




Nutrients in tropical and temperate rivers and floodplains – comparison of the Rivers Songkhram (Thailand) and Narew (Poland)

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Abstract

Ecological processes in floodplains may function differently across climate regions. We compared the river discharge, water chemistry, and nutrient budget and balance of floodplain vegetation in a temperate climate (River Narew, Poland) with those in a tropical climate (River Songkhram, Thailand). Both rivers show a discharge regime with a flood pulse, following snowmelt (Narew) or monsoon rainfall (Songkhram), with peak discharges roughly 25 times higher in the River Songkhram. Electrical Conductivity (EC) values of both rivers are generally comparable, while nutrient concentrations are somewhat higher in the temperate River Narew (with total phosphorus (TP) approximately 1.5 and total inorganic nitrogen (TIN) approximately 2.2 times higher than in Songkhram). A comparison of the nutrient budget of floodplain vegetation suggests that soil is the most important source of nutrients for most vegetation types, i.e., Narew sedge (N), Narew forest floor (N and P), Songkhram bamboo (N and P), and Songkhram grass (P). Additionally, floodwater is the main input source of P for the Narew sedge and a secondary input source for Songkhram grass. Vegetation close to the river tends to have higher productivity, emphasizing the nutrient-filtering function of floodplain vegetation. For both rivers, nutrient input into the floodplains by floodwater is higher than nutrient export from the floodplains, indicating that both floodplains have a nutrient sink function. These findings demonstrate that the floodwater pulse is a source of nutrient input for floodplain vegetation in both temperate and tropical climates, with the soil playing a vital role in the nutrient budgets and balance.

Keywords Nutrient budget · Flood Pulse · Temperate river · Tropical monsoon river

Introduction

River floodplains are fertile landscape components that provide ecosystem services such as water retention, nutrient accumulation, carbon sequestration, and productive vegetation that can be harvested. The ecological functioning of river floodplains is complex, and it is thought that variations in the ecological process of the floodplains are caused by the catchment's hydrology, geology, water chemistry, vegetation, topography, and climate (Spink et al. 1998;

Montgomery 1999; Tockner et al. 2000). Globally, undisturbed floodplains are becoming rare, and this is why it is of utmost importance to study the remaining relatively pristine rivers and their floodplains.

For pristine river catchments, the vegetation in the floodplains benefits from the nutrient-rich floodwater, resulting in high productivity, which is observed in both temperate and tropical climates (e.g. Olde Venterink et al. 2002; Walalite et al. 2018). The growing season of vegetation depends on the regional climate, which determines the hydrological regimes and the temperature to grow vegetation. For instance, vegetation in boreal or arctic floodplains only grows during the short summer period (< 3 months), whereas in temperate floodplains, the growing season lasts longer, and in tropical areas, there is no distinct growing season because the temperature is suitable for vegetation growth all year round. Furthermore, vegetation directly benefits during or after a flood since the river brings nutrients. Therefore, the hydrological regime and temperature together determine nutrient dynamics and vegetation production in floodplain ecosystems (Spink et al. 1998).

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Flood pulse is defined as a regular, predictable flooding characteristic of river floodplains. According to the Flood Pulse Concept (Junk et al. 1989), floodwater brings nutrients that drive nutrient cycles to the floodplain ecosystem. Based on this concept, floodplain ecosystems are seen as relatively high production systems because they import nutrients derived from the parent river and then convert and store nutrients in the floodplain's vegetation. Transitions between wet and dry periods accelerate nutrient cycling processes. In particular, decomposition of organic material will release nutrients and can return these to the vegetation. The processes of storage and release of nutrients in the floodplain are influenced by this flood pulse characteristic and are thus crucial to understanding the growing cycle of the vegetation. However, these processes appear to be different for individual floodplains (e.g., Spink et al. 1998; Capon 2003; Parolin et al. 2016), urging the need to study river floodplains under different climatic conditions.

Within floodplains, different zones in vegetation productivity are observed. The spatial pattern of vegetation and its nutrient cycling processes in floodplains is the effect of topography and flood pulse, combined with various sources of floodwater, i.e., river water, atmospheric water, and groundwater. Variations in the floodplain topography and the flood pulse characteristic cause differences in flood depth and the retention time of floodwater in the floodplain, while various sources of floodwater determine the nutrient content in the floodwater. This leads to a spatial difference in nutrient addition on floodplains and the zonation of vegetation type and production. Floodplain areas that directly influenced by floodwater from river benefit from nutrient rich water and sediments, while atmospheric water provides fewer nutrients, and the influence of groundwater depends on the infiltration capacity of the floodplain.

It has been shown for some temperate floodplains that the transition zone at the edge of the floodplain shows lower productivity than vegetation near the river. The high productivity zone near the river is the result of additional nutrients from the river water (e.g., Keizer et al. 2018), while the transitional zonation is caused by the mixing of river water and groundwater with rain or snow, which has lower nutrient concentrations (Wassen et al. 2003; Olde Venterink et al. 2006). In tropical monsoon floodplains, a high productivity zone also benefits from floodwater (e.g., Walalite et al. 2018). Zonation of vegetation productivity in a tropical floodplain was shown to be caused by a filtration function of the vegetation closer to the river (e.g., Walalite et al. 2016, 2018) and dilution by monsoon rain further away from the river. Furthermore, in the tropical floodplain, floodwater level and duration determine vegetation community and their productivity (Parolin 2002; Scholte 2007; Walalite et al. 2018).

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Floodplains in the temperate climate are well studied, especially in North America and Europe. In the temperate Biebrza River in Poland, it was demonstrated how floodplains contribute to nutrient accumulation (Wassen 1995; Olde Venterink et al. 2002). Although floodplains can act as a sink for nutrients, they can also turn into a source, depending on their position in the catchment and the nutrient status of the river water (Spink et al. 1998). The functioning of floodplains in the tropics has been studied less, although notable exceptions are the floodplains of the Amazon (Junk 1997; Wittmann et al. 2004), Orinoco (Lewis et al. 2000), Kafue (e.g., Rees 1978; Zurbruegg et al. 2012; Zuijdgeest et al. 2015) and Okavango (e.g., McCarthy and Ellery 1997; Arias et al. 2016). In earlier research, we demonstrated that the floodplains of a tropical monsoon river absorb nutrients, particularly N and P, from floodwater during the flood period while releasing soil organic carbon for downstream sections (Walalite et al. 2018). However, few studies have focused on comparing the functioning of floodplains in a tropical and a temperate climate. Comparing the functioning of floodplains in different climate zones can provide valuable insights into how these ecosystems respond to different environmental conditions.

This paper tries to contribute to a further understanding of nutrient transport, nutrient accumulation and nutrient release in tropical river floodplains and in temperate river floodplains. In particular, we aim to understand the sink-source relations of nutrients in river floodplains. We compare the river discharge, hydrochemistry and nutrient status of two rivers and their floodplains. We evaluate the importance of nutrient input by floodwater and its contribution to the nutrient budget of the floodplains. Although our study areas have completely different climate regimes, we found similar floodplain vegetation patterns. We seek to understand if these patterns are caused by similar processes, and we do so by analyzing the seasonal pattern of discharge, catchment retention time, nutrient concentration, and nutrient loads of both rivers in relation to the floodplain.

Study areas

The European Narew River basin is situated in north-eastern Poland (22°12' to 24°27' E and 52°36' to 54°16' N), and the Southeast Asian River Songkhram is situated in north-eastern Thailand (103°12' to 104°35' E and 16°55' to 18°23' N) (Fig. 1).

The River Narew has a temperate climate with a yearly average temperature of 7.2 °C and a mean annual precipitation of 617 mm (Gielczewski 2003). The drained area of the river basin at Lomza gauge station is around 15,000 km². This river is defined as a temperate snowmelt-fed river system (Mirosław-Świątek and Okruszko 2011) characterized by the maximum flood during spring (in March and April). Water level and discharge decrease in summer and autumn, and remain low during the frosty winter.

The River Songkhram has a tropical climate with a yearly average temperature of 26 °C and a yearly average precipitation of 1960 mm (Walalite et al. 2016). The drainage area of this river basin is around 13,000 km². This river is a tropical monsoon rain-fed river. The monsoon season occurs from May to October and flooding in the Songkhram floodplain occurs following the monsoon season. The peak flood generally occurs in late August, after which water discharge and water level gradually decrease towards the dry season that lasts from November until April.

The floodplains of both rivers show a relatively natural flood pulse, as well as natural patterns of floodplain vegetation communities and productivity. In the Narew floodplain, the general pattern consists of tall sedge vegetation in a wide belt adjacent to the river, and swamp forests occur at the edge of the

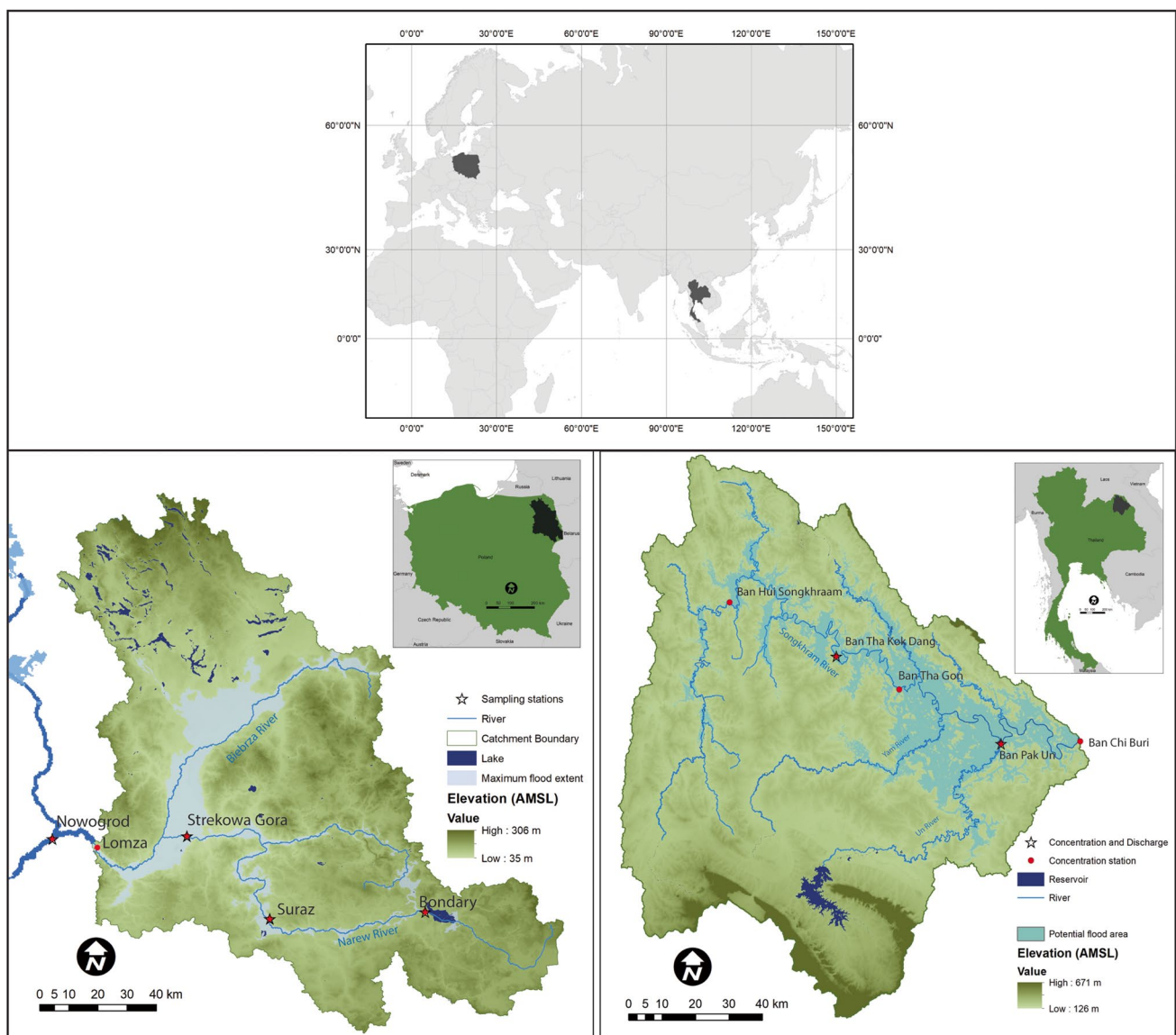


Fig. 1 Location of the River Narew catchment in northeast Poland (lower left) and the River Songkhram in northeast Thailand (lower right)

floodplain, where the floodplain meets the elevated hinterland. In the Songkhram floodplain, there are also two main vegetation zones: dense bamboo vegetation adjacent to the river and grass vegetation further away from the river (Walalite et al. 2016). The Narew floodplain is dominated by organic peat soil, and the Songkhram floodplain soil is dominated by mineral soil.

