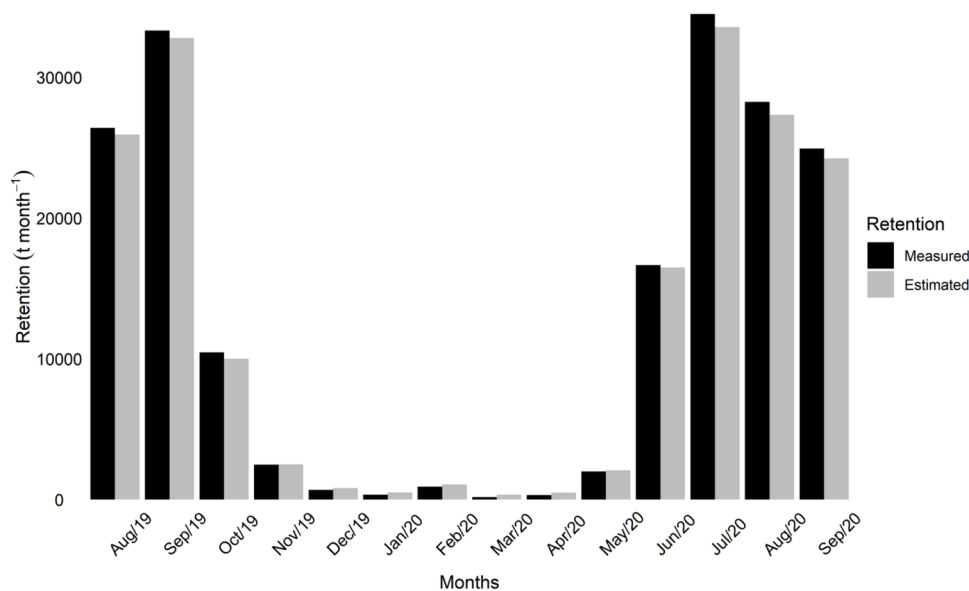


Fig. 12. A comparison between measured TN (total nitrogen) retention (through mass balance calculation) and estimated TN retention (through different retention processes) in the Padma River, Bangladesh.

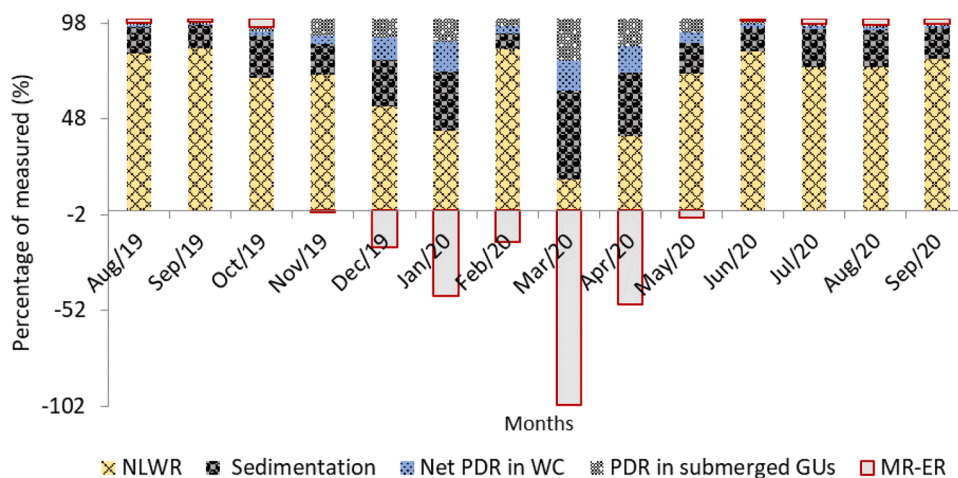


Fig. 13. Monthly comparison of NLWR (nitrogen loss due to water retention), sedimentation, and Net PDR (potential denitrification rate) in the water column, PDR in submerged GUs and MR-ER (MR= measured retention and ER= estimated retention) at the study area of Padma River, Bangladesh (Net PDR = PDR-NFR).

in other studies (Coupe et al., 2013; Loken et al., 2018). However, the present study showed that about 86 % of the retention estimated in the Padma River occurs during monsoon months (ST2). Several factors were apparently involved in regulating TN retention in the studied reach.

4.1. Role of discharge as an influencing factor of TN retention

In the Padma River, strong seasonal differences in precipitation and river discharge were observed, which is similar to other large rivers, where discharge is a major regulatory factor for nitrogen transport (Wang et al., 2020; Pan et al., 2020; Krishna et al., 2016).

