The influence of macrophytes on sedimentation and nutrient retention in the lower River Spree (Germany)

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Abstract

Nutrient retention due to sedimentation in running waters has been little studied. The knowledge about the processes of self-purification is important for the management of rivers. The principal aim of our investigations was to quantify nutrient retention by sedimentation within and adjacent to stands of submerged macrophytes. In addition, we examined the relationship between deposition and sedimentation patterns and the flow regime.

In the summer of 2001, investigations were performed in the lower River Spree with sediment traps and sediment cores and measurement of flow velocities. The spatial distribution of macrophytes was described and related to sedimentation and flow patterns. Water and sediment samples were analysed for total phosphorus and total organic nitrogen concentrations.

Macrophytes significantly enhanced water residence time by factors between 2 and 18. Trapping rates were high within and downstream of macrophyte stands due to the prevailing quiescent conditions. Trapping rates were low in regions not covered by macrophytes, where flow velocities were high. Calculated deposition of organic matter due to trapping rates accounted for 15–49% of observed deposition between May and September, the vegetation period. The difference between calculated and observed deposition can partly be attributed to an incomplete erosion of the organic sediments between October and April. Between May and September, nitrogen and phosphorus were retained by deposition by as much as 2.5% and 12.2%, respectively (% of total load).

Therefore, macrophytes considerably contributed to total monthly phosphorus retention (up to 25%) by increasing deposition of particulate organic matter.

1. Introduction

In running waters, macrophytes can effect nutrient retention by increasing the water residence time [1] and by acting as a filter for suspended particulate organic matter [2]. The major force regulating the deposition of particles is bottom shear stress [3], which in turn depends on flow velocity. Bottom shear stress is reduced when water is flowing through stocks of submerged plants, thus organic particles preferably settle within, and in vicinity of macrophyte stands [4]. Such organic sediments act as semi-permanent nutrient sinks, for after the senescence of vegetation, resuspension increases. Therefore, sediments become sources of nutrients for the water body, if resuspension is faster than gross sedimentation. Further, nutrient input to water occurs via leaching from sediments.

Few studies have attempted to quantify the influence of macrophytes on sedimentation or resuspension in running waters. Madsen et al. [5] reported that macrophytes reduced flow velocity and increased sedimentation and retention by deposition. Svendsen et al. [6]...
found that retention by deposition amounted to 12% of total nutrient export in a lowland river system. The highest monthly retention occurred in summer and reached values of 25% of total phosphorus load. In the lower River Spree, retention processes have been investigated, but not quantified and related to total nutrient load, in the past. In the present study, we followed a comprehensive approach using different sedimentological and hydrological methods to evaluate the magnitude of retention processes evoked by the presence of the aquatic flora.

We intended to relate deposition and sedimentation to flow regime by deploying plate and cylindrical traps and measuring flow velocities. Trapping rates measured by plate traps, a term herein used as synonym for sedimentation rates, have not previously been compared with deposition rates determined by stratigraphic descriptions. Our key questions were:

- Are there regular and typical flow patterns in macrophyte stands dependent on species composition?
- Does sedimentation follow these flow structures?
- Is deposition related to the flow regime and/or to sedimentation?
- Does sediment nutrient content in vegetated areas differ according to the prevailing macrophyte species?

In addition, we aimed to quantify and compare sedimentation and deposition. Retention due to deposition was calculated for vegetated areas and extrapolated to the entire Müggelspree, a section of the lower River Spree.

2. Study site

The River Spree is a lowland river in Northern Germany originating in the Lusatian mountains (Saxony, Germany) and flowing for 380 km through several shallow lakes to Berlin [7]. We investigated a river stretch near the village of Freienbrink (13°48'E, 52°22'N, approximately 10 km upstream of Berlin, Fig. 1). The study site is part of the Müggelspree, a sixth-order section that extends from the outflow of the Oder-Spree Channel near Fürstenwalde to the village of

Fig. 1. Topographical map of the study site.
Neu Zittau, east of Berlin. The Müggelpree flows in a wide glacigenic valley. As a result of straightening in the 1970’s, the Müggelspree has a trapezoid channel profile with a mean slope of 0.015%, a mean water depth of 1.25 m, and a mean channel width of 25 m. Since 1998, discharge has ranged between 2.5 m³ s⁻¹ in summer and 30 m³ s⁻¹ in early spring. In the early 1990’s the lower River Spree changed from a turbid to a macrophyte-dominated state [8]. Shifting sand covers the midstream riverbed, whereas stable sand prevails in the lateral parts of the riverbed and is often colonised by macrophytes or mussels.