Methods

Comparison of hydrochemistry and discharge patterns between the two rivers

To understand the seasonal pattern of flow characteristics and its relationship with hydrochemistry, we first analyzed the discharge and hydrochemical variables of the two rivers. We then compared discharge patterns and nutrient concentrations, which were mainly dissolved inorganic nitrogen and total phosphorus. To give a general view of the hydrochemistry, additional variables besides nutrients are also presented, i.e., electrical conductivity (EC), the potential of hydrogen (pH), dissolved oxygen (DO), and water temperature.

For the River Narew, the discharge and water chemistry variables, i.e., temperature, EC, pH, DO, TP, NO_2^- , NO_3^- , and NH_4^+ , were obtained from the Chief Inspectorate of Poland's Environmental Protection. We selected data from four gauge stations distributed from upstream to downstream (Fig. 1), namely Bondary (BND), Suraz (SRZ), Strekowa Gora (St. Gora), and Nowogrod up to Pisa (NWP). The variables were measured on a monthly basis, and data were available from 1991 to 2017, except for Suraz; for this station, data were available from 2001 to 2016. A summary of the number of hydrochemical measurements can be found in Appendix Table 7. Daily discharge data were available from 1991 to 2018 for two stations, namely Strekowa Gora and Nowogrod up to Pisa. For Suraz, discharge data were available from 2015 to 2018 (Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB)).

For the River Songkhram in Thailand, the hydrochemistry variables, i.e., temperature, EC, pH, DO, TP, NO_2^- , NO_3^- , and NH_3 , were available for five stations. The stations, distributed from upstream to downstream (Fig. 1), were Ban Hui Songkhram (BHSK), Ban Tha Kok Dange (BTKD), Ban Tha Gon (BTG), Ban Pak Un (BPU), and Ban Chi Buri (BCBR). The hydrochemical data were available from 1996 to 2015, and these were provided by the Thai Department of Pollution Control (unpublished data, personal communication). A summary of the number of measurements for each station can be found in Appendix Table 7. This river's daily discharge data were available only for Ban Tha Kok Dang from 1986 to 2010 and for Ban Pak Un station from 2013 to 2016 (Royal Irrigation Department of Thailand).

To compare the total inorganic nitrogen concentrations of these rivers, we used total inorganic nitrogen (TIN), which was the sum of the nitrogen from NO_2^- , NO_3^- , and NH_4^+ (for the River Narew), and NO_2^- , NO_3^- , and NH_3 (for the River Songkhram). Samples were taken from the River Narew monthly, while this was done every three months for the River Songkhram.

Nutrient load and specific nutrient load estimation

We assessed the outflow of nutrients from the catchments and the floodplain systems by estimating the rivers' nutrient loads and specific nutrient loads. For the River Narew, we estimated nutrient loads at three stations, i.e., Suraz, Strekowa Gora, and Nowogrod up to Pisa. We omitted the Bondary station because this station is situated close to a reservoir. As for the availability of discharge data for the River Songkhram, we estimated nutrient loads at Ban Tha Kok Dang and Ban Pak Un stations, situated upstream and downstream of the main floodplains in the River Songkhram. The nutrient loading rates were estimated using an averaging estimation approach (Quilbé et al. 2006; Górnjak 2018).

Monthly loads: we estimated the nutrient loads of each month using the average discharge and average concentration of nutrients measured in the month. The load of the month is given by:

$$L_m = \overline{C}_m \times \overline{Q}_m \times n \times k \quad (1)$$

Where

L_m the month load (tons/month).

\overline{C}_m average nutrient concentration per month (mg/l, equal to gr/m^3).

\overline{Q}_m average discharge per month (m^3/s).

n number of days in the month to convert from day to month

k unit conversion coefficient (0.0864, to convert from gram per second to ton per day, so $86,400 \times 10^{-6}$)

Seasonal loads: we calculated the seasonal loads in the two rivers for two seasons, based on the flow characteristics of the rivers. The flow characteristics of both rivers demonstrate a clear pattern of distinct seasonal high and low flows. The high flow season of the temperate River Narew is the winter/spring flow season, which runs from December to May of the following year, and the low flow summer/

autumn season runs from June to November. The high flow season of the River Songkhram starts in June and ends in November, and then the low flow season begins in December and ends in May of the following year. The concentrations measured in each seasonal six-month period were averaged and were then considered to be the average concentration of the season. The average concentrations were then multiplied by the average discharge of the season. The seasonal load was calculated by:

$$L_s = \overline{C}_s \times \overline{Q}_s \times n \times k \quad (2)$$

where

L_s the seasonal load (tons/season).

\overline{C}_s average nutrient concentration of the season (mg/l).

\overline{Q}_s average discharge of the season (m^3/s).

n number of days in the season period

k unit conversion coefficient (0.0864)

Annual loads: the annual load was the sum of the seasonal loads for both rivers.

Specific nutrient loads: specific nutrient load is the flux of nutrients from the upstream catchment area at a particular river outlet per unit area of the upstream watershed; this was calculated by dividing the annual nutrient load (in tons/year) by the area of the upstream watershed where the loads were estimated. The unit of the specific nutrient load is $\text{kg}/\text{km}^2/\text{year}$.

Nutrient budget estimation

Nutrient budget and balance model

In our simple nutrient budget and balance model, we assume that the increase in nutrients in vegetation biomass (B) equals the inflow of nutrients (Ext and $Soil$) subtracted by the outflow of nutrients from the system (Fig. 2):

$$\partial B_{N,P} = Ext_{N,P} + Soil_{N,P} - Outflow_{N,P} \quad (3)$$

In which ∂B is the measured change in annual biomass expressed as Nitrogen (N) or Phosphorus (P), and Ext is the observed annual input of nutrients (N or P) from floodwater and the atmosphere. Following Wassen and Olde Venterink (2006), the input from groundwater is neglected. $Soil$ is the amount of nutrients that vegetation takes up from the soil and is the only unknown in the equation. $Outflow$ is the amount of nutrients leaving the floodplain by discharged water. It should be noted that this equation is a simple model used to roughly estimate the nutrient budgets and balance of floodplain vegetation. There are uncertainties in this model since nutrient concentrations are measured monthly for the River Narew and once every three months for the River Songkhram. Instances of high precipitation between sampling events may have caused fluctuations in outflow that were not captured by these measurements. High precipitation occurred from late spring to summer (June – August), followed by a gradual increase in river discharge in the case of the River Narew (Fig. 3). For the River Songkhram, high precipitation occurs during the monsoon season (around May – September), and the river discharge quickly increases in response to the rainfall (Fig. 3).

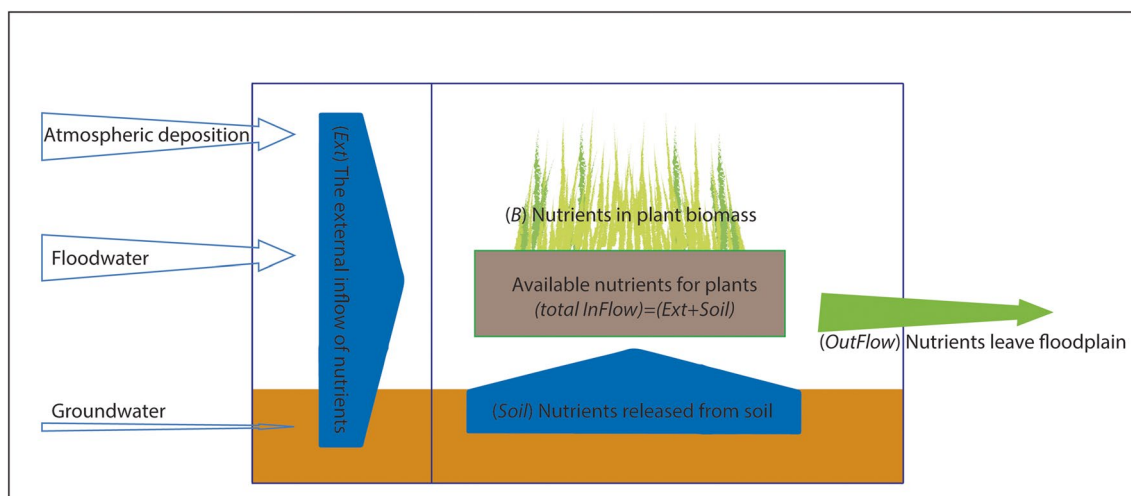


Fig. 2 Conceptual model of nutrient flows in the floodplains ecosystem. The assumption is that the change in vegetation biomass (B) equals the inflows of nutrients (Ext and $Soil$) minus the outflows of nutrients from the system

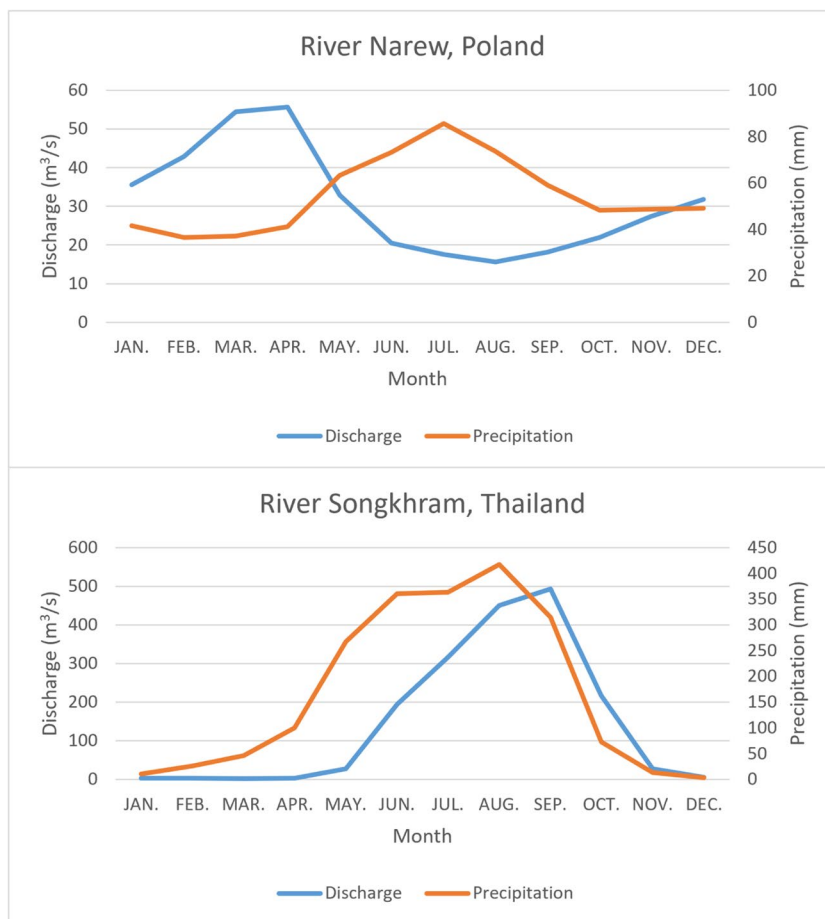
Observations for calculating the nutrient budget and balance model