In the river, water discharge of primary and secondary channels, which increased with the water flux, was significantly associated with estimated TN retention. However, the data showed three scenarios of non-monsoon, monsoon 2019 and monsoon 2020 (Fig. 14). The scenarios were observed mainly due to the variation of monsoon discharge events, which varied from 2019 to 2020 (Fig. 4). In 2020, flooding started unusually late in June and recorded the highest discharge and second longest residence time since 1989 and 1998, respectively (OCHA, 2023). The maximum TN retention was found during the flood peak in

July 2020. In contrast, in 2019, the highest peak was observed in September. Due to a lack of data (June and July 2019), it was not possible to show how flooding influenced retention throughout the whole monsoon of 2019.

The increase in discharge is because of higher surface runoff, higher nitrogen concentrations, and increased river nitrogen load. The positive difference in TN concentration from inflow to outflows in the Padma River showed more TN flux in monsoon 2020 than in monsoon 2019. Different monthly estimates of the nitrogen flux also occurred due to higher inflow concentrations relative to the main outflow, which was influenced by discharge. Owing to this phenomenon, the average retention estimate fluctuated widely across monsoon periods (Fig. 15). In the present study, the estimated PN concentration was based on its relationship with discharge, which also influenced TN concentrations, resulting in increased retention during monsoon months.

4.2. Role of submerged GUs and water column denitrification in TN retention

Net PDR in the water column and PDR in submerged GUs were

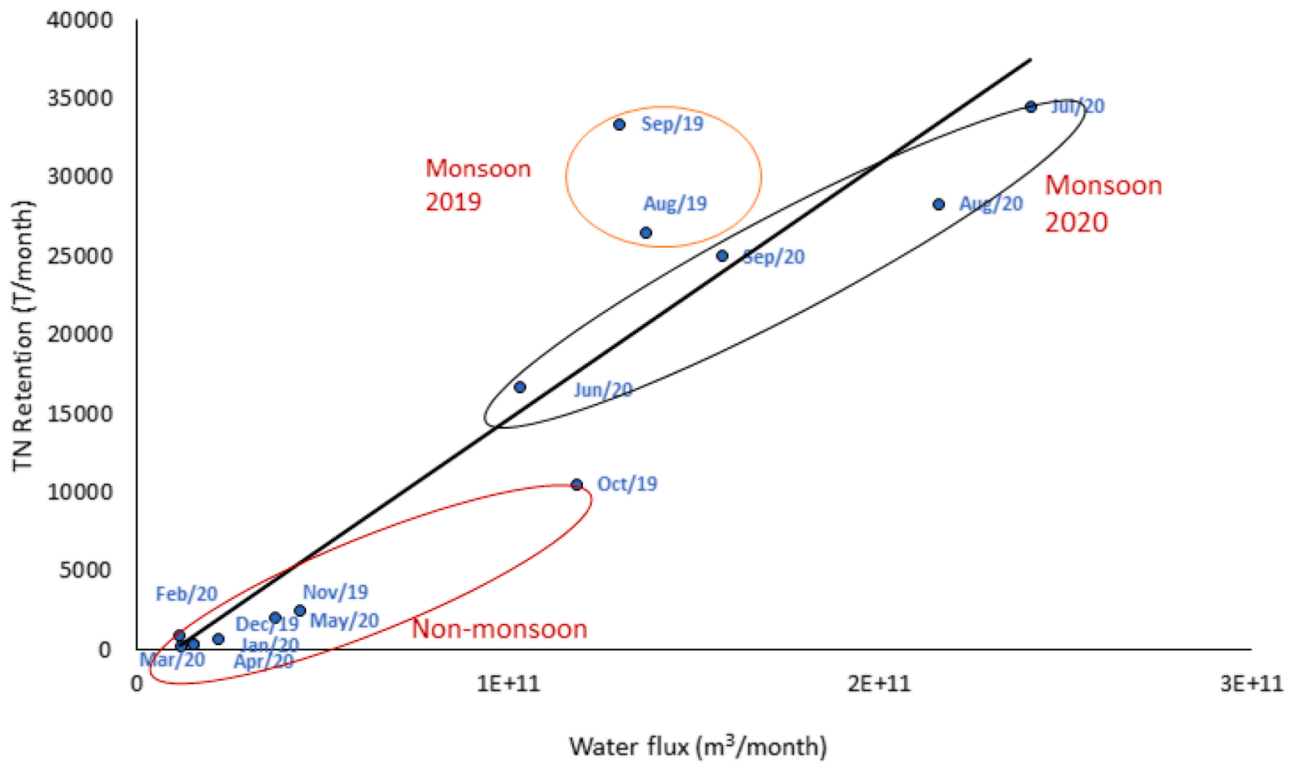


Fig. 14. Regression analysis ($y = 2 \times 10^{-7}x - 1666$; $R^2 = 0.87$) between water flux and nitrogen retention in the Padma River, Bangladesh, showing three scenarios represented by the ovals (non-monsoon, monsoon 2019 and monsoon 2020). Water flux was calculated based on the allocation of inflow discharge to the surface area of primary and secondary channels (C & S).

