Role of Active Floodplains for Nutrient Retention in the River Rhine

H. Olde Venterink,* F. Wiegman, G. E. M. Van der Lee, and J. E. Vermaat

ABSTRACT

We evaluated the importance of floodplains for nutrient retention in two distributaries of the river Rhine (Waal and IJssel) by monitoring N and P retention in a body of water during downstream transport. We hypothesized that (i) retention of P is much larger than retention of N and (ii) nutrient retention increases with an increasing amount of the discharge flowing through floodplains (Q_F). The second hypothesis was tested by comparing retention between the rivers Waal (low Q_F) and IJssel (high Q_F), as well as at different discharges. Total nitrogen (TN) did not decrease significantly during downstream transport in both rivers, whereas 20 to 45% of total phosphorus (TP) disappeared during transport in the river IJssel. This difference between N and P retention—supporting the first hypothesis—was probably caused by differences in sedimentation through a much lower proportion of N adsorbed to particles than of P (2–3% of N vs. 50–70% of P). Phosphorus retention was only observed in the IJssel and not in the Waal, and absolute P retention (g P s^{-1} km^{-1}) in the IJssel increased with increasing Q_F. The second hypothesis was, nevertheless, not fully supported, because the percentage P retention (% of P load) decreased (instead of increased) with increasing Q_F. The percentage P retention increased with decreasing river depth and flow velocity; it seemed related to the efficiency of sediment trapping.

INCREASED NUTRIENT loads in rivers from human activities in catchments have caused eutrophication of many rivers and coastal marine waters in Europe and North America (Haycock et al., 1993; Caraco and Cole, 1994; Howarth et al., 1996). Such eutrophication may be reduced by nutrient retention in floodplains. Floodplains may contribute to the natural polishing of river water through sorption, trapping, or biological transformations of nutrients (Johnston, 1991; Pinay et al., 1994; Naiman and Décamps, 1997; Sjodin et al., 1997). However, due to embankment and reclamation, floodplain areas of many European rivers have been reduced in the past (Haycock et al., 1993; Naiman and Décamps, 1997; Keddy, 2000). Recently, policy developments have supported reestablishment of floodplains, mainly for flood containment and hazard reduction of dike breaks.

Because retention mechanisms such as denitrification and sedimentation are likely to be higher in floodplains than in the main channel, it is expected that nutrient retention will increase with an increasing proportion of the river flow passing through floodplains. The reasons why denitrification and sedimentation are probably higher in floodplains than in the main channel are the lower oxygen levels (McMahon et al., 1995; Sjodin et al., 1997) and the lower water velocity (Brueske and Barrett, 1994; Vought et al., 1994), respectively. In a previous study, we measured denitrification and sedimentation in floodplains along river Rhine distributaries, and concluded that sedimentation was far more important for nutrient retention than denitrification (unpublished data, 2001). Moreover, we concluded that nutrient retention in these rivers appeared largely restricted to phosphorus, since often phosphorus is to a large extent adsorbed to sediment in river water whereas nitrogen is mainly present as dissolved nitrate (Admiraal et al., 1992). These conclusions were, however, only based on upscaling of measurements in the floodplains, they were not tested by measuring changes in nutrient levels in the rivers themselves.

The delta of the river Rhine includes three distributaries: the rivers Waal, Nederrijn, and IJssel, receiving 6/9, 2/9, and 1/9 of the total discharge, respectively (Fig. 1). As the three distributaries receive the same water, but differ strongly in river morphology, they offer a unique opportunity to study the importance of floodplains for nutrient retention. The river Waal has a very deep main channel and its floodplains only receive water at peak discharges. In contrast, the river IJssel has a relatively small channel and its floodplains are more frequently flooded.

Our objective was to evaluate the importance of floodplains for nutrient retention in rivers. We compared nutrient retention rates between the rivers Waal and IJssel by monitoring N and P concentrations in a body of river water during its downstream transport ("flowing wave approach"; Admiraal et al., 1990, 1992; De Ruyter van Steveninck et al., 1992). We hypothesized that (i) retention of phosphorus is larger than retention of nitrogen and (ii) nutrient retention increases with an increasing amount of the discharge flowing through floodplains (Q_F). The second hypothesis was tested by comparing retention between the rivers Waal (low Q_F) and IJssel (high Q_F), as well as at different discharges within each river.