Change in biomass (∂B) was measured by multiplying plant tissue nutrient concentration with the annual aboveground biomass production. In both the Narew floodplain and the Songkhram floodplain, two types of vegetation were distinguished. In the River Narew, floodplain sedge and floodplain forest floor vegetation were found. The species that dominated the floodplain sedge community were *Phalaris arundinacea*, *Carex acuta*, *Glyceria maxima*, and *Carex elata*, whereas the forest floor was dominated by herbaceous plants such as *Urtica dioica* and diverse forbs, grasses, and sedges. In the River Songkhram, floodplain vegetation was identified as flooded bamboo and flooded grass types (Walalite et al. 2018). For the Narew vegetation, we harvested the aboveground living biomass at the peak of the growing season, which is a reliable estimate for aboveground annual production in herbaceous temperate plant communities (Wassen et al. 2005). We applied the same method for the grass vegetation at Songkhram, and for the bamboo, we followed the approach of Walalite (2018), in which only the yearly increase in biomass was measured by sorting fresh shoots from shoots of previous years.

For the River Songkhram, the external inflow of N by atmospheric deposition was 650 kg/km²/year, whereas floodwater provided 2,170 and 1,240 kg/km²/year to the flooded bamboo and grass zones, respectively, as was calculated by Walalite et al. (2016). The external inflow of atmospheric N deposition for Narew was estimated as 500–1000 kg/km²/year, and N import from floodwater as 3,460 kg/km²/year, based on measurements in the nearby Biebrza River floodplains (Wassen and Olde Venterink 2006). This is an adjacent tributary of the Narew, for which we assume an equal amount of external nutrient fluxes as for the Narew. The Narew and Biebrza catchments have share a similar geomorphology, hydrology, and floodplains characteristics (see Gielczewski 2003; Wassen et al. 2006).

The external inflow of P by atmospheric deposition had not been reported for the Songkhram area, which is why we used information from Tipping et al. (2014), who reported an average P deposition for Asia of 20 kg/km²/year. Floodwater provided 150 kg/km²/year and 100 kg/km²/year of P to the flooded bamboo and flooded grass zones, respectively (Walalite et al. 2016). For the River Narew, atmospheric P was 5 kg/km²/year (Wassen and Olde Venterink 2006). In addition, floodwater provided 740 kg/km²/year of P to the floodplain meadow at the Narew floodplain (Wassen and Olde Venterink 2006).

Fig. 3 Annual patterns of precipitation and discharge of the River Narew (St.Gora station) and the River Songkhram (Ban Tha Kok Dang station)



Outflow was calculated using Eq. (2) at a specific location in the river.

Plant tissue nutrient concentrations

Nutrient concentration in plant tissues was measured from collected plant material. For the River Songkhram, this included 15 samples of bamboo leaves and 27 samples of grass biomass (see Walalite et al. 2018), and for the River Narew, 18 samples of sedge biomass and 3 samples of forest floor vegetation biomass. The samples were dried at 70 °C for 48 h. Subsequently, the dry plant material was ground and analyzed for nitrogen (N) and carbon (C), using a C/N analyzer. Part of the ground sample was digested in nitric acid (65% HNO₃) and analyzed for phosphorus (P) and potassium (K), using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES).

Following Olde Venterink et al. (2003), determining the type of nutrient limitation was based on critical values of N: P, N: K, and K: P ratios in aboveground plant material. N-limitation is indicated by N: P ratio < 14.5 and N: K ratio < 2.1, whereas P-limitation and co-limitation by both P and N was indicated by N: P ratios > 14.5 and K: P ratios > 3.4. K or in K+N co-limitation was indicated by N: K ratios > 2.1 and K: P ratios < 3.4.

Results

Hydrology and Hydrochemistry

Discharge patterns of the two rivers The discharge patterns of both rivers show a seasonal flood pulse (Table 1).

In the River Narew (Poland), the peak discharge occurs in spring, around March and April, and the minimum discharge occurs in late summer, around August. The highest discharge occurred in March and April for SRZ and St. Gora stations, with approximately 26 and 55 m³/s (Table 1). Thailand's Songkhram River demonstrates a flood pulse and peak discharge during the tropical monsoon season around August and September (Fig. 4). The average monthly discharge at the upstream station (BTKD) ranged from 3.1 – 493 m³/s and the average monthly discharge at the downstream station (BPU) ranged from 2.5 – 1486 m³/s (Table 1). During the dry season, from December to April, discharge in the River Songkhram was minimal. Peak discharges were roughly 25 times higher in the River Songkhram than in the River Narew. As the catchment area of the River Songkhram is around 30 to 40% smaller than that of the River Narew (Table 1), the specific peak discharge difference is even larger. No relationship between mean monthly discharge and monthly precipitation was observed for the River Narew, in contrast to the River Songkhram, where a significant relationship was found (see Fig. 5: Pearson correlation coefficient $R=0.7$ at BTKD and 0.5 at BTU, $p < 0.05$).

Differences between water chemistry and nutrient concentration of the two rivers To understand the difference between the water chemistry and nutrient concentrations of the two rivers, the average EC and nutrient concentration were calculated from 4 (River Narew) and 5 (River Songkhram) stations, which were distributed from upstream to downstream (Table 2).

The average EC from the four selected stations of the River Narew ranged from 301 to 450 μS/cm and tended to

Table 1 Mean monthly discharge (m³/s) of the temperate River Narew (Poland) and the tropical monsoon River Songkhram (Thailand). The numbers in bold indicate each station's two highest discharges

Month	River Narew			River Songkhram	
	Suraz (SRZ)	Strekowa Gora (St. Gora)	Nowogrod up to Pisa (NWP)	Ban Tha Kok Dang (BTKD)	Ban Pak Un (BPU)
January	16.3	35.6	80.2	3.7	8.5
February	19.8	42.9	98.2	3.1	2.5
March	26.3	54.5	127.9	2.6	4.9
April	26.2	55.7	136.1	2.9	3.2
May	14.6	33.0	84.6	27.9	38.5
June	9.6	20.5	51.7	194.0	279.3
July	8.5	17.5	39.7	316.2	739.9
August	7.1	15.6	35.0	450.3	1485.9
September	8.2	18.2	39.8	493.4	1213.0
October	8.9	22.0	48.5	216.5	458.7
November	12.8	27.4	61.9	27.5	187.5
December	15.0	31.8	70.7	5.6	50.1
Average	14.4	31.2	72.9	145.3	372.7
Catchment area (km ²)	3,377	7,181	20,106	5,089	12,328

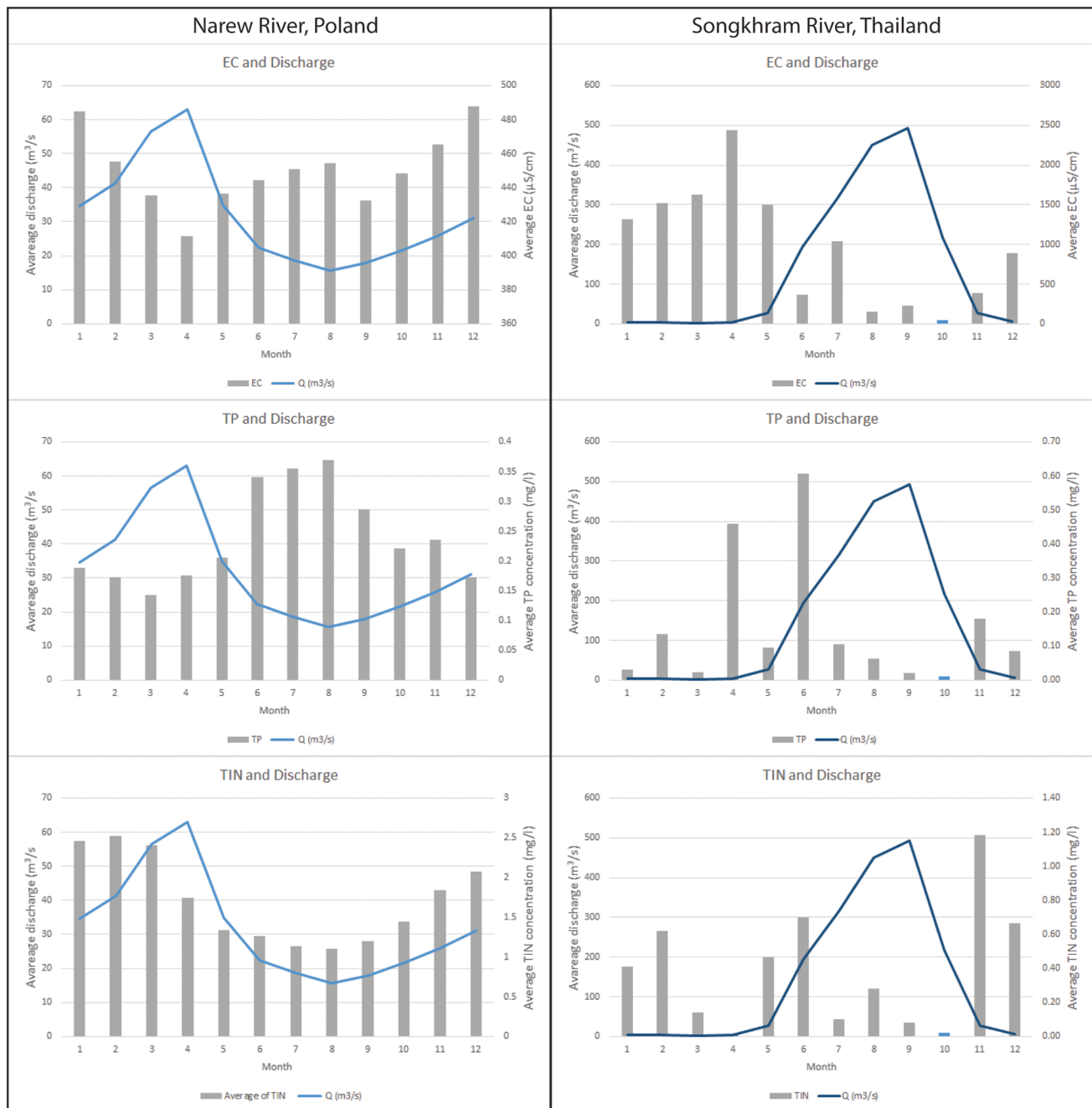


Fig. 4 Annual patterns of discharge (lines), EC, TP, and TIN (bars) of the River Narew (St. Gora station) and the River Songkhram (Ban Tha Kok Dang station)

increase downstream. The River Songkhram showed a higher range of average EC, from 345 to 952 µS/cm, and had the highest values midstream. In general, EC values were comparable for both rivers (ca. 300–450), except for stations 2 and 3 on the River Songkhram (EC ca. 800–950). The average total phosphorus (TP) concentration of the Narew River water was highest (0.31 mg/l) at the most upstream station at Bondary, and lowest (0.18 mg/l) at the most downstream

station. A similar trend was observed in the River Songkhram, where the highest average TP concentration (0.23 mg/l) was at the most upstream Ban Hui Songkhram station, and the lowest TP concentration (0.12 mg/l) was at Ban Pak Un station (Table 3). The average annual nitrate-nitrogen (N-NO₃⁻) concentration (Table 2) of the River Narew was lowest (0.58 mg/l) at the most upstream station Bondary, and highest (1.26 mg/l) at St. Gora station. The N-NH₄⁺