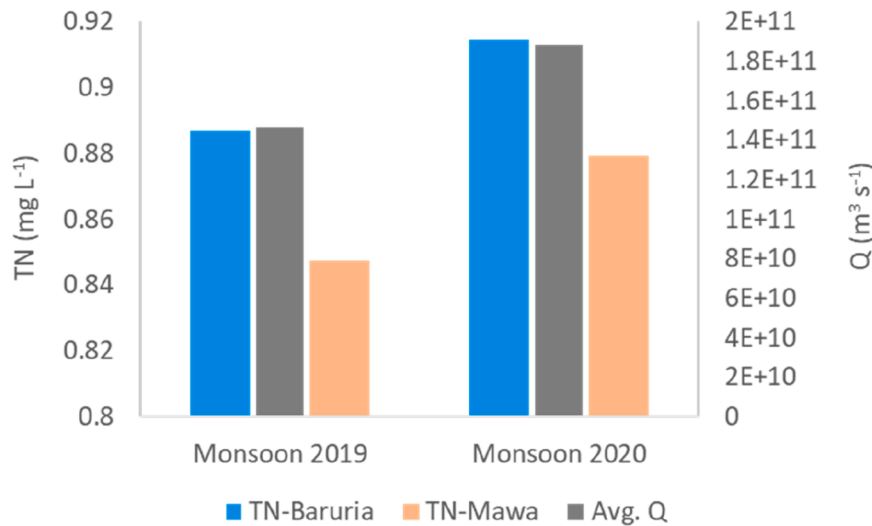


Fig. 15. Mean TN (total nitrogen) concentrations in the Baruria (inflow) and Mawa (outflow) during monsoon 2019 and 2020. Avg. Q (average discharge) from inflow and outflow stations during this period is also depicted in this figure.

influenced by the total discharge flowing from the reach in each season. TN retention via net PDR in the water column was a rate per water volume, so the retention value increased or decreased as volume increased or decreased. TN retention via PDR in submerged GUs was measured per area of submerged GUs, so retention increased or decreased as the area (and type) of submerged GUs increased or decreased. The area changed as discharge fluctuated.

In the study reach, PDR in submerged GUs appears to be much more important than the water column PDR (2795 t year⁻¹ vs. 2152 t year⁻¹, respectively). Annually, denitrification associated with GUs increases

from 2795 to 3197 due to the inundation of geomorphic units exposed during the post-monsoon, dry/winter, and pre-monsoon seasons (Gani et al., 2025). PDR in the water column and in GUs were most significant to total N retention in the pre-monsoon and dry/winter seasons, accounting for 28 % and 31 % of total N retention, respectively. During the monsoon and post-monsoon seasons, PDR in the water column and in GUs accounted for only 2 % and 7 % of total N retention, respectively. PDR estimates in submerged GUs were strongly dependent on the assumed depth of hyporheic exchange, which was set at 10 cm in the present study. Other studies have shown exchange up to 1 m (Fischer

et al., 2005; Bartoli et al., 2021).

4.3. Role of water retention in TN retention and retention processes

During the present study, NLWR and sedimentation were estimated to contribute a significant portion to TN retention, which occurred due to water retention. Estimated TN retention values for NLWR and sedimentation were influenced by the water retention seasonally in the reach. Differences in downstream versus upstream discharge determined the amount of water retention, which included the retention of 100 % of TN in the retained water (NLWR). Suspended sediment concentrations (and associated PN) were estimated as a function of discharge. Suspended sediment concentrations decreased downstream, and the difference in suspended sediment loads was equated to sedimentation, with associated PN retained. Comparatively higher TN retention was observed in September 2019 and July 2020, due to higher water retention, which influenced NLWR and sedimentation. Unexpectedly, after January 2019, more water retention was observed in February 2020, which enhanced NLWR and sedimentation. However, this appeared mainly due to direct or indirect groundwater recharge during the dry season induced by intensive groundwater abstraction for irrigation (Nowreen et al., 2020). Another factor might be dredging activities during that time, i.e., sediment removal via water, which led to high NLWR and sedimentation. In addition, during non-monsoon periods, as a percentage, denitrification was comparatively higher in the water column, likely due to lower flow velocity (1.65 times lower than during monsoon), resulting in nitrogen loss.

