Retention of particulate matter by macrophytes in a first-order stream

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Abstract

Retention of coarse particulate organic matter (CPOM) in streams is affected by channel complexity, especially three-dimensional structures in stream channels. Much attention has focused on woody debris as retention structures, but macrophytes should function similarly. Retention and flow characteristics were measured in 5 m long reaches at four-replicate sites in the Breitenbach (Hessen, Germany). CPOM retention was measured by releasing chips of paper (6 mm diameter) as analog CPOM. Triplicate releases (200 chips each) were done before and after submerged, emergent and overhanging macrophytes were removed. Discharge ranged between 3 and 4.5 l s⁻¹ during the experimental releases. Macrophyte biomass removed was 3.047, 3.012, 0.164, and 1.392 kg m⁻² (fresh weight) respectively from sites 1 to 4. Instantaneous retention rates, calculated with an exponential decay function, were significantly higher (P < 0.001) with macrophytes than without macrophytes (0.8 ± 0.2 versus 0.2 ± 0.1). Velocity also was significantly reduced by macrophyte presence (P < 0.001). Macrophyte biomass was a significant predictor of retention (P < 0.001), whereas discharge was not (P = 0.3). Hence, retention appears to be positively related to macrophyte biomass. Macrophytes in the Breitenbach increase retention by forming effective sieve-like structures in the stream physically trapping CPOM and by reducing water velocity.

Keywords: Streams; Retention; Macrophytes; Organic matter; CPOM

1. Introduction

Retention of particulate matter plays a central role in a number of stream processes. For example, course particulate organic matter (CPOM) generally is available to shredders only after it is retained in the benthic zone (Dawson, 1980). The concept of nutrient spiraling...
depends on retention of dissolved nutrients in certain zones (Fisher et al., 1998). Particle retention in streams is a physical phenomenon, and thus is influenced in part by flow conditions and the size of the particle being retained. Stream discharge affects retention such that increases in discharge often are associated with reductions in retention within the channel of low-order streams (Bilby and Likens, 1980). In larger rivers, floodplain retention of sediments during peak discharge increases due to trapping by floodplain vegetation (Asselman and Middelkoop, 1998). Larger-sized particles typically are retained more effectively than smaller-sized particles (Erman and Lamberti, 1992). The three-dimensional characteristics of the stream channel (i.e., channel complexity) also affects retention.

The presence of plants and plant material in and along the stream channel can greatly enhance retention by increasing channel complexity. Large woody debris increases surface area that physically traps particulate matter (Diez et al., 2000), and is a major retention structure in smaller-order streams (Allan, 1995). Non-woody vegetation may be equally important. Streams with little or no riparian canopy (i.e., trees) often exhibit increased herbaceous plant biomass in and along the channel (Friedman and Lee, 2002). These riparian plants can create a sieve-like matrix in the water column, when they are suspended into the stream channel. Additionally, emergent and submerged macrophytes in the stream channel influence flow characteristics and retention. For example, flow velocities decreased substantially in beds of macrophytes compared to reaches outside of macrophyte beds (Gregg and Rose, 1982; Sand-Jensen and Mebus, 1996). Decreased velocities and the additional surface area in the channel created by macrophytes should increase particle retention.

The effects of macrophytes on small-scale flow characteristics and on coarse particulate organic matter retention were tested experimentally in a small stream lacking substantial woody riparian vegetation. In previous studies concerning hydrodynamic characteristics (Sand-Jensen and Mebus, 1996; Sand-Jensen and Pedersen, 1999), retention was compared between stream sections with macrophyte beds and open stream sections. Comparisons between stream reaches can confound interpretation because different sections can have different channel morphologies, and thus hydraulics, that would influence flow characteristics. The present study has a different approach in conducting with- and without-macrophyte trials in the same stream reaches, in effect comparing macrophyte effects within a reach.

2. Study area and methods

The study was conducted in the Breitenbach, a first-order stream in central Germany (9°39′E, 51°39′N). The stream originates from springs and flows about 4 km until it empties into the Fulda River. The valley is bordered by both hard and soft wood trees, and the valley floor is mostly under grass. These floodplain meadows are harvested twice a year, although the riparian vegetation is left untouched for at least 1 m laterally along the stream course. Beech trees are few but grow scattered along the stream bank. A detailed description of the stream can be found in Marxsen et al. (1997). Riparian herbaceous vegetation along this untouched zone has a biomass of about 0.350 kg AFDW m$^{-2}$ during summer and early fall and many of the plants hang into the stream. Emergent and submerged macrophytes also are present in the stream during much of the year (see Section 3 for biomass), and together with the overhanging vegetation, occupy a large proportion of the stream’s water column.
Experimental retention measurements were made using experimentally released particles at four different sites in the stream, each site being done on a separate day (17 September 1998 (site 1), 21 September 1998 (site 4), 22 September 1998 (site 2) and 23 September 1998 (site 3)). At each site, a 5 m long stream reach was mapped to note vegetation and other three-dimensional obstructions. The reach at site 1 was straight with dense patches of *Myosotis palustris* within the stream channel, and many *Juncus effusus* L. and other *Juncus* spp. leaves hanging in from both sides of the bank. The reach at site 2 was slightly sinuous, and the stream channel was clear of rooted macrophytes. Small riffles were present within the first meter and again in the third meter of the reach. Riparian plants (*Filipendula ulmaria* L. and grasses) were hanging in along the entire reach, but were most dense within the first 2 m of the reach. Site 3 was a straight reach, and macrophytes were patchy, with sparse patches of *M. palustris* and *Cardamine* sp. throughout the reach. *Sparganium erectum* L. was also abundant especially near the end of the reach. *Juncus* spp. were hanging into the stream along the entire reach, and a dense patch of rooted and overhanging macrophytes was present at the very end of the reach. The reach at site 4 had a slight bend in the channel and macrophytes were patchy. *M. palustris* was heavy on the inside of the bend, whereas the outside of the bend was free of macrophytes in the channel. However, grasses were hanging into the stream from the outside bend’s riparian area. A dense bed of *M. palustris* was present across the channel within the last meter of the reach.