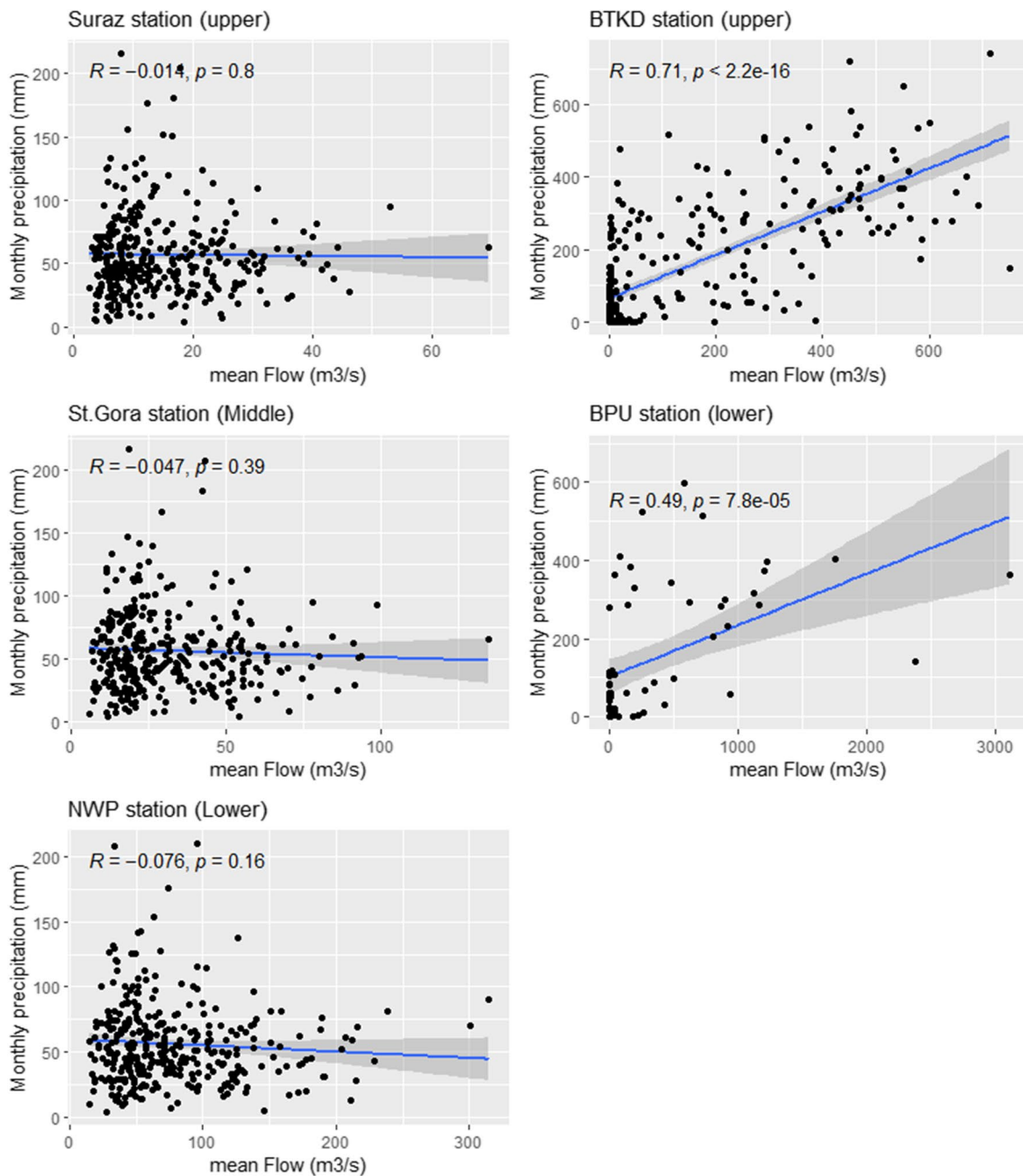


Fig. 5 Relationship between precipitation and discharge (mean flow) of the River Narew where correlation is not significant and River Songkhram where the flow increase when the precipitation increase. R is the Pearson correlation coefficient, followed by a p -value

concentrations for the River Narew ranged from 0.11 mg/l at Suraz station to 0.48 mg/l at St. Gora station. The N-NO_2^- concentrations (Table 2) appeared to be consistently low along the river from upstream to downstream (~ 0.02 mg/l), with the exception of the most upstream Bondary station (0.37 mg/l). For the River Songkhram, the average N-NO_3^- concentration ranged from 0.38 to 0.57 mg/l and upstream stations tended to have a slightly lower concentration than downstream stations. Average N-NO_2^- concentrations were

low along the whole river. In general, inorganic nutrient concentrations – both TP and TIN – were almost twice as high in the River Narew as in the River Songkhram (Table 2).

Combining hydrology and hydrochemistry To elucidate the effect of seasonal flow characteristics and the dilution effect on nutrient concentration and EC, Fig. 4 shows the monthly dynamics for both rivers. For the River Narew, we found a decreasing trend of EC during peak discharge in April, with

Table 2 Hydrochemical characteristics of the River Narew and the River Songkhram. Total inorganic nitrogen (TIN) was the sum of N-NO_2^- , N-NO_3^- , and N-NH_4^+ (for the River Narew) and of N-NO_2^- , N-NO_3^- , and N-NH_3 (for the River Songkhram). Stations are listed from upstream to downstream

River	Station Name	Annual average										
		Water Temp (°C)	EC ($\mu\text{S}/\text{cm}$)	pH	O_2 (mg/l)	TP (mg-P/l)	N-NO_3^- (mg/l)	N-NO_2^- (mg/l)	$\text{N-NH}_4^+/\text{N-NH}_3$ (mg/l)	TIN (mg/l)		
Narew	Boundary (BND)	9.79	301	7.9	9.4	0.31	0.58	0.37	0.25	1.08		
	Suraz (SRZ)	10.3	389	7.8	9.4	0.2	1.03	0.02	0.11	1.16		
	Strekowa Gora (St. Gora)	9.97	450	7.8	8.9	0.24	1.26	0.02	0.48	1.7		
Songkhram	Nowogrod up to Pisa (NWP)	10.23	444	8	9.3	0.18	0.87	0.02	0.36	1.18		
	Ban Hui Songkhram (BHS)	27.92	441	7	6.2	0.23	0.38	0.04	0.17	0.46		
	Ban Tha Kok Dang (BTKD)	28.56	952	7.1	6.9	0.14	0.49	0.03	0.18	0.57		
	Ban Tha Ghon (BTG)	28.42	818	7.1	6.8	0.14	0.51	0.02	0.16	0.57		
	Ban Pak Un (BPU)	28.24	454	7	6.4	0.12	0.57	0.04	0.14	0.65		
	Ban Chat Buri (BCBR)	27.95	345	7.2	6	0.13	0.55	0.03	0.17	0.64		

the highest ECs during winter. TP concentrations had the lowest values during peak discharge and the highest during the summer months (June–August). Interestingly, the dynamics in TIN align with the dynamics in the discharge pattern in the River Narew. The River Songkhram showed the lowest EC, TP, and TIN values during peak discharge. In contrast to the River Narew, the TIN values do not align with the discharge dynamics. Here, TP fluctuated before and at the start of the rainy season (April–July), whereas TIN concentrations were clearly highest after the peak discharge (Fig. 4). The Pearson correlation coefficient revealed a negative correlation between discharge and TP concentration across all stations of the River Narew. In contrast, a positive correlation was observed between TIN concentration and discharge at all stations (see Fig. 6). For the River Songkhram, no distinct correlation was found between TP and TIN concentration and discharge at the upper station (BTKD). However, a decreasing trend in the concentration of TP and TIN was observed at the lower station (BPU), although it was not statistically significant (see Fig. 7).

Nutrient loads

Seasonal loads for P and N were integrated from the observed monthly loads (Appendixes Tables 8 and 9). For the River Narew, between 77–79% of TIN was exported during winter (Table 3). For the River Songkhram, 97% of the TIN load was exported during the peak flow (Jun–Nov). Total annual TIN load and specific loads in the River Songkhram were twice as high as in the River Narew (Table 4). Clearly, for both rivers, the downstream stations exported more TIN due to higher discharges. In contrast, there was almost no difference in the TP load between summer and winter in the River Narew (Table 3), while for the River Songkhram, 98% of all P load was exported during the peak flow, comparable to the TIN dynamics. Total annual TP and specific loads were around six times larger for the River Songkhram than for the River Narew. Moreover, downstream stations exported a higher annual TP load. The nutrient loads of TP and TIN exhibited a significant increase with rising discharge at all stations of both rivers, as indicated by the Pearson correlation ($p < 0.05$) (see Fig. 8).

Nutrient budget for biomass

We found a significantly higher nutrient concentration (N, P, K) in the biomass from the Narew floodplains compared to the nutrient concentrations in the biomass from the Songkhram floodplain (t-test, $p < 0.05$; Table 5.). In the Narew floodplain, the herbaceous plants in the forest where no flooding occurs showed significantly higher N and P concentrations than in the floodplain sedge vegetation. In the River Songkhram, the bamboo, which is affected by flooding more than the flooded grass zone, had a higher nutrient concentration in biomass tissues and was the only vegetation type having P-limitation.

Table 3 Average discharge, nutrient concentrations, and nutrient loads of the River Narew and the River Songkhram. The table shows values for winter/spring (Dec.-May.) and summer/autumn (Jun.-Nov.)

of the River Narew and dry season (Dec.-May.) and rain season (Jun.-Nov.) for the River Songkhram

	Period	River Narew			River Songkhram	
		Suraz (SRZ)	Strekowa Gora (St. Gora)	Nowogrod up to Pisa (NWP)	Ban Tha Kok Dang (BTKD)	Ban Pak Un (BPU)
Average Q (m ³ /s)	Dec.-May	16.08	42.25	99.62	7.65	17.96
	Jun. -Nov	9.16	20.19	46.10	283.00	727.38
Average TIN concentration (mg/l)	Dec.-May	1.58	2.09	1.47	0.46	0.62
	Jun. -Nov	0.75	1.33	0.90	0.47	0.49
Average TP concentration (mg/l)	Dec.-May	0.17	0.18	0.13	0.14	0.09
	Jun. -Nov	0.23	0.30	0.23	0.20	0.14
TIN load (tons)	Dec.-May	399.5	1390.0	2299.2	55.3	173.8
	Jun. -Nov	108.1	424.7	659.2	2101.4	5633.1
TP load (tons)	Dec.-May	42.5	117.2	195.9	16.6	26.7
	Jun. -Nov	33.6	96.3	170.6	873.4	1644.2
TIN load (%)	Dec.-May	79%	77%	78%	3%	3%
	Jun. -Nov	21%	23%	22%	97%	97%
TP load (%)	Dec.-May	56%	55%	53%	2%	2%
	Jun. -Nov	44%	45%	47%	98%	98%

Nutrient accumulation in the aboveground biomass, calculated as the product of nutrient concentration and aboveground production, showed that vegetation zones with flooding had accumulated higher amounts of nutrients in aboveground biomass (Table 5). The amount of nitrogen in the Narew floodplain sedge community and the Songkhram bamboo was comparable, 9,894 and 9,743 kg/km²/y, respectively (Table 5). In contrast, the amount of nitrogen in the aboveground production of the herbaceous vegetation in the forest floor of the Narew floodplain and the flooded grass in the Songkhram floodplain were much lower, 4,428 and 2,436 kg/km²/year, respectively.