4.4. Processes that are responsible for the difference between measured and estimated retention

Measured and estimated N retention were within 2 % of each other overall, but differences were higher in the individual seasons. Measured values were higher than estimated in the monsoon and post-monsoon seasons, while measured values were less than estimated in the pre-monsoon and dry/winter seasons. The differences are minor and may fall within the range of uncertainty in measurements and estimations, but other explanations are also possible. During the monsoon, the surplus of measured retention suggested that other retention processes might be responsible for the difference, which was not addressed in the present research. For example, gaseous nitrogen loss to the atmosphere through processes other than denitrification during the monsoon can be the cause, which was not considered during the retention process estimation.

Variation in GUs and fertilisation for cropping can explain the surplus in the estimated value during the pre-monsoon and dry/winter seasons. Fertiliser application in the GUs for high crop yield began during or after the post-monsoon. The nitrogen status of the study area was categorised by the Bangladesh Agricultural Research Council as very low and low, where the expected maximum yield ranged from 25–75 % without fertiliser. Fertiliser is applied between November and March to increase the crop yield (Ahmed et al., 2018). As the surface area of terrestrial GUs increased from post-monsoon to the winter/dry season (Gani et al., 2022), an increase in fertiliser application might be expected to increase PDR and be higher in the dry/winter season. However, the submerged surface area was higher in the pre-monsoon than in the dry/winter season (ST1). As the inundation began, the stored nitrogen in the soil was released due to increased water volume and readily available nitrate for denitrification. So, a higher PDR was observed in March 2020.

4.5. Limitations and scope for future research

The present study is based primarily on a single hydrological year, supplemented by additional sampling during extreme events such as cyclones and flooding. Due to the strong monsoon-driven variability of

the Padma River, nitrogen retention processes may differ substantially from year to year depending on flood magnitude, frequency and residence time. Interannual climate anomalies, e.g. late-onset monsoons as found in 2020, can significantly shift nitrogen dynamics. So, estimating the annual TN budget without measuring all forms of nitrogen and accounting for several years of data was challenging, given the high monthly variation in TN flux from inflow to outflow. Frequent changes in channel geomorphology additionally contributed to this difficulty. These factors alter the nitrogen transport scenario from season to season, so slight temporal scale variation can influence long-term predictions. Thus, while monthly patterns are robust, long-term trends cannot be inferred without multi-year datasets.

In addition, the PDR and NFR measurements were obtained from a single campaign (the dry season). Upscaling these rates to other seasons, while based on hydrology, does not account for potential seasonal changes in microbial community or activity. The PDR estimate for submerged GUs is highly sensitive to the assumed depth of hyporheic exchange (10 cm in this study), which other studies suggest could be deeper. The slight but systematic differences between measured and estimated retention suggest other processes, such as benthic denitrification in the river channel, nitrification, and alternative gaseous losses, may be at play, particularly during the monsoon, which was not accounted for in the present study.

The Padma River is highly dynamic, with high water discharge, extreme seasonality, and extensive floodplain connectivity, characteristics that are not representative of all tropical rivers. Therefore, although our process-level insights are broadly relevant, exact retention magnitudes should not be extrapolated to other systems without accounting for hydrological and geomorphic differences.

Beyond these limitations, the current research can explain various retention processes, including NLWR, sedimentation, and PDR in the water column, as well as submerged GUs, on monthly basis. The contributions of these processes to TN retention were highly variable and can impact nitrogen budget estimation. Moreover, flooding events and altered geomorphic complexity can affect year-to-year retention calculations. Therefore, these facts should be taken into consideration when estimating nitrogen budgets in tropical floodplain rivers.

5. Conclusion

The nitrogen retention dynamics of large tropical floodplain rivers are complex and shaped by a combination of hydrological, biogeochemical, and ecological processes. The present study shows that nitrogen retention in the Padma River is highly seasonal and mainly governed by river discharge, with the monsoon accounting for over 85 % of the annual total retention. In other seasons, retention is lower due to lower water retention. Retention as NLWR and sedimentation were the main retention processes in the river; however, during non-monsoon periods, a comparatively significant amount of nitrogen was lost through denitrification. Denitrification, particularly in submerged geomorphic units, becomes relatively more important in dry seasons. Although discharge is the main controlling factor, flooding events can alter the retention mechanism on an interannual basis. In addition, the concentration of nitrogen in particulate and dissolved forms can regulate overall nitrogen retention. To sum up, it is recommended to increase our efforts in comprehensive long-term monitoring and innovative modelling to accurately forecast how nitrogen cycling in tropical floodplain rivers will adapt to environmental changes. This is especially crucial to ensure the sustainability of river basins as we face the challenges posed by climate change and increased land-use activities.