Before any flow or retention measurements were made, a piece of window screen (1 mm mesh) was secured at 0.5 m downstream of the 5 m experimental reach to collect released particles. This placement was intended to minimize the screen influence on flow within the experimental reach. The screen was cleaned frequently during experiments to prevent clogging, which would have influenced flow. At each site, five transects were established at 1 m intervals, and each transect was divided laterally into five subsections. At subsections within each transect, water velocity measurements were taken just below the surface, at 0.6 depth and near the streambed, with a MiniAir2 velocity meter (Schlitknecht Messtechnik AG) with a MiniWater2 micro propeller (10 mm diameter) that gave an average velocity reading over a 10 s interval. The propeller is enclosed within a protective tube, which prevents the propeller from becoming entangled or otherwise hindered by macrophytes, thus avoiding problems outlined by Machata-Wenninger and Janauer (1991). Wetted-channel width was measured after removal of the vegetation (see below) because macrophytes made it difficult to see the channel boundaries. Discharge was measured continuously at a weir approximately 30 m upstream of the furthest upstream experimental reach to monitor mean stream discharge.

Uniform round chips (6 mm diameter) were made from colored and white copier paper (80 g m$^{-2}$, Sky Rainbow Paper, G. Schneider and Soehne); colors were used to distinguish triplicate releases. Personal observations indicate that coarse particles transported in the Breitenbach can be as large as whole leaves of oaks (*Quercus* spp.) or as small as 1 mm, the lower size-limit for CPOM (Cummings, 1974). The 6 mm chips are intermediate in size and can be considered representative. These chips were soaked in water 24 h prior to release to achieve neutral buoyancy. At site 1, white chips were found to be negatively buoyant when soaked for 24 h, and thus were wetted just prior to subsequent releases to achieve neutral buoyancy. Chips ($n = 200$) were released uniformly across the wetted-channel. After 1 h, chips that had been caught in the window screen were collected and later counted. After
three releases had been made over a 3 h period, all the macrophytes in the water column were carefully removed and later weighed to obtain fresh weight. Only the submerged parts of emergent and riparian plants were collected, whereas all submerged macrophytes were removed. Larger detritus particles, such as twigs and plant material already lying on the streambed, were left in place. Some smaller material was transported out of the reach after macrophyte removal. Velocity was measured again along transects, just as above, but now after removal of the macrophytes. Chips of the same color but with a small pencil mark on the paper were then released ($n = 3$ releases) and collected as above.

Generally, a curve describing the retention efficiency of a stream is generated by collecting the released particles and noting the distance from the release point they traveled before being retained (e.g., Lamberti and Gregory (1996)). However, this was too difficult in the present experiments because the particles were small and the stream channel too complex to locate all the particles without disturbing or dislodging other particles, or disturbing the stream before subsequent releases. Therefore, I modeled retention based on the negative exponential decay equation using the number of released particles and the number of collected particles at the end of the measured stretch of stream, which is commonly done (Diez et al., 2000; Erman and Lamberti, 1992; Speaker et al., 1984). The negative exponential model is $P_d = P_0 e^{-kd}$, where $P_d$ is the number of chips caught in the screen, $P_0$ the number of chips released, $-k$ the slope or instantaneous retention rate, and $d$ the length of the experimental stream reach (5 m). The average distance traveled by a particle can be calculated as the inverse of the slope (Young et al., 1978).