3. Materials and methods

On July 29, 2001, we made a detailed description of the spatial macrophyte distribution at the sampling locations in order to relate flow patterns and trapping rates to vegetation structures. For sampling and measurements, we chose macrophyte stands with 70–100% degree of area coverage.

On August 2 and 3, 2001, sediment traps were deployed at 15 locations in and around 3 macrophyte stands each consisting of one different species (Sagittaria sagittifolia (C. Linnaeus), Nuphar lutea (J. E. Smith) and Potamogeton pectinatus (C. Linnaeus)). Sediment traps were held in vertical quadratic tubes rammed into the river bottom, with each tube carrying one cylindrical and one plate trap 40 cm above the river bottom. A detailed description of the trap design is given by Kozerski and Leuschner (Fig. 2, [9]). Plate traps were developed to take into account the effects of the bottom shear stress, which influences sedimentation near the riverbed of running waters [3]. Plate traps approximate net sedimentation, whereas cylindrical traps measure gross sedimentation rates. Traps were deployed once for 12 h, and once for 6 h. At each trapping location, water samples were taken at the beginning and at the end of exposure to quantify particle concentrations. One part (approximately 100 ml) of the trapped material was filtered and dried to determine the trapping rates of particulate dry matter, and for analyses of total organic carbon (TOC) and total organic nitrogen (TON). The remaining part of the trapped material was kept frozen pending analyses for total phosphorus (TP). Flow velocities were measured at the trap locations and at additional positions in and adjacent to macrophyte stands. The locations of measurement were adapted to a grid of 2 m × 2 m in longitudinal and latitudinal direction. For the measurements carried out twice or three times at the beginning of the trap deployment, we used a Nautilus Sensa Z300 flow meter (Ott Hydrometrie), which is a magnetic inductive measuring device. Disturbances caused by the flow metre penetrating the vegetation were negligible, since we took care to avoid changes of the leaf distribution. Values were integrated over time intervals of 120 s. The total error was approximately 8.5%.

On July 30, 2001, sediment cores were taken at 15 locations in and adjacent to three macrophyte stands, each dominated by a different species (S. sagittifolia, N. lutea and P. pectinatus). After stratigraphic description of the sediments, two or three sub-samples were taken from the surface and from deeper strata of each core to analyse the substrates for TP, TON and TOC concentrations. Deposition was dedicated from the thickness of the surface organic layer. In addition, deposition was calculated using the trapping rates in plate traps.

For analysis of TON and TOC the sub-samples of the sediment cores were dried at 60 °C for 3 d, and then ground with an automatic Agate grinder for 15 min. Filters of trap and water samples and dried samples of the sediment cores were analysed for TON and TOC with a thermal conductivity measuring analyser (Vario EL, Elementar). Analyses for TP were conducted according to the standard procedures of the German Industries, DIN EN 1189.

In August 2000, a preliminary campaign was performed in the lower River Spree deploying sediment traps and measuring flow velocities at 32 locations. In addition to the studies in 2001, macrophyte stands of S. emersum (A. Rehmann) were investigated. The latter species only occurred with submerged streamlined leaves similar to those of S. sagittifolia. Trapping rates were

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Fig. 2. Scheme of the plate sediment trap [9]. The arrow marks the water flow. The measuring area is formed by the piston, which moves down before recovery of the trap to protect the entrapped materials against washing away during lifting.
determined according to the procedures described above.

Multiple regression analyses and significance tests were carried out taking flow velocities, seston concentrations and trapping rates of both campaigns in 2000 and 2001.

4. Results

We found dense vegetation at the shallow banks as well as in the centre of the river profile, where depth were high. Species composition varied depending on flow and light conditions. Stocks of *N. lutea* were abundant in quiescent and shadowed areas, whereas the other species were also growing in the pelagial region.