Phosphorus storage in the aboveground biomass of the Narew floodplain sedge community and the forest floor was 1149 and 779 kg/km²/year, respectively. In comparison, this was higher than P in aboveground production in the Songkhram River bamboo and grass vegetation, both flooded, which was 657 and 263 kg/km²/year.

Potassium storage in the aboveground biomass of the Narew floodplain sedge and forest floor were 6,720 and 2,900 kg/km²/year, respectively. For the River Songkhram, potassium stored in the aboveground bamboo and flooded grass was 5,471 and 2,876 kg/km²/year, respectively.

Integrated Nitrogen and Phosphorus Budget and Balance Model

Based on Eq. (3), we calculated all annual N and P flows for the different vegetation types in both rivers. The $Soil_{N,P}$ was the only unknown in the equation. In Table 6 and Figs. 9 and

10, all flows are listed for all four vegetation types, both in kg/km²/year and in percentages.

In the Narew floodplain, nitrogen input from the soil was the main source for both floodplain sedge (56%) and forest floor community (79%), and nitrogen outflow from the Narew floodplain was low, 2% and 5%, respectively. On the Songkhram floodplain, the soil was the major N source for flooded bamboo (72%), while the soil provided only 35% of the N for flooded grass. As a result, the external input flow (atmosphere and flooded water) was important in the flooded grass and provided 65%. The outflow of N from the Songkhram floodplain was about twice as high as the outflow from the Narew floodplain, 471 and 253 kg/km²/y, respectively. In both river floodplains, the outflow of N was much lower than the inflow.

Clear differences were found in the P budget and balance. In the River Narew, floodwater was the major source of P for the sedge community; thus, it is more important than the input from the soil, and this is in clear contrast to the findings for N. In the Narew forest, P was only derived from the soil, as P from the atmosphere was extremely low and no input from floodwater was registered for the forest. The outflow of P from the Narew floodplain was low compared to the input from soil and floodwater. In the River Songkhram, as in the Narew forest, the soil was the main source of P, but here this was comparable for both vegetation types (79% and 70%). The outflow proportion of P from the Songkhram floodplain accounted for 17% and 34% of the total inflow budget for flooded bamboo and grass, respectively. This proportion was much higher than the N exported from the flooded bamboo and grass (5% and 17%). The exported

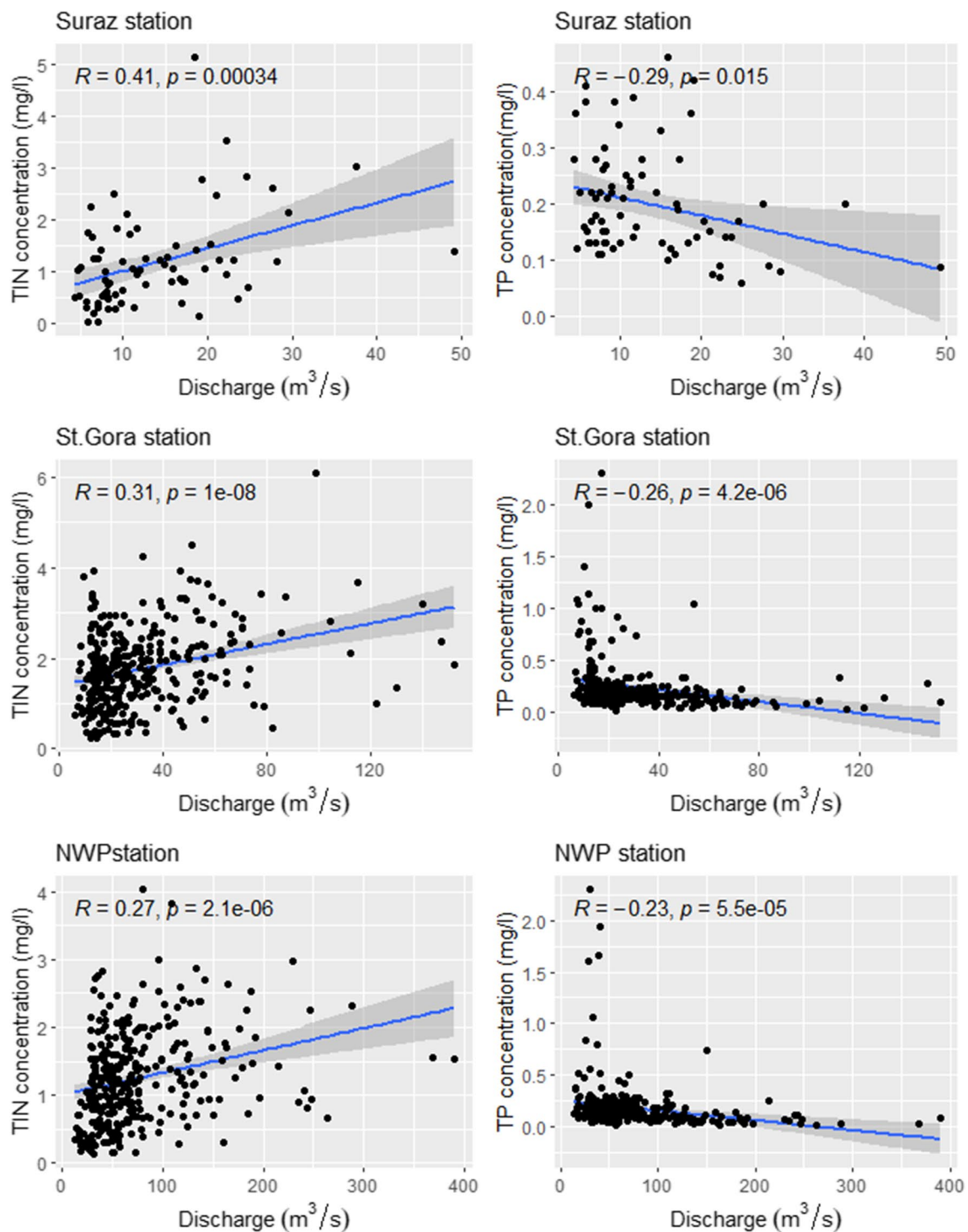


Fig. 6 The relationship between nutrient concentration (TIN and TP) and the average discharge during the month in which the concentration sampling was conducted for the River Narew. The results indicate a significant correlation between TIN and TP concentrations and

discharge (Pearson correlation, $p < 0.05$). Specifically, TIN concentrations tend to increase as discharge increases, while TP concentrations tend to decrease

amount of P was much higher (by a factor of 7.5) than in the Narew floodplain. It appears that the flooded grass vegetation type exported more P ($136 \text{ kg}/\text{km}^2/\text{y}$) than it received

from floodwater ($100 \text{ kg}/\text{km}^2/\text{y}$). For the flooded bamboo, the exported amount ($136 \text{ kg}/\text{km}^2/\text{y}$) was slightly lower than the input from floodwater ($150 \text{ kg}/\text{km}^2/\text{y}$).

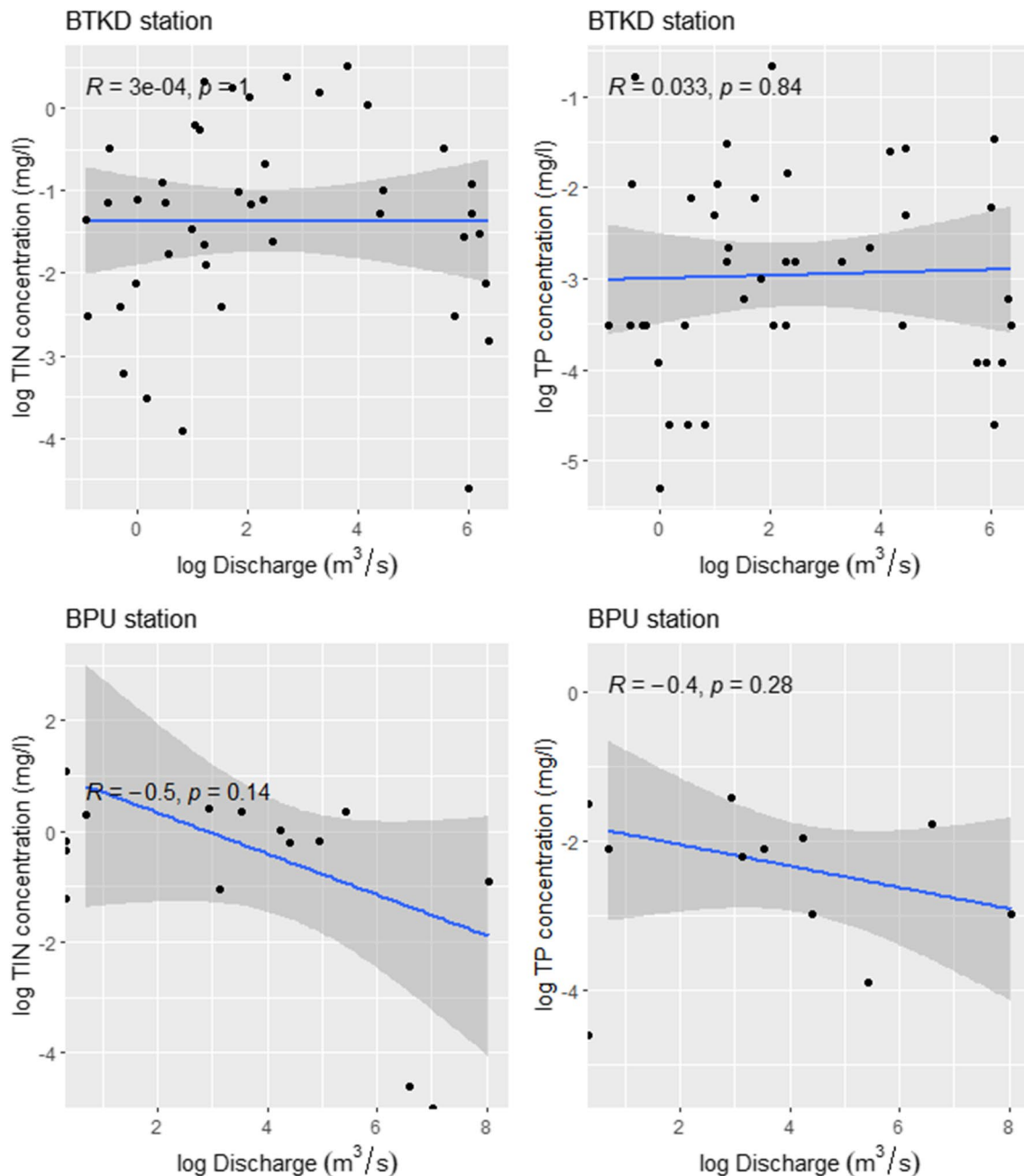


Fig. 7 The relationship between nutrient concentration (TIN and TP) and the average discharge during the month in which the concentration sampling was conducted for the River Songkhram was found to be insignificant

Discussion

The aim of our paper was to better understand the relationship between riverine nutrient transport and nutrient accumulation and release in floodplains, for a tropical monsoon river and a temperate snowmelt river. Furthermore, we tried to shed light on the question of whether the comparable vegetation patterns in the two floodplains stem from similar processes, by analyzing

the seasonal patterns of discharge, nutrient concentration, and nutrient loads of both rivers in relation to the floodplain.