MATERIALS AND METHODS

We measured N and P concentrations in a body of river water, which we followed during its downstream transport in the rivers Waal and IJssel. Water from the IJssel was sampled from bridges near Doesburg, Zutphen, and Zwolle. Water from the Waal was sampled from bridges near Tiel, Zaltbommel, and Gorinchem (Fig. 1). Water samples were taken during two flood events (12–13 Feb. 2001 and 28–29 Mar. 2001) and

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Abbreviations: DON, dissolved organic nitrogen; DOP, dissolved organic phosphorus; PN, particulate nitrogen; PP, particulate phosphorus; Q_F, proportion of discharge flowing through floodplains; TDN, total dissolved nitrogen; TDP, total dissolved phosphorus; TN, total nitrogen; TP, total phosphorus.

during a low-water period (31 July–1 Aug. 2001). At the three sampling events, five replicate samples were taken from five sites at every bridge covering the entire river width (Fig. 2).

Flow velocities of the river water, and hence moments of sampling (from the same water mass) at the various bridges, were assessed with the Rhine Alarm Model (Van Mazijk et al., 1991). This model is used by the Dutch water authority to assess movement of water and hazardous pollutants. The predicted transport time of this model has an error of 5 to 10% in these rivers (Van Mazijk, personal communication, 2002). Discharges of the rivers Waal and IJssel at the sampling events, as well as percentages of the discharges flowing through their floodplains (Fig. 2), were based on measured discharges near Lobith (RIZA, unpublished data, 2002) and the one-dimensional hydraulic model SOBEK (WL Delft Hydraulics and Rijkswaterstaat, 1995). The model schematization of SOBEK consists of cross-sections, defined at 500-m intervals. Each cross-section consists of three subsections: main channel, groyne area, and floodplain. The model computes water levels and discharges for each interval. The total discharge is subdivided into the discharge through the three subsections as defined in the cross-section. The percent floodplain discharges in Fig. 2 are average values of the 500-m intervals located in the investigated sections of the rivers Waal and IJssel.

After sampling, water was frozen until analysis. After thawing, a part of the water was centrifuged. In the noncentrifuged samples, total nitrogen (TN) concentrations were measured using a Koroleff digestion (McKee et al., 2000). Total phosphorus (TP) was measured after digestion with H_2SO_4 and HNO_3 (Kruis, 1999). In the centrifuged samples, NO_3^-, NH_4^+, and PO_4^{3-} concentrations were measured, as well as total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) after the same digestions as used for the centrifuged samples. Nitrate concentrations in water and digests were measured by means of UV-VIS photospectrometry (Lambda 20, Perkin-Elmer, Wellesley, MA; direct UV photospectrometric method; Kruis, 1999) and ammonium concentrations in water by means of photospectrometry (dichloroisocyanurate method; Kruis, 1999). Phosphate concentrations in water and digests were measured by means of photospectrometry (ascorbic acid method; Kruis, 1999). Concentrations of particulate nitrogen and phosphorus fractions (PN, PP) were calculated as TN − TDN and TP − TDP, respectively. Concentrations of dissolved organic nitrogen and phosphorus fractions (DON, DOP) were calculated as TDN − NO_3–N − NH_4–N and TDP − PO_4–P, respectively (McKee et al., 2000). At first we wanted to apply filtering (0.2-μm pore size) instead of centrifugation. Because nitrate was released from the filters, we had to apply centrifugation. Besides nitrate, filtering and centrifugation did not yield different results.