There were regular and typical flow patterns in the macrophyte stands that were dependent on macrophyte species. There was a considerable decrease of flow velocity within and downstream of a stand of *S. sagittifolia* (Fig. 3), but beside vegetation flow velocity was not decreased. The reduction of flow velocity was of the same order in all water layers, although flow velocity was highest at the water surface and lowest near to the river bottom. In a stand of *P. pectinatus*, the spatial distribution of flow velocity was similar to flow patterns in a stand of *S. sagittifolia*. In stands of *N. lutea* the largest decrease of flow velocity occurred at the water

![Flow direction diagram](image)

Fig. 3. Spatial distribution of flow velocities (cm s\(^{-1}\)) in and around a macrophyte stand of *S. sagittifolia*. 
Within another stock of *S. sagittifolia*, flow velocity was lowered to nearly zero (Fig. 4), and only 1% of total discharge flowed through the macrophyte stand. Water residence time within the stand was increased by a factor of 18 in comparison to the unvegetated area of the river. Water residence time was also significantly increased when comparing the macrophyte stand with the shallow left-hand bank. Measurements at other cross-sections showed that water residence time in macrophyte stands were significantly increased by factors between 2 and 18; the largest increases were observed in macrophyte stands, which were longitudinally extended up to more than hundred metres.

Cylindrical traps did not provide trapping rates varying significantly in dependency on their location,
indicating that in quiescence the concentration and settling velocity of suspended particles were of the same order of magnitude at all sites.

There were typical spatial distributions of trapping rates in plate traps, within and adjacent to macrophyte stands. We found a negative relationship between trapping rates in plate traps and flow velocities \((p < 0.19)\). In a stock of \(S.\ sagittifolia\) with great longitudinal extension, a gradient was evident from low trapping rates upstream \((17.5 \text{ g m}^{-2} \text{ d}^{-1})\) to high rates downstream \((47.5 \text{ g m}^{-2} \text{ d}^{-1})\). Trapping rates varied laterally in dependency on flow velocity. In contrast to the stand of \(S.\ sagittifolia\), trapping rates were high in the centre of a stock of \(N.\ lutea\) \((30 \text{ g m}^{-2} \text{ d}^{-1})\). Lower trapping rates were measured upstream, downstream and beside the stand. In a macrophyte stand mainly consisting of \(S.\ emersum\) trapping rates in the cylindrical traps were of the same order of magnitude \((\text{Fig. 5})\). Trapping rates in plate traps were related to flow velocities determined by the macrophytes. Trapping rates were high within the macrophyte stand, especially at the upstream margin of the vegetated area, where flow velocity was decreased. Trapping rates were low in plantless sectors, where flow velocities were high. In and around a macrophyte stand mainly consisting of \(P.\ pectinatus\) highest sedimentation rates were downstream of the plants, where flow velocities were decreased \((\text{Fig. 6})\). At a sampling position located only a few metres beside the macrophytes, in the centre of the river, trapping rates were significantly lower.

The correlation between flow velocities and trapping rates in plate traps for all locations was weak \((r^2 = 0.26)\). Concentrations of seston \((\text{dry weight l}^{-1})\) had a moderate impact on sedimentation \((r^2 = 0.39)\).
Significance was low ($p < 0.19$) for correlations between trapping rates in plate traps on the one hand, and flow velocities and seston concentrations on the other hand.

Particulate phosphorus, measured via plate traps ranged between 0.5 and 192 $\mu$g P m$^{-2}$ d$^{-1}$ demonstrating a high spatial heterogeneity of seston sedimentation. TON concentrations in seston and trapped material varied between 0.7%DW and 2.2%DW, and were significantly higher than in organic sediments at the river bottom.

Sediment core investigations indicate a similar stratigraphic pattern for the majority of depth profiles, in which three different sediment types were distinguished. Substrates deeper than 10 cm usually consisted of dark medium to coarse-grained sand. Above, we found layers consisting of fine to medium grained brownish sand. Within and adjacent to macrophyte stands a dark organic layer superimposed the sandy sediments. The thickness of the organic layer varied between 0.3 and 8 cm depending on the species of and the relative position to submerged macrophytes (Table 1). Within and downstream of vegetation the layer was thickest, beside vegetation it was thin to negligible. A singular longitudinal transect through the substrate of a N. lutea stand is shown (Fig. 7). In October 2001, a few weeks after the senescence and abrasion of submerged macrophytes, the organic surface layers had disappeared in the entire investigated river reach, except for dead-zones downstream of wood debris.