The rivers Both rivers show a clear flood pulse, with the discharge of the tropical monsoon River Songkhram showing far more seasonal variation in discharge than the temperate River Narew. Songkhram peak discharges are more than 25 times higher than those of the Narew, reflecting the much

Table 4 Annual nutrients load and specific nutrient load of the River Narew and the River Songkhram

River	Station Name	Discharge area (km ²)	Load (tons/year)		Specific load (kg/km ² /year)	
			TIN	TP	TIN	TP
Narew	Suraz (SRZ)	3,420	507.5	76.1	148.4	22.3
	Strekowa Gora (St. Gora)	7,167	1,814.7	213.4	253.2	29.8
	Nowogrod up to Pisa (NWP)	20,106	2,958.4	366.5	147.1	18.2
Songkhram	Ban Tha Kok Dang (BTKD)	5,089	2,156.7	890.0	423.8	174.9
	Ban Pak Un (BPU)	12,328	5,806.9	1,671.0	471.0	135.5

higher tropical monsoon rainfall compared to the temperate, mainly snowmelt-driven Narew peak discharges.

The River Narew: this river shows a typical discharge pattern for a lowland river with a snowmelt water regime (Dingman 2015). In winter, snow accumulates with freezing temperatures, resulting in low flows and discharge mainly being fed by groundwater. In late winter and early spring (February and March), discharge increases to reach a maximum in April, reflecting significant snowmelt and rainfall feeding the river.

TP concentration in the River Narew shows a decreasing pattern when the discharge increases (see Fig. 6). TP, which includes particulate and dissolved phosphorus, has low concentrations during peak discharge, while the highest concentration of TP occurs during the lowest discharge of the River Narew. A similar dynamic pattern of phosphorus concentration was also reported in earlier research in the upper Narew by Banaszuk and Wysocka-Czubaszek (2005), who found that soluble reactive phosphorus (SRP) and TP concentrations generally decrease with increasing discharge. They also found that particulate phosphorus concentrations were higher during peak discharge after high rainfall events in summer and during the elevated autumn flow.

In contrast to TP, the dynamics of TIN concentration in the River Narew showed a pattern that aligned with the discharge dynamic. The concentration of TIN tended to increase when discharge increased (see Fig. 6) and was high during winter (highest in February) before it dropped in April when the discharge reached the maximum level. This suggests that dissolved inorganic nitrogen was transported from the catchment by snow-melted water and rainwater to the river during the rising stage of the flow. At the peak discharge in April, overbank flow occurred, with the floodplain receiving water from the river. Floodplain vegetation and other aquatic organisms consume nitrogen, resulting in decreased TIN concentration until the river discharge reaches its minimum in August. Subsequently, TIN concentration increased again, following higher river discharge, probably due to autumn rains. This suggests that TIN is transported by water (surface runoff and groundwater) from the catchment area to the river.

The River Songkhram: this river displays the typical flow characteristic of the monsoon river, with the discharge steeply

increasing during and after the intense rainy season, which generally starts in May. During the dry season, discharge is extremely low and almost stops completely. This flow pattern is generally observed in monsoon rivers (e.g., Sarma et al. 2009).

The concentration of TP and TIN in the River Songkhram was not correlated with the discharge pattern (Fig. 7), but it can be observed that the TP concentrations increased after heavy rainfall at the beginning of the rainy season (Fig. 4). This may be explained by the resuspension of the bottom material from the river bed due to turbulence (Van der Grift et al. 2018) as well as runoff of particulate and dissolved phosphorus accumulated in the catchment soil during the dry period. It is likely that the decreasing TP concentration during peak discharges is caused by dilution. However, this was not the case for TIN in the monsoon River Songkhram. Increasing TIN concentrations were observed in the rising stage of the discharge, and the decrease during peak discharge was similar to the TP concentration dynamic pattern in this river.

Similarity and differences between the river:

- Dissolved inorganic material, represented by EC, decreased during peak discharge in both river systems, reflecting dilution due to a large amount of atmospheric water input (rain, snow). EC and TP concentrations for both rivers tend to decrease downstream. It should also be noted that nitrogen concentrations are lower in the River Songkhram than in the River Narew, while a downstream increase was found for the River Narew. Surface runoff is the main mechanism that transports particulate and dissolved material to the river. It may be expected that concentrations of these materials increase during and shortly after the peak discharge, but our observations for EC, TP, and TIN from the two rivers show inconsistent variation patterns.
- The average annual TP concentration of the River Narew was around 1.5 times higher than that of the River Songkhram, and the average TIN concentration was 2.2 times higher. This might reflect differences in agricultural land use, with high intensity farming in the Narew catchment and less intense agricultural land use in the Songkhram catchment. More natural land cover typically releases

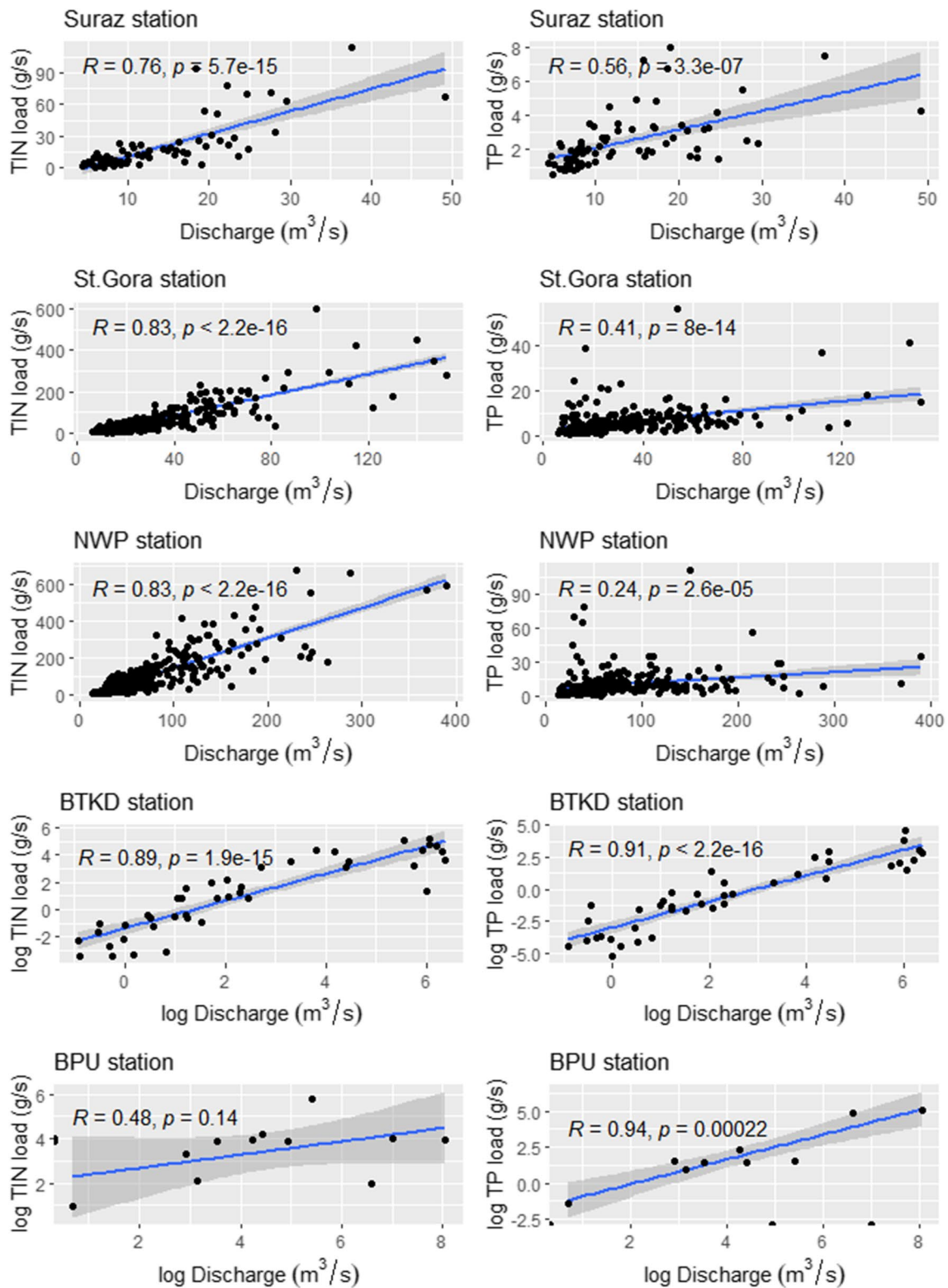


Fig. 8 The significant relationship between nutrient loads and discharge for both the River Narew (Suraz, St. Gora, and NWP stations) and the River Songkham (BTKD and BPU stations). The plot show

that nutrient loads (TIN and TP) in both rivers tend to increase with increasing discharge. The Pearson correlation coefficient (R) and corresponding *p*-value are included for each relationship

lower nutrients than agricultural land use (e.g., Weller et al. 2003; Ngoye and Machiwa 2004). However, the land use of the River Narew and the River Songkhram basin was not much different regarding the proportion of agricultural land use. Most land of the Narew River basin is used for agriculture and forest, which account for 55% and 32%, respectively (Gielczewski 2003). In the Songkhram River basin, agricultural land use and forest/planted trees cover 50% and 33% of the basin area, respectively (Shrestha et al. 2020). The main agricultural land use of the Songkhram River basin is rice paddy, which covers 45% of the basin area. The rice paddy land used in north-east Thailand has the characteristic of retaining rainwater during the monsoon rain season to support rice growth. The retention capability of the rice paddy possibly reduces erosion and keeps nutrients in the catchment. The higher concentration of TP and TIN in the River Narew than in the River Songkhram may result from differences in agricultural practices and soil nutrient status in the catchments. Typically, in the Narew catchment, the prevalent agriculture is arable farming, in which the fields are plowed in autumn and then left bare until spring, thus making them vulnerable to erosion. Soil total nitrogen in the Narew floodplain was reported to be around 6 g/kg dry weight (Antheunisse et al. 2006), which is around 3 times higher than the total nitrogen in the Songkhram floodplain (1.7 g/kg dry weight) (Walalite et al. 2018). Similarly, extractable P in the Narew floodplain soil was higher than in the

Songkhram floodplain soil, ranging from 8–20 mg/kg dry weight for Narew (Walalite et al. submitted to Wetlands Ecology and Management) and around 8–11 mg/kg dry weight for Songkhram (Walalite et al. 2018).