CRediT authorship contribution statement

Md Ataul Gani: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation,

Conceptualization. **Gretchen M. Gettel**: Writing – review & editing, Supervision, Resources, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Johannes van der Kwast**: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kenneth A. Irvine**: Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Michael E. McClain**: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, 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.

References

- Ahmed, S., Jahiruddin, M., Razia, S., Begum, R.S., Biswas, J.S., Rahman, ASMM, Ali, M. M., Islam, K.M.S., Hossain, M.M., Gani, M.N., Hossain, G.M.A., Sultan, M.A., 2018. Fertilizer recommendation Guide- 2018. Bangladesh Agricultural Research Council (BARC). Farmgate, Dhaka, p. 1215.
- APHA (American Public Health Association), 2005. Standard Methods for the Examination of Water and Wastewater, 21st ed. American Public Health Association, Washington, DC.
- Balakrishna, K., Probst, J.L., 2005. Organic carbon transport and C/N ratio variations in a large tropical river: Godavari as a case study, India. *Biogeochemistry* 73 (3), 457–473. <https://doi.org/10.1007/s10533-004-0879-2>.
- Bartoli, M., Nizzoli, D., Zilius, M., Bresciani, M., Pusceddu, A., Bianchelli, S., Sundbäck, K., Razinkovas-Baziukas, A., Viaroli, P., 2021. Denitrification, nitrogen uptake, and organic matter quality undergo different seasonality in Sandy and muddy sediments of a turbid estuary. *Front. Microbiol.* 11 (January). <https://doi.org/10.3389/fmicb.2020.612700>.
- Best, J., 2019. Anthropogenic stresses on the world's big rivers. *Nat. Geosci.* 12 (1), 7–21. <https://doi.org/10.1038/s41561-018-0262-x>.
- Böck, K., Polt, R., Schilting, L., 2018. Ecosystem services in river landscapes. *Riverine Ecosyst. Manage.* 413–433. https://doi.org/10.1007/978-3-319-73250-3_21.
- Bouwman A.F., Bierkens M.F.P., Griffioen J., Hefting M.M., Middelburg J.J., & Middelkoop H. (2013). Nutrient dynamics, transfer and retention along the aquatic continuum from land to ocean: towards integration of ecological and biogeochemical models. <https://doi.org/10.5194/bg-10-1-2013>.
- Bukaveckas, P.A., Isenberg, W.N., 2013. Loading, transformation, and retention of nitrogen and phosphorus in the tidal Freshwater James River (Virginia). *Estuar. Coast.* 36 (6), 1219–1236. <https://doi.org/10.1007/s12237-013-9644-x>.
- Campbell, I., 2009. Chapter 1 - Introduction, Editor(s): Ian C. Campbell, In *Aquatic Ecology, The Mekong*. Academic Press. <https://doi.org/10.1016/B978-0-12-374026-7.00001-2>. Pages 1-11, ISBN 9780123740267. <https://www.sciencedirect.com/science/article/pii/B9780123740267000012>.
- Chen, D., Lu, J., Wang, H., Shen, Y., Kimberley, M.O., 2009. Seasonal variations of nitrogen and phosphorus retention in an agricultural drainage river in East China. *Environ. Sci. Pollut. Res.* 17 (2), 312–320. <https://doi.org/10.1007/s11356-009-0246-x>.
- Cotrim da Cunha, L., Buitenhuis, E.T., Le Quéré, C., Giraud, X., Ludwig, W., 2007. Potential impact of changes in river nutrient supply on global ocean biogeochemistry. *Global. Biogeochem. Cycles.* 21 (4), 1–15. <https://doi.org/10.1029/2006GB002718>.
- Coupe, R.H., Goolsby, D.A., Battaglin, W.A., Böhlke, J.K., McMahon, P.B., Kendall, C., 2013. Transport of nitrate in the Mississippi River in July–August 1999. *Ann. Environ. Sci.* 7 (3), 31–46.
- Davidson, E.A., De Araújo, A.C., Artaxo, P., Balch, J.K., Brown, I.F., Mercedes, M.M., Coe, M.T., Defries, R.S., Keller, M., Longo, M., Munger, J.W., Schroeder, W., Soares-Filho, B.S., Souza, C.M., Wofsy, S.C., 2012. The Amazon basin in transition. *Nature* 481 (7381), 321–328. <https://doi.org/10.1038/nature10717>.