A deep organic surface layer was associated with high nutrient concentrations in the sediments. Concentrations of particulate phosphorus ranged from 0.03%DW to 0.08%DW in deeper strata and from 0.05%DW to 0.19%DW in organic surface layers. Particulate organic nitrogen concentrations were slightly higher in surface sediments (0.07%DW–0.46%DW) than in deeper sediments (0.03%DW–0.23%DW). Mean nutrient contents (g m$^{-2}$) varied with species composition of the macrophyte stands (Fig. 8), and were highest for the substrate of S. sagittifolia, intermediate for sediments of N. lutea and lowest for sediments of P. pectinatus.

In addition to observed deposition, deposition was calculated using measured trapping rates and assuming a water content of 80% and a density of 1.2 g cm$^{-3}$ for organic sediments. Calculated deposition accounted for only 15–49% of observed deposition (comparison based on 10 values).

Nutrient retention due to deposition was a major part of total nutrient retention. Calculations to quantify retention due to deposition assumed 30% for total vegetation coverage of the lower River Spree between Fürstenwalde and Neu Zittau and that deposition of organic sediments mainly occurred during vegetation period, between May and September. Organic sediments were assumed to be totally eroded in the absence of vegetation cover. Retention of nitrogen and phosphorus in stands of different macrophyte species is given in Table 2. Calculated absolute nutrient retention was set into relation to nutrient load. During the vegetation period, the mean load-weighted monthly retention due

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Table 1

<table>
<thead>
<tr>
<th>Macrophyte species</th>
<th>Upstream</th>
<th>Within, upstream</th>
<th>Within, downstream</th>
<th>Beside, upstream</th>
<th>Beside, downstream</th>
<th>Downstream</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. sagittifolia</td>
<td>0.0</td>
<td>3.0</td>
<td>8.0</td>
<td>0.5</td>
<td>1.5</td>
<td>No data</td>
</tr>
<tr>
<td>N. lutea</td>
<td>0.5</td>
<td>1.5</td>
<td>2.5</td>
<td>1.0</td>
<td>No data</td>
<td>0.5</td>
</tr>
<tr>
<td>P. pectinatus</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>0.0</td>
<td>No data</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Values are based on singular core descriptions.
to deposition was 2.5% for nitrogen and 12.2% for phosphorus in the lower River Spree.

5. Discussion

In the lower River Spree, the abundance of macrophytes was scarcely restricted by physical parameters, such as water depth and flow velocity, since water depths were smaller than 1.2 m over the entire river profile and flow velocities ranged not higher than 30 cm s$^{-1}$. Therefore, we assume that at the study site, macrophytes changed environmental factors rather than adapting their growth to them.

Flow patterns followed the spatial distribution of plant biomass, a finding in agreement with Sand-Jensen and Petersen [10]. The shape of macrophytes strongly influences flow patterns in and adjacent to macrophyte stands. Species with streamlined leaves and uniform distribution of biomass throughout the entire water column ($S$. sagittifolia, $S$. emersum and $P$. pectinatus) cause an approximately 10-fold reduction of flow velocity at all water depths. The first two species belonged to the same ecotype, mainly growing in stocks and patches with streamlined submerged leaves. In stands of $N$. lutea, the decrease of flow velocity was highest at the water surface due to the fact that most leaves are floating upon the water surface.

Sedimentation rates were affected by flow patterns evoked by vegetation. Our results of high trapping rates downstream of vegetated areas agree with Tsujimoto [11], who predicted via a hydrodynamic model high sedimentation rates downstream of macrophyte stands. High sedimentation also occurred within macrophyte stands due to the fact that aquatic plants lower flow velocity and provide a low-energetic environment. Correlation between trapping rates and flow velocities was weak when the complete data set was taken into account reflecting the high temporal and spatial variability of the flow regime. Supply of seston is assumed to be an important factor determining trapping rates, for we found a mediocre relation between seston concentration and sedimentation. Therefore, we measured lower trapping rates within a macrophyte stand of $S$. emersum than at its upstream margins, where low current velocities coincided with high seston concentrations. Chambers and Prepas [12] also provided evidence for a combination of seston supply and flow-regime regulating sedimentation in running waters.