- In contrast to the concentration of TP and TIN, the River Narew has much lower nutrient loads than the River Songkhram, which is explained by the much higher discharges in Songkhram. Total annual nitrogen loads and specific loads are twice as high for Songkhram as for Narew, with increased values downstream for both rivers. This emphasizes the considerable influence of high monsoonal precipitation on the nutrient loads in the River Songkhram.

The floodplains We roughly estimated nutrient budgets and balances for the vegetation following earlier work by Wassen and Olde Venterink (2006). This approach allowed us to differentiate between various nutrient fluxes and storage in the floodplain systems. However, in the Narew floodplains, we did not have a direct measurement for nutrient concentration in floodwater due to an extreme drought that resulted in no flooding during our field campaign. For this reason, we hypothesized that nutrient input from floodwater would have been in the same range as for its tributary, the Biebrza, which has been investigated intensively (e.g., Wassen 1995; Olde Venterink et al. 2002). Furthermore, we did not measure nutrient release from the soil but estimated this part of the budget from the unknown in Eq. (3). For these reasons,

Table 5 Nutrient concentrations in aboveground vegetation, aboveground production (dry weight), and the estimated nutrient storage in aboveground biomass of the River Songkhram floodplain and the River Narew floodplain. The data of Songkhram floodplain was com-

pared from (Walalite et al 2018), and data of the Narew floodplain was compiled from Walalite et al. (submitted to Wetlands Ecology and Management)

Plant tissue concentration	Unit	Mean ± SE			
		Poland		Thailand	
		Sedge (n = 18)	Forest floor (n = 3)	Bamboo (n = 15)	Grass (n = 27)
C	mg/g-dw	426.3 ± 5.1a	391.7 ± 7.98b	408.7 ± 4.5b	425.2 ± 2.6a
N	mg/g-dw	21.01 ± 0.71b	27.33 ± 2.36a	18.7 ± 0.8c	6.31 ± 0.30d
P	mg/g-dw	2.44 ± 0.07b	4.81 ± 0.39a	1.26 ± 0.08c	0.68 ± 0.05d
K	mg/g-dw	14.27 ± 0.96a	17.9 ± 1.74a	10.5 ± 0.5b	7.45 ± 0.30c
N/P	-	6.68 ± 0.27 ^{N-limited}	5.71 ± 0.47 ^{N-limited}	15.4 ± 0.7 ^{P-limited}	10.7 ± 1.0 ^{N-limited}
K/P	-	5.95 ± 0.42	3.72 ± 0.01	8.5 ± 0.4	12.6 ± 1.1
N/K	-	1.59 ± 0.13	1.53 ± 0.1	1.83 ± 0.09	0.91 ± 0.08
Aboveground production	g/m ² /year	471 ± 78 (n sample = 5)	162 ± 15 (n sample = 3)	521 ± ? (n sample = 1)	386 ± 58 (n sample = 18)
Nutrient accumulation in aboveground biomass		Sedge (n site = 5)	Forest floor (n site = 1)	Bamboo (n site = 1)	Grass (n site = 6)
N	kg/km ² /year	9894.2	4427.5	9742.7	2435.7
P	kg/km ² /year	1149.1	779.2	656.5	262.5
K	kg/km ² /year	6720.2	2899.8	5470.5	2875.7

The same letters per row indicate no significant difference (t-test, *p* < 0.05)

the numbers in the budget calculations should be treated with caution as these are only rough estimates and are partly based on assumptions and data obtained from other areas. Still, it seems safe to conclude that the results of our simple nutrient budget and balance model suggest that in both floodplains, the soil is an important nutrient source for the vegetation. However, the extent to which the soil adds to the nutrient budget is different for the vegetation zones. For the bamboo vegetation adjacent to the river (Songkhram River) and forest floor vegetation (Narew River) far away from the river, the soil is the most important source of both nitrogen and phosphorus. This is not fully the case for the grass vegetation (Songkhram; further away from the river) and sedge (Narew; next to the river) vegetation, where the soil seems most important only for P in the Songkhram grass vegetation and for N in the Narew sedge vegetation. As expected, besides soil, floodwater also plays a key role as a source of N for floodplain vegetation. Nitrogen from floodwater contributed 34% of the N input for the Narew floodplain sedge vegetation, and 21% and 43% for the River Songkhram

flooded bamboo and grasses, respectively. Floodwater was the main source of P, contributing 63% to the P budget of the Narew floodplain sedge vegetation, while it was less important for the Songkhram floodplain bamboo and grass (contribution of 19% and 25%, respectively). It is noteworthy that in the Narew floodplain there is a distinct difference in river influence with a dominance of river water in the tall sedge vegetation and no river flooding in the forest, whereas in the Songkhram floodplain, the difference in river dominance is less extreme as river floods occur in both the bamboo and the grass vegetation. The outflow of N and P in both the Narew floodplain sedge and the Songkhram floodplain bamboo vegetation were lower than the inflow by floodwater, suggesting a sink function of these vegetation types for N and P. Interestingly, nutrient concentration in the biomass is higher for the Narew floodplain sedge than for the Songkhram flooded bamboo and grass, which might be related to interspecific differences in growth traits (Roeling et al. 2018). Nitrogen and potassium storage in plant biomass is higher for the Narew sedge and Songkhram bamboo

Table 6 Nitrogen and Phosphorus balance of floodplain vegetation in River Songkhram and River Narew floodplains in kg/km²/year (left) and in percentage (right). The percentage of the inflow from different sources was compared to the total inflow (*Ext+Soil*), which was considered as 100%. Also, the percentage of the nutrients in veg-

etation and the outflow were compared to the total inflow. Blue indicates the inflow of nutrients from different sources, grey is the total inflow, and green indicates nutrients stored in aboveground vegetation and the outflow from the floodplains

Nitrogen		Narew		Songkhram		Narew		Songkhram	
		Floodplain sedge	Forest-floor	Bamboo	Grass	Floodplain sedge	Forest-floor	Bamboo	Grass
<i>Ext</i>	N from Atmospheric	500 - 1000b	500 - 1000b	650a	650a	10%	21%	6%	22%
	N from Floodwater	3460b	-	2170a	1240a	34%	0%	21%	43%
	Sub-total	4460	1000	2820	1890	44%	21%	28%	65%
<i>Soil</i>	(<i>B+OutFlow</i>)- <i>Ext</i>	5687	3681	7394	1017	56%	79%	72%	35%
<i>Total Inflow</i>	<i>Ext+Soil</i>	10147	4681	10214	2907	100%	100%	100%	100%
<i>B</i>	N in Vegetation	9894	4428	9743	2436	98%	95%	95%	84%
<i>OutFlow</i>	N River-specific load	253	253	471	471	2%	5%	5%	16%

Phosphorus		Narew		Songkhram		Narew		Songkhram	
		Floodplain sedge	Forest-floor	Bamboo	Grass	Floodplain sedge	Forest-floor	Bamboo	Grass
<i>Ext</i>	P from Atmospheric	5c	5c	20d	20d	0.4%	0.6%	3%	5%
	P from Floodwater	740	-	150	100	63.4%	0%	19%	25%
	Sub-total	745	5	170	120	64%	0.6%	21%	30%
<i>Soil</i>	(<i>B+OutFlow</i>)- <i>Ext</i>	422	792	622	278	36%	99%	79%	70%
<i>Total Inflow</i>	<i>Ext+Soil</i>	1167	797	792	398	100%	100%	100%	100%
<i>B</i>	P in Vegetation	1149	779	657	263	98%	98%	83%	66%
<i>OutFlow</i>	P River-specific load	18	18	136	136	2%	2%	17%	34%

vegetation than for the non-flooded forest and less flooded grass vegetation. The fact that P does not follow this pattern with generally low storage in Songkhram compared to Narew is probably related to differences in the sediment. The repeated glaciations during the Quaternary in northern Eurasia left substantial amounts of P-rich unweathered sediments exposed, providing ecosystems with a steady supply of P compared to aged and weathered soils in the tropics (Reich and Oleksyn 2004; Hopper 2009).

Synthesis Generally, when vegetation is flooded, higher amounts of nutrients are stored in the vegetation than in non-flooded or rarely flooded vegetation (Tockner and Stanford 2002; Wassen et al. 2003; Olde Venterink et al. 2006; Keizer et al. 2018). Vegetation in a flood zone closer to the main river channel clearly receives more nutrients than vegetation in zones further away. Our results emphasize the capacity of nutrient filtering and the nutrient retention function of floodplain vegetation. The above observations imply that the floodplains of both rivers tend to act

as a sink for nutrients that are stored in both vegetation biomass and soil. This implies that the floodplains of both rivers absorb nutrients and retain them in the biomass and soil produced. Literature provides evidence for the processes that might be involved. Gordon et al. (2020) reviewed North American and European floodplains and concluded that floodplains in temperate climates remove N and P from river water. Prolonged contact with the parent river can decrease the concentration of NO_3^- and increase dissolved organic forms of N and P during a flood pulse. The floodplain can also increase NH_4^+ , particulate N, and P, and dissolved reactive P (Tockner et al. 1999, 2002; Hein et al. 2003). Increased particulate nutrients are even thought to be the key to the high productivity of vegetation in the floodplain (e.g., Keizer et al. 2018). Apparently, it is likely that in temperate floodplains, dissolved nutrients brought to the floodplain are transformed into particulate form and accumulate in soil and vegetation.

Similarly, in tropical river floodplains, as for example demonstrated by Zuidgeest et al. (2015) for the pristine

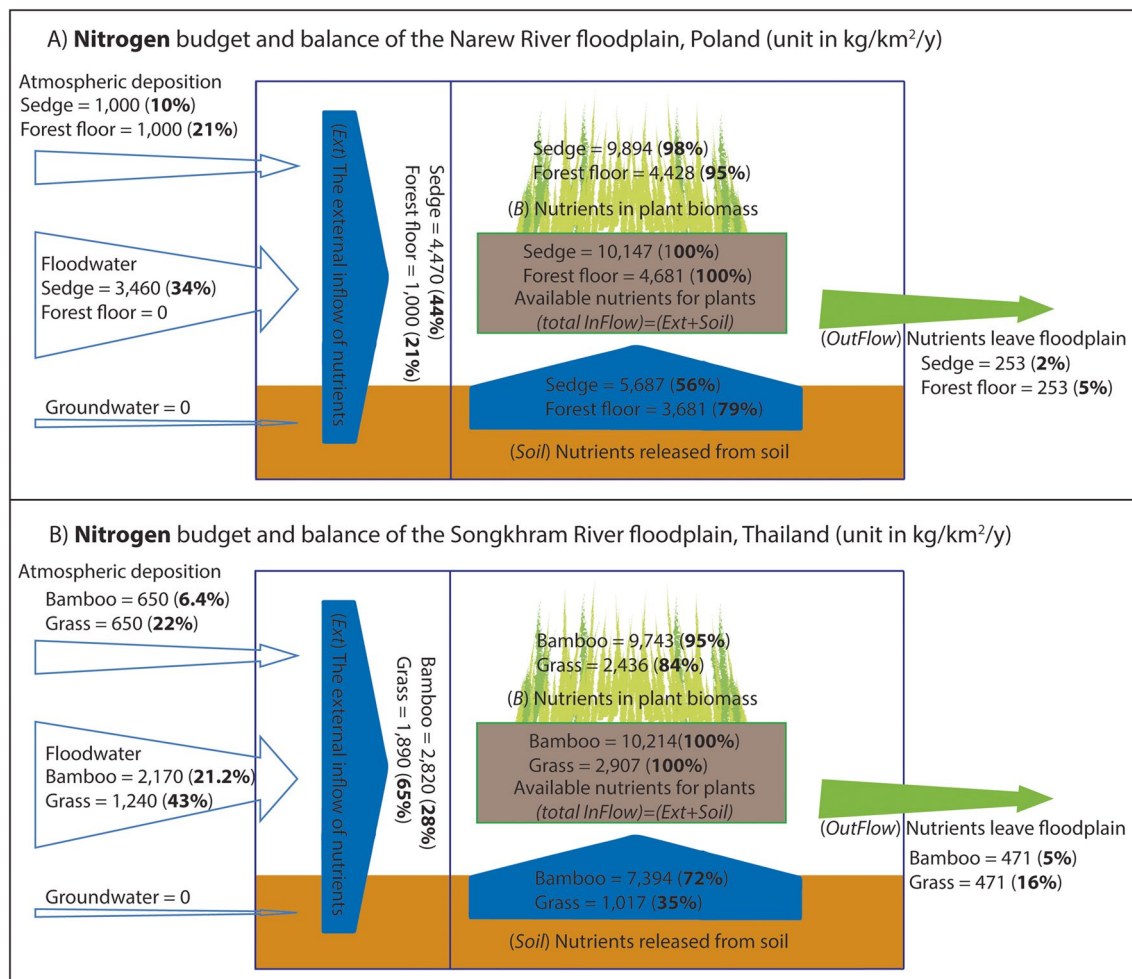


Fig. 9 Estimated N budgets and balance of floodplain vegetation in the River Narew (sedge and forest floor; A) and the River Songkhram (bamboo and grass; B)