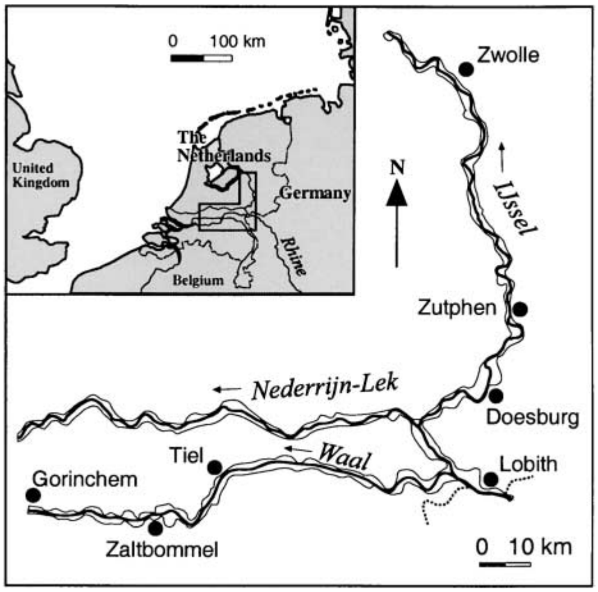

Fig. 1. The river Rhine and its delta in the Netherlands. After the city of Lobith, the Rhine is split into three distributaries. Water samples were collected from bridges near Doesburg, Zutphen, and Zwolle (IJssel) and Tiel, Zaltbommel, and Gorinchem (Waal).

Retention of nitrogen and phosphorus between two bridges was calculated by means of Eq. [1] and [2] where R is nutrient retention (g N km^{-1} or g P km^{-1}), $\%R$ is retention as percentage of nutrient load (% km^{-1}), L_1 is nutrient load at the upstream bridge (g N s^{-1} or g P s^{-1}), L_2 is nutrient load at

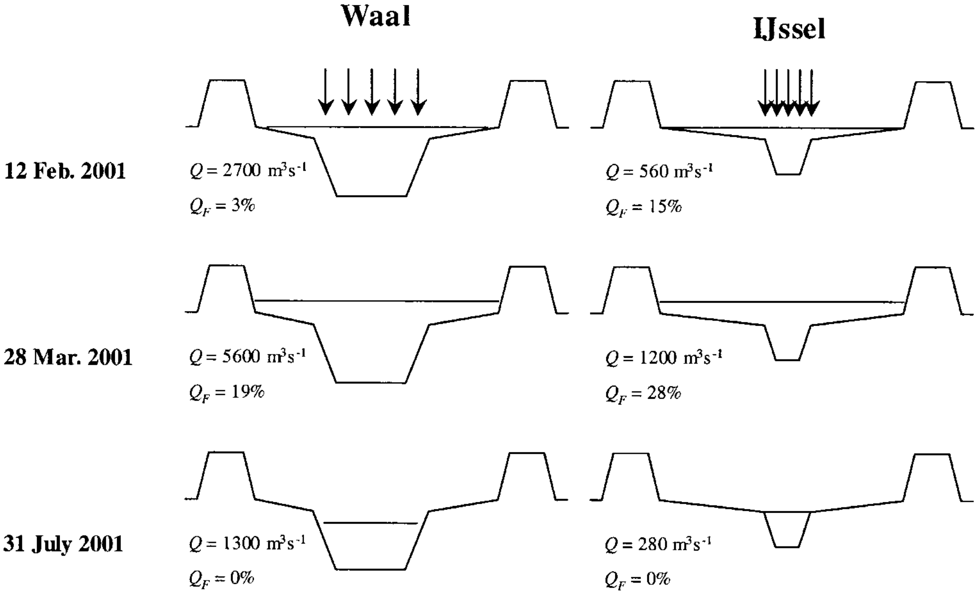

Fig. 2. Schematic cross-sections of the rivers Waal and IJssel showing discharges (Q), as well as percentages of the discharge flowing through floodplains (Q_F), during the three sampling events. Arrows indicate sampling locations.

the downstream bridge (g N s^{-1} or g P s^{-1}), and D is distance between the two bridges (km).

$$R = \frac{L_1 - L_2}{D} \quad [1]$$

$$\%R = \frac{\left(\dfrac{L_1 - L_2}{L_1}\right)}{D} \times 100 \quad [2]$$

In our flowing wave approach, the increase of discharge during downstream transport was considered negligible compared with the monitored volume of water. This may seem odd to outsiders, but the Dutch branches of the river Rhine have been engineered for centuries to serve as conducts for the rapid disposal of discharge. During the rapid passage of water through the Waal and IJssel very few inputs or outputs of water exist, particularly in comparison with the large amount of water already present. During pronounced flooding of the floodplains, some seepage through the dikes into adjacent polders can be observed, but we consider this a minor loss, as seepage is not flooding.

Assuming a constant discharge during transport in Waal and IJssel, R and $\%R$ in Eq. [1] and [2] can also be calculated using nutrient concentrations instead of nutrient loads; in which case R is expressed in mg N L^{-1} km^{-1} or mg P L^{-1} km^{-1}.