- de Klein, J.J.M., Koelmans, A.A., 2011. Quantifying seasonal export and retention of nutrients in West European lowland rivers at catchment scale. *Hydrol. Process.* 25 (13), 2102–2111. <https://doi.org/10.1002/hyp.7964>.
- Eisner, S., Flörke, M., Chamorro, A., Daggupati, P., 2017. An Ensemble Analysis of Climate Change Impacts On Streamflow Seasonality Across 11 Large River Basins, pp. 401–417. <https://doi.org/10.1007/s10584-016-1844-5>.
- Fischer, H., Kloepf, F., Wilzcek, S., Pusch, M.T., 2005. A river's liver - microbial processes within the hyporheic zone of a large lowland river. *Biogeochemistry* 76 (2), 349–371. <https://doi.org/10.1007/s10533-005-6896-y>.
- Forsberg, B.R., Melack, J.M., Dunne, T., Barthem, R.B., Goulding, M., Paiva, R.C.D., Sorribas Jr., M.V., Silva, U.L., Sabine Weisser, S., 2017. The potential impact of new Andean dams on Amazon fluvial ecosystems. *PLoS One* 12 (8), e0182254. <https://doi.org/10.1371/journal.pone.0182254>.
- Gani, M.A., van der Kwast, J., McClain, M.E., Gettel, G., Irvine, K., 2022. Classification of geomorphic units and their relevance for nutrient retention or export of a large lowland Padma River, Bangladesh: a NDVI based approach. *Remote Sens. (Basel)* 14 (6). <https://doi.org/10.3390/rs14061481>.
- Gani, M.A., van Dam, A.A., E., Kwast, J.v.d., McClain, M.E., Irvine, K.A., Gettel, M.G., 2025. Estimation of potential denitrification and its spatiotemporal dynamics in seasonally inundated geomorphic units of a large tropical river using satellite data. *Sci. Total Environ.* 959 (6771). <https://doi.org/10.1016/j.scitotenv.2024.178287>.
- Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P., Sutton, M.A., 2008. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. *Science* (1979) 320 (5878), 889–892. <https://doi.org/10.1126/science.1136674>, PMID: 18487183.
- Gode, B.B., Tshimanga, R.M., Neal, J., Trigg, M.A., Hawker, L., Lukanda, V.M., Bates, P., 2022. Understanding flood seasonality and flood regime shift in the Congo River Basin. *Hydrolog. Sci. J.* 67 (10), 1496–1515. <https://doi.org/10.1080/02626667.2022.2083966>.
- Grimm N.B., & Petrone K.C. (1997). *Nitrogen fixation in a desert stream ecosystem author (s): Nancy B . Grimm and Kevin C .Petrone published by : Springer Stable http://www.jstor.org/stable/1469163* REFERENCES Linked references are available on JSTOR for this article : You may need. 37(1), 33–61.
- Grizzetti, B., Passy, P., Billen, G., Bouraoui, F., Garnier, J., Lassaletta, L., 2015. The role of water nitrogen retention in integrated nutrient management: assessment in a large basin using different modelling approaches. *Environ. Res. Lett.* 10 (6), 65008. <https://doi.org/10.1088/1748-9326/10/6/065008>.
- Groffman, P.M., Holland, E.A., Myrold, D.D., Robertson, G.P., 1999. Denitrification. C.S. In: Robertson, S.P., Coleman, G.P., Bledsoe, DC. (Eds.), *Standard Soil Methods For Long-Term Ecological Research*. Oxford University Press, pp. 272–288.
- Hamilton, S.K., 2010. Biogeochemical implications of climate change for tropical rivers and floodplains. *Hydrobiologia* 657 (1), 19–35. <https://doi.org/10.1007/s10750-009-0086-1>.
- Hauer, C., Leitner, P., Unfer, G., Pulg, U., Habersack, H., Graf, W., 2018. The role of sediment and sediment dynamics in the aquatic environment. *River. Ecosyst. Manage.* 151–169. https://doi.org/10.1007/978-3-319-73250-3_8.
- Islam, S.N., 2016. Deltaic floodplains development and wetland ecosystems management in the Ganges–Brahmaputra–Meghna Rivers Delta in Bangladesh. *Sustain. Water. Resour. Manage.* 2 (3), 237–256. <https://doi.org/10.1007/s40899-016-0047-6>.