Figures at the surface of the riverbed reveal a better order of spatial distribution than trapping rates. Low flow velocities coincide with extended deposits of particulate organic matter within and downstream of macrophyte stocks. The presence of organic substrates can be attributed to the vegetation, which provides a low-energetic environment where organic seston can easily settle. On the other hand, it is possible that macrophytes directly contribute to the formation of organic sediments, but senescence started one month

Table 2
Mean monthly retention of nitrogen and phosphorus by deposition in stands of three macrophyte species during the vegetation period

<table>
<thead>
<tr>
<th>Macrophyte species</th>
<th>Nitrogen [g m$^{-2}$ month$^{-1}$]</th>
<th>Phosphorus [g m$^{-2}$ month$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagittaria sagittifolia</td>
<td>2.3 ± 0.9</td>
<td>1.5 ± 0.6</td>
</tr>
<tr>
<td>Nuphar lutea</td>
<td>1.6 ± 0.6</td>
<td>0.8 ± 0.3</td>
</tr>
<tr>
<td>Potamogeton pectinatus</td>
<td>1.4 ± 0.5</td>
<td>0.8 ± 0.3</td>
</tr>
</tbody>
</table>

Fig. 8. Carbon, nitrogen and phosphorus content (g m$^{-2}$) in the sediment beneath stands of three macrophyte species. Mean and standard error are presented.
after our studies. We also could not observe abundant leaves or stems in the organic layers, which mainly consisted of dark organic aggregates. Furthermore, TON concentrations were significantly higher in seston and trapped material than in sediments, indicating higher sedimentation rates of inorganic than of organic particles. The concentration pattern would be different from our results, if macrophytes considerably contributed to the formation of organic sediments.

The difference between measured and calculated deposition of up to 83% becomes larger when considering permanent resuspension and compaction of sediments. The difference can be explained by several factors. Our assumed water content of 80% for organic sediments may have been too low, although preliminary studies provided such data of water content. Sediment concentration may have been lower than usual during vegetation period. Seston concentrations significantly vary between seasons and are usually low in August, when we deployed sediment traps. Organic layers in greater sediment depths of river substrates, indicate incomplete erosion of organic substrates during autumn and winter. Nevertheless, the surface organic layer had disappeared short time after the senescence and abrasion of macrophytes, in October 2001.

In the literature, macrophytes are discussed as temporary nutrient sinks [13,14], Wanner and Pusch [15] found stocks of macrophytes to be highly effective retentive structures for suspended matter during the vegetation period. As demonstrated in Fig. 6, nutrient content in sediment, and therefore, nutrient retention due to deposition are dependent on the composition of plant species. On the one hand, flow patterns, sedimentation and therefore retention due to deposition are dependent on the shape of macrophytes. On the other hand, breakdown of organic matter and leaching of nutrients from the sediments decrease nutrient retention. After senescence or sedimentation, decomposition and diagenesis is regulated by the quality of dead particulate organic matter [16].

In summer, total load-weighted phosphorus retention reaches up to 25% per month in the lower River Spree, based on daily monitoring of discharge and weekly to biweekly monitoring of TP concentration. Therefore, a retention of 12.2% of phosphorus due to deposition is a reasonable value. Nitrogen losses mainly occurred by denitrification, as was found in a Danish lowland river [17]. In addition, Svendsen and Kronvang calculated a nitrogen export of 6.4% and a phosphorus export of 65% caused by a storm event. Our results concerning nutrient retention by deposition show a similar relation as described by Svendsen and Kronvang. In comparison, nutrient retention due to biomass uptake and following deposition of plant matter is of little importance, as evidenced by Körner [18].

Overall, sedimentation and deposition followed regular flow patterns caused by the fluvial vegetation, and deposition is the major process causing phosphorus retention in the lower River Spree. Macrophytes are important retentive structures enhancing sedimentation and water residence time.

6. Conclusions

Macrophytes significantly reduced flow velocities, and therefore improved conditions for the settlement of organic seston. Sedimentation corresponded to flow velocity and supply of seston. The spatial distribution of deposition followed the flow regime. Sedimentation and deposition were of the same order. Differences between calculated and observed deposition can be explained by a high temporal and spatial variability of sedimentological parameters, such as seston concentration.

Macrophytes cause a considerable nutrient retention by reinforcing sedimentation of organic seston. The retention by deposition was dependent on the species composition of macrophyte stands. For the lower River Spree, mean load-weighted phosphorus retention and nitrogen retention were 12.2% and 2.5%, respectively. Deposition is the major process, which causes phosphorus retention in the lower River Spree.

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