Repeated measures analysis of variance (ANOVA; three-way: one river, two date, three bridge or transport) was used to determine whether concentrations of the various N and P fractions in river water showed a significant increasing or decreasing trend during transportation, as well as whether these fractions differed significantly between river (Waal vs. IJssel) and/or month (February, March, July). Only linear trends during transportation were taken into account. The statistical analyzes were performed with SPSS 8.0 (SPSS, 1997).

RESULTS

Total P concentrations varied between 0.1 and 0.3 mg P L^{-1}, in both IJssel and Waal (Table 1). The major fractions were PP and DOP; both were significantly higher in winter than in summer (Tables 1 and 2). Total P concentrations decreased during downstream transport, but only in the river IJssel (Table 1; transport ×

Table 1. Fractions of phosphorus and nitrogen concentrations in water of the rivers IJssel and Waal during downstream transportation along three bridges. Mean (±SE) concentrations of five replicates are shown. Concentrations are in mg N L^{-1} or mg P L^{-1}. For statistics, refer to Tables 2 and 3.

	IJssel			Waal		
	Site and position (km)					
Characteristic†	Bridge 1, Doesburg (905)	Bridge 2, Zutphen (923)	Bridge 3, Zwolle (981)	Bridge 1, Tiel (911)	Bridge 2, Zaltbommel (933)	Bridge 3, Gorinchem (957)
12 February						
Travel time, h	0	5.0	22.8	0	4.2	8.5
TP	0.26 ± 0.025	0.21 ± 0.024	0.17 ± 0.002	0.21 ± 0.024	0.27 ± 0.019	0.20 ± 0.023
TDP	0.13 ± 0.019	0.12 ± 0.032	0.04 ± 0.004	0.07 ± 0.010	0.07 ± 0.013	0.06 ± 0.011
PP	0.12 ± 0.013	0.10 ± 0.032	0.13 ± 0.004	0.14 ± 0.020	0.19 ± 0.011	0.14 ± 0.019
DOP	0.11 ± 0.023	0.09 ± 0.028	0.01 ± 0.005	0.03 ± 0.010	0.03 ± 0.014	0.02 ± 0.008
PO_4–P	0.02 ± 0.007	0.02 ± 0.005	0.03 ± 0.006	0.04 ± 0.004	0.05 ± 0.002	0.04 ± 0.006
TN	3.75 ± 0.188	3.71 ± 0.188	3.93 ± 0.193	3.67 ± 0.075	3.68 ± 0.036	3.47 ± 0.346
TDN	3.71 ± 0.187	3.66 ± 0.184	3.82 ± 0.215	3.59 ± 0.066	3.54 ± 0.055	3.35 ± 0.329
PN	0.04 ± 0.013	0.05 ± 0.012	0.11 ± 0.050	0.08 ± 0.016	0.14 ± 0.027	0.12 ± 0.044
DON	0.08 ± 0.042	0.05 ± 0.018	0.07 ± 0.029	0.07 ± 0.031	0.00 ± 0.004	0.03 ± 0.010
NH_4–N	0.10 ± 0.008	0.09 ± 0.003	0.12 ± 0.004	0.09 ± 0.011	0.09 ± 0.005	0.07 ± 0.004
NO_3–N	3.53 ± 0.159	3.53 ± 0.175	3.64 ± 0.204	3.43 ± 0.054	3.51 ± 0.030	3.25 ± 0.335
28 March						