- Junk, W.J., Bayley, P.B., Sparks, R.E., 1989. The flood pulse concept in river-floodplain systems. In: Dodge, D.P. (Ed.), *Proceedings of the International Large River Symposium*. Canadian Special Publication of Fisheries and Aquatic Sciences, pp. 110–127.
- Krishna, M.S., Prasad, M.H.K., Rao, D.B., Viswanadham, R., Sarma, V.V.S.S., Reddy, N.P. C., 2016. ScienceDirect export of dissolved inorganic nutrients to the northern Indian Ocean from the Indian monsoonal rivers during discharge period. *Geochim. Cosmochim. Acta* 172, 430–443. <https://doi.org/10.1016/j.gca.2015.10.013>.
- Latruesse, E.M., Stevaux, J.C., Sinha, R., 2005. Tropical rivers. *Geomorphology* 70, 187–206. <https://doi.org/10.1016/j.geomorph.2005.02.005>, 3-4 SPEC. ISS.
- Loken, L.C., Crawford, J.T., Dornblaser, M.M., Striegl, R.G., Houser, J.N., Turner, P.A., Stanley, E.H., 2018. Limited nitrate retention capacity in the Upper Mississippi River. *Environ. Res. Lett.* 13 (7), 74030. <https://doi.org/10.1088/1748-9326/aacd51>.
- Mckee, L.J., Eyre, B.D., Hossain, S., 2000. Transport and retention of nitrogen and phosphorus in the sub-tropical Richmond River estuary, Australia-A budget approach. *Biogeochemistry* 50, 241–278. <https://link.springer.com/content/pdf/10.1023%2FA%3A1006339910533.pdf>.
- Mekong River Commission (MRC), 2023. *State of the Basin Report 2023*. Vientiane, Lao PDR.
- Melack, J.M., Forsberg, B.R., 2001. Biogeochemistry of Amazon Floodplain Lakes and Associated wetlands'. Michael E McClain, Reynaldo Victoria, and Jeffrey E Richey *The Biogeochemistry of the Amazon Basin*. online edn, Oxford Academic, New York. <https://doi.org/10.1093/oso/9780195114317.003.0017>, 200112 Nov. 2020.
- Metcalfe, I., 2003. Environmental concerns for Bangladesh. S. Asia: J. S. Asia Stud. 26 (3), 423–438. <https://doi.org/10.1080/0085640032000178961>.
- Mulholland, P.J., Webster, J.R., 2010. Nutrient dynamics in streams and the role of J-NABS. *J. N. Am. Benthol. Soc.* 29 (1), 100–117. <https://doi.org/10.1899/08-035.1>.
- NASA Earth Observatory, 2019. Available online: <https://earthobservatory.nasa.gov/world-of-change/PadmaRiver>. accessed on 27 March 2019.
- Natho, S., Venohr, M., Henle, K., Schulz-Zunkel, C., 2013. Modelling nitrogen retention in floodplains with different degrees of degradation for three large rivers in Germany. *J. Environ. Manage.* 122, 47–55. <https://doi.org/10.1016/j.jenvman.2013.02.049>.
- Neill, C., Deegan, L.A., Thomas, S.M., Cerri, C.C., 2001. Deforestation for pasture alters nitrogen and phosphorus in small Amazonian streams. *Ecolog. Applic.* 11, 1817–1828.
- Nicole, A., 2003. *The Nile: Moving Beyond Cooperation (SC-2003/WS/61)*. UNESCO /IHP / WWPAP, Paris, France.
- Nowreen, S., Taylor, R.G., Shamsudduha, M., Salehin, M., Zahid, A., Ahmed, K.M., 2020. Groundwater recharge processes in an Asian mega-delta: hydrometric evidence from Bangladesh. *Hydrogeol. J.* 28 (8), 2917–2932. <https://doi.org/10.1007/s10040-020-02238-3>.
- OCHA, 2023. <https://www.unocha.org/our-work/humanitarian-financing/anticipatory-action/summary-bangladesh-pilot>. Accessed on 16 February 2023.
- Pan, L., Dai, J., Wu, Z., Wan, Z., Zhang, Z., Han, J., Li, Z., Xie, X., Xu, B., 2020. Spatio-temporal dynamics of riverine nitrogen and phosphorus at different catchment scales in Huixian Karst wetland, Southwest China. *Water (Basel)* 12 (10), 2924. <https://doi.org/10.3390/w12102924>.
- Ritz, S., Fischer, H., 2019. A mass balance of nitrogen in a large lowland river (Elbe, Germany). *Water (Basel)* 11 (11), 2383. <https://doi.org/10.3390/w11112383>.