floodplain of the Zambezi River, the floodplain may act as a sink for particulate nutrients and a source of dissolved organic carbon during the flood. This was also found in previous studies in the Songkhram floodplain, which acts as a sink for dissolved nutrients and sediment and exports organic carbon during the flood (Walalite et al. 2016, 2018).

The growing season of floodplain vegetation is aligned with the flood pattern for the Narew floodplain. The vegetation starts to grow after the spring flood (Feb-Mar), allowing vegetation to benefit from the nutrient input from floodwater. In contrast, the bamboo and grass in the Songkhram floodplain may not directly benefit from the floodwater since the magnitude of the flood is exceedingly high and prohibits the growth of the floodplain vegetation during the flood (authors' personal observations). However, this prolonged period of water on the floodplain does allow the aquatic vegetation and algae to grow (Walalite et al. 2016). After the flood recedes, these aquatic organisms decay, and the bamboo and grasses benefit from this nutrient source later in the growing season.

Our analysis demonstrates that the seasonal flood pulse is an important mechanism that brings in additional nutrients for floodplain vegetation in both rivers. Although the floodplain vegetation benefits from nutrient input from floodwater, nutrients stored in the soil are seen to be important too. In our view, this works as follows: the floodplain vegetation consumes the nutrients brought in by the flood, then produces biomass and build up the soil organic matter leading to the retention of nutrients in the floodplain. The floodplains of both rivers function as a sink for N and P, although this capability differed in extent, depending on the type of nutrient and the vegetation zone with different infiltration capacities of the floodwater into the soil and retention time of the floodwater. We recommend further research into the processes and forms of nutrients in both river floodplains; such research should focus on disentangling the most important hydrogeochemical processes, e.g., nutrient cycling in both the floodplain soil and the vegetation, and how this nutrient cycling is related to the river dynamics.

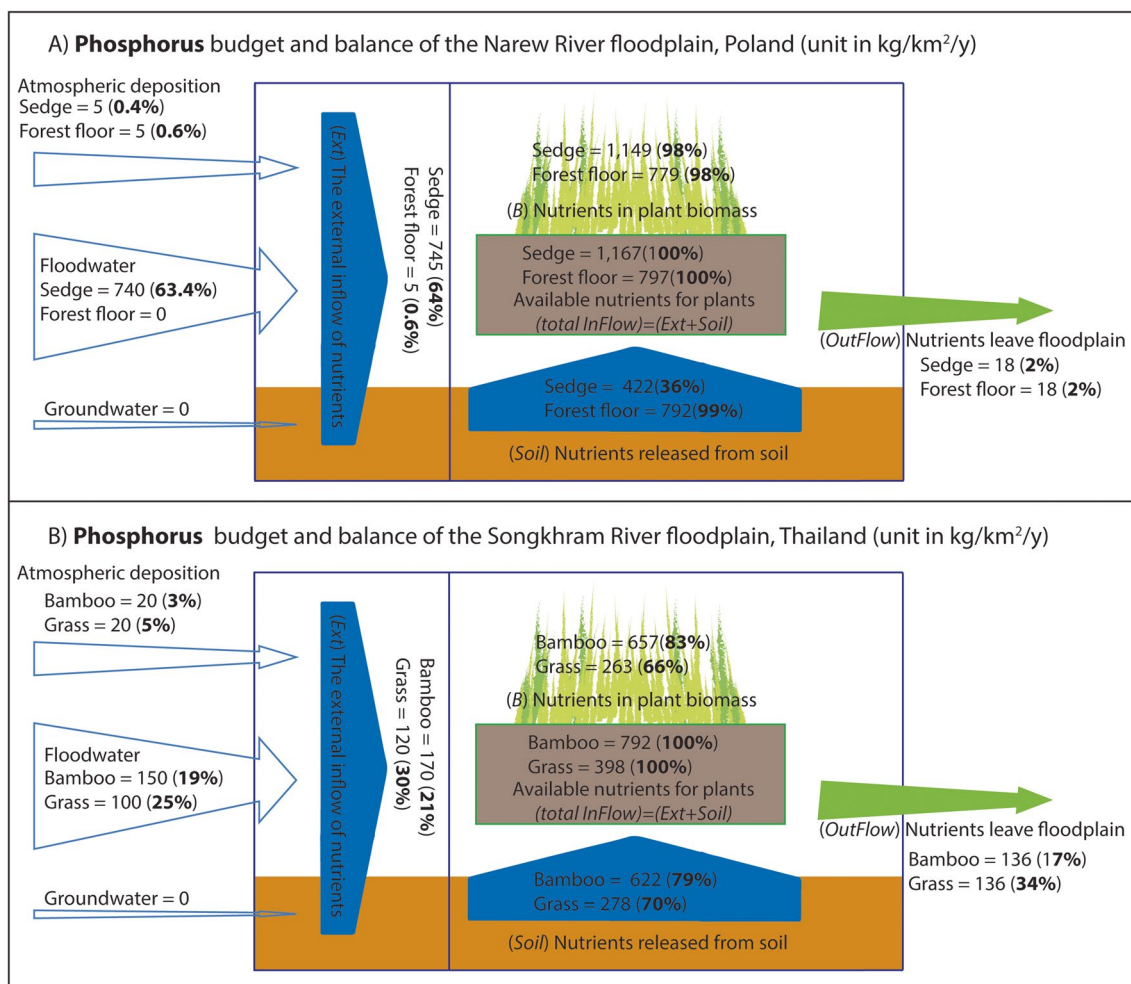


Fig. 10 Estimated P budgets and balance of floodplain vegetation in the River Narew (A) and the River Songkhram (B) floodplains

Appendix 1

Table 7 Summary of the number of measurements for each station from the Narew River, Poland, and the Songkhram River, Thailand

	Narew River, Poland				Songkhram River, Thailand					
	Boundary	Suraz	Strekowa Gora	Nowogrod -UpTo Pisa	Ban Hui Songkhram	Ban Tha Kok Dang	Ban Tha Gon	Ban Pak Un	Ban Chai Buri	
Flow data	(BND) 1991–2018	(SRZ) 2005–2018	(St.Gora) 1991–2018	(NWP) 1991–2018	(BHSK) -	(BTKD) 1986–2010	(BTG) -	(BPU) 2013–2016	(BCBR) -	
Concentration data	1992–2016	2001–2016	1991–2017	1991–2017	1996–2015	1996–2015	1996–2015	1996–2015	1996–2015	
Average annual Q (m ³ /s)	4	14	31	75	-	145	-	373	-	
Discharge area (km ₂)	1050	3420	7167	20,106	-	5089	-	12,328	-	
Temp. (C)	356	73	328	328	57	58	56	56	56	
EC	322	73	287	268	57	57	56	56	56	
pH	304	55	331	308	57	58	56	56	56	
DO	322	73	308	308	57	58	56	56	56	
TP	322	72	302	307	53	54	52	52	52	
N-NO ₃ ⁻	345	73	331	311	54	56	53	54	54	
N-NO ₂ ⁻	276	72	257	267	54	55	53	53	53	
N-NH ₄ ⁺ /NH ₃	323	73	332	311	52	53	51	51	51	

Table 8 Monthly average TP concentration (mg/l)

Month	River Narew			River Songkham	
	Suraz (SRZ))	Strekowa Gora (St. Gora)	Nowogrod up to Pisa (NWP)	Ban Tha Kok Dang (BTKD)	Ban Pak Un (BPU)
Jan	0.16	0.19	0.12	0.03	0.05
Feb	0.14	0.17	0.12	0.13	0.16
Mar	0.18	0.14	0.11	0.02	0.05
Apr	0.13	0.18	0.13	0.46	-
May	0.17	0.20	0.13	0.10	0.07
Jun	0.21	0.34	0.26	0.61	0.42
Jul	0.28	0.36	0.25	0.11	0.14
Aug	0.29	0.37	0.23	0.06	0.06
Sep	0.23	0.29	0.26	0.02	0.01
Oct	0.18	0.22	0.18	-	-
Nov	0.21	0.24	0.22	0.18	0.09
Dec	0.22	0.17	0.13	0.09	0.14
average	0.20	0.24	0.18	-	-

Table 9 Monthly average TIN concentration (mg/l)

Month	River Narew			River Songkham	
	Suraz (SRZ))	Strekowa Gora (St. Gora)	Nowogrod up to Pisa (NWP)	Ban Tha Kok Dang (BTKD)	Ban Pak Un (BPU)
Jan	1.94	2.46	1.83	0.41	0.46
Feb	2.39	2.52	1.96	0.62	0.97
Mar	2.11	2.41	1.50	0.14	0.31
Apr	1.17	1.74	1.15	-	-
May	0.61	1.34	0.85	0.46	0.58
Jun	0.57	1.26	0.77	0.70	0.88
Jul	0.32	1.14	0.72	0.10	0.18
Aug	0.51	1.10	0.73	0.28	0.30
Sep	0.67	1.20	0.96	0.08	0.05
Oct	0.84	1.45	0.97	-	-
Nov	1.57	1.84	1.29	1.18	1.04
Dec	1.27	2.08	1.52	0.66	0.76
average	1.16	1.71	1.19	-	-

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Authors' contributions TW, PS, SD, TO, and MW conceived and planned the study. TW, IK, PS, SD, TO, and MW contributed to the interpretation of the results. TW performed data analysis and was a major contributor to writing the manuscript. The study was directed and coordinated by TO and MW. All authors provided critical feedback and helped shape the research, analysis, and manuscript. All authors read and approved the final manuscript.

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Data availability All data produced from this study are provided in this manuscript.

Declarations

Conflicts of interest/Competing interests The authors declare that they have no competing interests.

Ethics approval This study was conducted in accordance with local legislation. Any samples (e.g., soil samples, plant samples.) obtained from reserved/protected/conserved/privately owned areas/national parks, etc., had permission for carrying out the study in the respective area.

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