Travel time, h	0	4.5	21.5	0	3.9	8.0
TP	0.21 ± 0.020	0.18 ± 0.035	0.17 ± 0.015	0.15 ± 0.011	0.14 ± 0.023	0.29 ± 0.068
TDP	0.06 ± 0.006	0.08 ± 0.013	0.08 ± 0.012	0.06 ± 0.005	0.07 ± 0.007	0.08 ± 0.006
PP	0.15 ± 0.020	0.10 ± 0.023	0.09 ± 0.013	0.09 ± 0.015	0.07 ± 0.016	0.21 ± 0.064
DOP	0.02 ± 0.009	0.03 ± 0.013	0.04 ± 0.012	0.02 ± 0.004	0.03 ± 0.008	0.03 ± 0.009
PO_4–P	0.04 ± 0.004	0.04 ± 0.002	0.04 ± 0.002	0.04 ± 0.002	0.04 ± 0.002	0.05 ± 0.005
TN	3.22 ± 0.034	3.10 ± 0.060	3.32 ± 0.026	3.07 ± 0.016	3.02 ± 0.033	3.08 ± 0.048
TDN	3.15 ± 0.052	3.00 ± 0.040	3.19 ± 0.023	3.03 ± 0.008	2.95 ± 0.022	2.99 ± 0.034
PN	0.07 ± 0.024	0.10 ± 0.032	0.13 ± 0.040	0.04 ± 0.013	0.08 ± 0.030	0.09 ± 0.042
DON	0.17 ± 0.053	0.10 ± 0.015	0.08 ± 0.023	0.11 ± 0.011	0.08 ± 0.020	0.11 ± 0.034
NH_4–N	0.08 ± 0.008	0.08 ± 0.007	0.08 ± 0.003	0.07 ± 0.002	0.07 ± 0.004	0.07 ± 0.007
NO_3–N	2.90 ± 0.014	2.83 ± 0.040	3.03 ± 0.004	2.84 ± 0.005	2.79 ± 0.017	2.81 ± 0.015
31 July						
Travel time, h	0	5.5	24.0	0	4.4	8.9
TP	0.17 ± 0.020	0.13 ± 0.008	0.09 ± 0.005	0.10 ± 0.008	0.11 ± 0.006	0.12 ± 0.013
TDP	0.06 ± 0.016	0.07 ± 0.002	0.04 ± 0.000	0.05 ± 0.005	0.06 ± 0.009	0.05 ± 0.000
PP	0.11 ± 0.016	0.06 ± 0.007	0.05 ± 0.005	0.05 ± 0.011	0.04 ± 0.008	0.07 ± 0.013
DOP	0.04 ± 0.012	0.03 ± 0.007	0.01 ± 0.005	0.04 ± 0.006	0.05 ± 0.010	0.03 ± 0.000
PO_4–P	0.02 ± 0.006	0.04 ± 0.005	0.03 ± 0.005	0.01 ± 0.002	0.01 ± 0.004	0.02 ± 0.000
TN	2.04 ± 0.033	2.01 ± 0.020	2.05 ± 0.035	2.02 ± 0.024	1.98 ± 0.016	2.09 ± 0.104
TDN	1.98 ± 0.031	1.92 ± 0.028	1.91 ± 0.024	1.91 ± 0.035	1.89 ± 0.022	1.97 ± 0.126
PN	0.07 ± 0.040	0.09 ± 0.042	0.14 ± 0.045	0.11 ± 0.030	0.09 ± 0.035	0.12 ± 0.051
DON	0.16 ± 0.028	0.13 ± 0.022	0.14 ± 0.023	0.12 ± 0.033	0.15 ± 0.023	0.21 ± 0.038
NH_4–N	0.02 ± 0.002	0.02 ± 0.003	0.03 ± 0.002	0.02 ± 0.002	0.02 ± 0.002	0.02 ± 0.002
NO_3–N	1.81 ± 0.002	1.77 ± 0.022	1.74 ± 0.005	1.78 ± 0.004	1.72 ± 0.023	1.74 ± 0.023

† DON, dissolved organic nitrogen; DOP, dissolved organic phosphorus; PN, particulate nitrogen; PP, particulate phosphorus; TDN, total dissolved nitrogen; TDP, total dissolved phosphorus; TN, total nitrogen; TP, total phosphorus.

Table 2. Effects of downstream transport (place of sampling), river (IJssel vs. Waal), month (February, March, July), and their interactions on concentrations of phosphorus fractions† (*F* values of repeated measures analysis of variance [ANOVA]).