- Sarker, M.H., Thorne, C.R., 2006. Morphological Response of the Brahmaputra-Padma-Lower Meghna River System to the Assam Earthquake of 1950. In: Sambrook Smith, G.H., et al. (Eds.), *Braided Rivers: Process, Deposits, Ecology and Management*. Blackwell, Oxford, pp. 289–310.
- Sattar, M.A., Kroeze, C., Stokral, M., 2014. The increasing impact of food production on nutrient export by rivers to the Bay of Bengal 1970-2050. *Mar. Pollut. Bull.* 80 (1–2), 168–178. <https://doi.org/10.1016/j.marpolbul.2014.01.017>.
- Saunders, D.L., Kalf, J., 2001. Nitrogen retention in wetlands, lakes and rivers. *Hydrobiologia* 443 (1), 205–212.
- Seitzinger, S.P., Styles, R.V., Boyer, E.W., Alexander, R.B., Billen, G., Howarth, R.W., Mayer, B., Van Breemen, N., 2002. Nitrogen retention in rivers: model development and application to watersheds in the northeastern U.S.A. *Biogeochemistry* 57–58, 199–237. <https://doi.org/10.1023/A:1015745629794>.
- Seitzinger, S., Harrison, J.A., Böhlke, J.K., Bouwman, A.F., Lowrance, R., Peterson, B., Tobias, C., Van Drecht, G., 2006. Denitrification across landscapes and waterscapes: a synthesis. *Ecol. Appl.* 16 (6), 2064–2090. [https://doi.org/10.1890/1051-0761\(2006\)016\[2064:dalawa\]2.0.co;2](https://doi.org/10.1890/1051-0761(2006)016[2064:dalawa]2.0.co;2). PMID: 17205890.
- Shaika, N.A., Khan, S., Sultana, S., 2022. Harmful algal blooms in the coastal waters of Bangladesh: an overview. *J. Aquac. Mar. Biol.* 11 (3), 105–111. <https://doi.org/10.15406/jamb.2022.11.00344>.
- Subramanian, V., 2008. Nitrogen transport by rivers of south Asia. *Curr. Sci.* 94 (11), 1413–1418.
- Syvitski, J.P.M., Cohen, S., Kettner, A.J., Brakenridge, G.R., 2014. How important and different are tropical rivers? - An overview. *Geomorphology* 227, 5–17. <https://doi.org/10.1016/j.geomorph.2014.02.029>.
- Tanaka, Y., Minggat, E., Roseli, W., 2021. The impact of tropical land-use change on downstream riverine and estuarine water properties and biogeochemical cycles: a review. *Ecol. Process.* 10 (1). <https://doi.org/10.1186/s13717-021-00315-3>.
- Tockner, K., Stanford, J.A., 2002. Riverine flood plains: present state and future trends. *Environ. Conserv.* 29 (3), 308–330.
- Vitousek, P.M., Aber, J.D., Howarth, R.W., Likens, G.E., Matson, P.A., Schindler, D.W., Tilman, D.G., 1997. Human alteration of the global nitrogen cycle: sources and consequences. *Ecol. Applic.* 7 (3), 737–750.
- Wang, A., Yang, D., Tang, L., 2020. Spatiotemporal variation in nitrogen loads and their impacts on river water quality in the upper Yangtze River basin. *J. Hydrol.* 590, 125487. <https://doi.org/10.1016/j.jhydrol.2020.125487>. ISSN 0022-1694.
- Wang, J., Xia, X., Liu, S., Zhang, S., Zhang, L., Jiang, C., Zhang, Z., Xin, Y., Chen, X., Huang, J., Bao, J., McDowell, W.H., Michalski, G., Yang, Z., Xia, J., 2022. The dominant role of the water column in nitrogen removal and N₂O emissions in large rivers. *Geophys. Res. Lett.* 49 (12), 1–12. <https://doi.org/10.1029/2022GL098955>.
- Weigelhofer, G., Hein, T., Bondar-Kunze, E., 2018. Phosphorus and nitrogen dynamics in riverine systems: human impacts and management options. *Riverine Ecosystem Management*. Springer International Publishing, pp. 187–202. https://doi.org/10.1007/978-3-319-73250-3_10.
- Winemiller, K.O., McIntyre, P.B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., Baird, I.G., Darwall, W., Lujan, N.K., Harrison, I., Stiassny, M.L.J., Silvano, R.A.M., Fitzgerald, D.B., Pelicice, F.M., Agostinho, A.A., Gomes, L.C., Albert, J.S., Baran, E., Petrere, M., Sáenz, L., 2016. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science* (1979) 351 (6269), 128–129. <https://doi.org/10.1126/science.aac7082>.
- Wollheim, W.M., Vörösmarty, C.J., Peterson, B.J., Seitzinger, S.P., Hopkinson, C.S., 2006. Relationship between river size and nutrient removal. *Geophys. Res. Lett.* 33 (6). <https://doi.org/10.1029/2006GL025845>.
- Zinia, N.J., Kroeze, C., 2015. Future trends in urbanization and coastal water pollution in the Bay of Bengal: the lived experience. *Environ. Develop. Sustain.* 17, 531–546. <https://doi.org/10.1007/s10668-014-9558-1>.