Variable	df	TP	TDP	PP	DOP	PO_4–P
Transport	1	0.4	6.1*	0.1	7.4*	0.5
River	1	0.0	6.0*	1.3	10.1**	0.5
Month	2	31.9***	13.1***	20.9***	11.6***	25.6***
Transport × river	1	14.7***	5.8*	9.8**	6.0*	0.1
Transport × month	2	3.5*	11.4***	1.0	11.2***	1.6
River × month	2	1.0	5.2*	3.9*	21.9***	16.0***
Transport × river × month	2	1.0	3.7*	3.4	4.9*	0.6

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† DOP, dissolved organic phosphorus; PP, particulate phosphorus; TDP, total dissolved phosphorus; TP, total phosphorus.

river in Table 2). After 76 km of transport in the IJssel, 21 to 45% of TP had disappeared; this is the difference between the first and the third bridge (Table 1). This corresponds with 1 to 2% of TP per hour traveling time of the water in this river. In an absolute sense (i.e., expressed as load in g P s^{-1}), P retention increased with an increasing proportion of the discharge flowing through floodplains along the IJssel; however, expressed as a percentage of P load, P retention declined with increasing floodplain discharge (Fig. 3).

Total N concentrations varied between 2 and 4 mg N L^{-1} in both rivers, with nitrate as the only major N fraction (Table 1). Total N concentrations were clearly higher in winter than in summer (Tables 1 and 3). We found no significant decrease in TN concentrations during transport in the two rivers (Table 3). Although PN concentrations increased significantly in both rivers, and ammonium concentrations decreased significantly in the Waal, these changes were of negligible importance for TN concentrations (Tables 1 and 3).

DISCUSSION

The objective of this study was to evaluate the importance of floodplains for nutrient retention in the river Rhine. We hypothesized that retention of phosphorus would be much larger than retention of nitrogen because (i) sedimentation appeared to be the major retention mechanism in these floodplains and (ii) nitrogen is often only marginally adsorbed to sediment. Our results supported this hypothesis since only 2 to 3% of the nitrogen load in the rivers Waal and IJssel were in particulate form, and TN load did not decrease significantly during downstream transport, whereas 20 to 45% of TP load disappeared during transport in the river IJssel (Tables 1, 2, and 3; assuming a constant water load, see Materials and Methods section). This difference between N and P retention is consistent with assessments of retention of these nutrients in Canadian wetlands (Devito et al., 1989). Nitrogen retention is often rather low in rivers (0–20%, which is generally lower than in lakes; Seitzinger et al., 2002), although in some rivers N retention can be clearly higher through high denitrification rates (e.g., Sjodin et al., 1997). High N retention rates have also been reported for river catchments studies, but in these studies N retention by denitrification during subsurface ground water transport is generally included (Osborne and Kovacic, 1993; Triska et al., 1993).

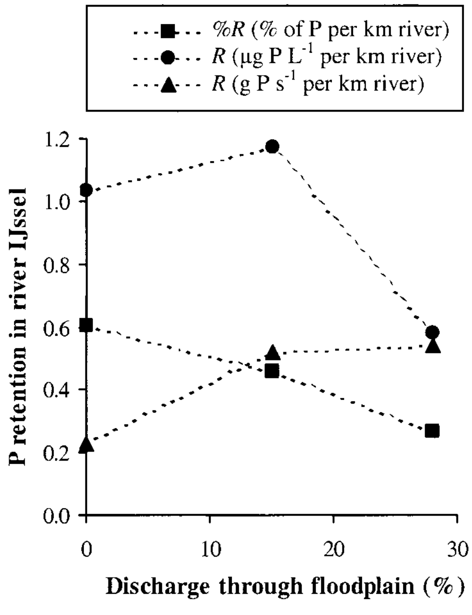

Fig. 3. Phosphorus retention in the river IJssel vs. the percentage of river discharge flowing through its floodplain.

We also hypothesized that phosphorus retention would increase with an increasing amount of river water flowing through floodplains. We tested this hypothesis by comparing retention between the rivers Waal and IJssel, as well as at different discharges in these rivers (Fig. 2). We found no P retention along the river Waal in contrast to 20 to 45% P retention along the IJssel, where floodplains transported a substantial fraction of the river discharge. This was consistent with our hypothesis and also confirms P retention estimates from our direct quantification of sedimentation rates during the same flood events in these floodplains (on average, 5% P retention in the Waal for the February and March flood versus 18% in the IJssel; unpublished data, 2001). A higher P retention along the IJssel is also consistent with Asselman and Van Wijngaarden (2002) who computed a sediment trapping efficiency of >80% for the river IJssel compared with <30% for the river Waal for the discharges of this study.

However, instead of the hypothesized increase in P retention, we observed a decrease of the proportional P retention with an increasing volume of water in the floodplain of the river IJssel (Fig. 3). In our hypothesis we incorrectly assumed that retention processes such as sedimentation in the river channel would be negligible

Table 3. Effects of downstream transport (place of sampling), river (IJssel vs. Waal), month (February, March, July), and their interactions on concentrations of nitrogen fractions† (*F* values of repeated measures analysis of variance [ANOVA]).

Variable	df	TN	TDN	PN	DON	NH_4–N	NO_3–N
Transport	1	0.1	0.1	11.0**	0.4	0.4	0.1
River	1	4.7*	4.9*	0.1	0.4	15.0***	3.1
Month	2	342.0***	312.3***	0.3	13.6***	278.7***	320.3***
Transport × river	1	0.9	0.6	1.0	2.6	5.7*	1.2
Transport × month	2	0.1	0.1	0.2	2.2	0.7	0.2
River × month	2	1.2	1.3	1.2	0.7	7.1**	0.5
Transport × river × month	2	0.7	1.1	0.2	1.8	1.5	0.6

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† DON, dissolved organic nitrogen; PN, particulate nitrogen; TDN, total dissolved nitrogen; TN, total nitrogen.

compared with those in floodplains. Instead, we found a retention rate of 0.23 g P s^{-1} km^{-1} in the main channel of the IJssel in summer (Fig. 3). Although this rate was less than half the absolute P retention rates observed at higher discharges (approximately 0.53 g P s^{-1} km^{-1}), the TP concentrations in river water were also clearly lower at low discharge (Table 1). Together, this led to maximal proportional P retention at the low summer discharge (Fig. 3). In fact, our results are consistent with those of Alexander et al. (2000) who found that nutrient retention increased with decreasing water depth in streams and rivers of the Mississippi catchment. It is noteworthy that the absolute P retention in the river IJssel was hardly higher in March than in February. This can also be explained by the water depth, as both in February and in March the floodplains were mostly filled with water, but with a larger flood depth in March. Apparently, the proportional P retention (% of P load) is highest in shallow rivers with a maximum contact between water and soil surface of channels or floodplains. Such conditions are favorable for sedimentation, which is considered the major mechanism for P retention (Johnston, 1991). Furthermore, Asselman and Van Wijngaarden (2002) demonstrated that sediment trapping efficiency in the rivers Waal, IJssel, and Nederrijn was dependent on the river discharge, not only because of the amount of water in floodplains but also through its relationship with flow velocity. At a discharge of 8000 m^3 s^{-1} at Lobith (comparable with the high discharge of this study in March 2001; i.e., 8500 m^3 s^{-1} at Lobith), Asselman and Van Wijngaarden (2002) assessed sediment trapping efficiency at only 9% in the river Waal compared with 94% in the river IJssel. In the river Waal, flow velocity was too high for sedimentation at this discharge. The relationship with the flow velocity explains the absence of P retention in the Waal at the highest discharge despite the fact that 19% of the discharge was flowing through floodplains.

A priori, nutrient uptake by bentic algae, or planktonic algae followed by sedimentation, may be significant in the nutrient budgets of rivers. However, the deep and turbid Rhine has very limited bentic algae, and sedimentation of planktonic algae only occurs in the last stretches, downstream of our study area (Admiraal et al., 1992). Still, planktonic algae may have been important in reducing dissolved N and P in downstream water transport in the German part of the Rhine during the growing season. Indeed, lower TN and TP in July were mainly due to lower concentrations of DOP and NO_3 (Table 1).

We conclude that nutrient retention in the distributaries of the river Rhine in the Netherlands appears to be largely influenced by the process of sedimentation through (i) the nutrient fraction in river water that is adsorbed to sediment and (ii) the efficiency of sediment trapping. Nitrogen retention is low because it is hardly adsorbed to sediment. Phosphorus retention does occur because of the predominance of PP. The efficiency of sediment trapping, and hence P retention, depends on both the contact area between water and soil and on flow velocity. An increase in inundated floodplain area will generally affect both factors, and may therefore increase P retention. It is noteworthy that in other rivers N retention also may occur when conditions are more favorable for another retention process, denitrification (i.e., shallower and slower-flowing rivers; Seitzinger et al., 2002).

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