Differences in current velocities before and after macrophyte removal were compared using a split-plot ANOVA (Underwood, 1997). The mean of the latitudinal velocity measurements was used for each transect. The model considered the two treatment levels (with and without macrophytes; fixed factor), velocity measurements at the three depth positions (fixed factor), and the four sites (random factor), with the treatment being nested in site. A nested ANOVA design was used to test for differences in retention (Underwood, 1997), with the two treatment levels being nested in site. An outlier was identified from the studentized residual values generated from the ANOVA model. This outlier, the instantaneous retention value from the without-macrophyte release of the negatively buoyant white chips at site 1, was eliminated and the model rerun. Results suggested that the site factor was important, and I further tested the relationship between discharge and macrophyte biomass versus instantaneous retention using a multiple regression model. No statistical analysis was done on average transport distance because it is the inverse of the instantaneous retention. All statistical analyses were done using SYSTAT Version 9. I had to hand-calculate the $F$-ratio for the treatment factor in the nested analysis because SYSTAT treats both factors as fixed (Quinn and Keough, 2002), whilst site was a random factor here.

3. Results

Macrophyte biomass removed was 3.047, 3.012, 0.164, and 1.392 kg FW m$^{-2}$, respectively, at sites 1–4. At the time of the releases, deciduous leaves had begun to accumulate in the macrophyte patches, which likely affected particle retention. Deciduous leaf biomass was not included.
Mean daily discharge (L s\(^{-1}\) ±1S.E.) based on hourly means was 4.42 ± 0.06 for 17 September 1998, 4.01 ± 0.09 for 21 September 1998, 4.42 ± 0.10 for 22 September 1998, and 3.09 ± 0.11 for 23 September 1998. Comparing across dates, discharge was highest on 17 September due to a heavy rain throughout that morning. Mean hourly discharge varied during the releases but differences were minor between the macrophyte and without-macrophyte releases. The possible exception was on 23 September, when discharge decreased by over 1 L s\(^{-1}\) in a 2 h period (Fig. 1). However, this 2.42 L s\(^{-1}\) datum is suspect because the gage malfunctioned prior to it and because of the rapid decline.

Mean instantaneous retention rates were higher with macrophytes than without macrophytes (Fig. 2). The effect of the macrophyte removal significantly reduced retention; however, significant variation was also detected among the sites (Table 1). Based on the regression model, the different macrophyte biomass at sites appears to be contributing to the variation among sites, whereas discharge does not appear to be a significant factor (Fig. 3). Although the regression contains few data points, the relationship between

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum-of-squares</th>
<th>d.f.</th>
<th>Mean-square</th>
<th>F-ratio</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macrophyte</td>
<td>2.784</td>
<td>1</td>
<td>2.784</td>
<td>11.456</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Site (macrophyte)</td>
<td>1.456</td>
<td>6</td>
<td>0.243</td>
<td>40.117</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Error</td>
<td>0.091</td>
<td>15</td>
<td>0.006</td>
<td></td>
<td></td>
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</tbody>
</table>

The dependent variable was instantaneous retention. Macrophyte was the treatment with two levels: before and after removal. Experimental releases of CPOM analogs was done at four sites indicated by site (macrophyte). The F-ratio for macrophytes uses the site (macrophyte) mean-square because the site is considered a random factor (Quinn and Keough, 2002).
macrophyte biomass and instantaneous retention rate appears to be linear (Fig. 3). Similarly, the average transport distance was longer without macrophytes than with macrophytes, with the average particle transport distance being about 10× longer without macrophytes than with macrophytes.

Presence of macrophytes significantly reduced the current velocity (Table 2). The interaction terms of the model were not significant, but the variation among site was significant.
Table 2
Results of a split-plot ANOVA

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum-of-squares</th>
<th>d.f.</th>
<th>Mean-square</th>
<th>F-ratio</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macrophyte</td>
<td>0.018</td>
<td>1</td>
<td>0.018</td>
<td>15.534</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Depth</td>
<td>0.022</td>
<td>2</td>
<td>0.011</td>
<td>9.404</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Macrophyte × depth</td>
<td>0.001</td>
<td>2</td>
<td>&lt;0.001</td>
<td>0.396</td>
<td>0.674</td>
</tr>
<tr>
<td>Site (macrophyte)</td>
<td>0.077</td>
<td>6</td>
<td>0.013</td>
<td>10.847</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Depth × site (macrophyte)</td>
<td>0.008</td>
<td>12</td>
<td>0.001</td>
<td>0.531</td>
<td>0.890</td>
</tr>
<tr>
<td>Error</td>
<td>0.114</td>
<td>96</td>
<td>0.001</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The dependent variable was current velocity. Macrophyte was the treatment with two levels: before and after removal. Depth was the position of the velocity measurement in the water column and had three levels: surface, mid-depth, near streambed. Four sites were sampled and the treatment was nested within these four sites, indicated by site (macrophyte).

(Table 2). As was the case with retention, differences in macrophyte biomass among sites likely were contributing to this variation. Depth also was significant in the model. The near-bed depth velocity was consistently lower than the other two positions, which was expected because of friction at the streambed (Fig. 4). Surface and mid-depth velocities were similar.

![Graph](image-url) Fig. 4. Means from velocity measurements taken at various depths in the Breitenbach. Bars are means of five transects at each site, and error bars are ±1S.E. Five measurements were made at each transect to encompass the full width of the channel.
4. Discussion

One drawback of using analog particles is relevance to the natural conditions. Except for the first trial using the white chips, which were strongly negatively buoyant, the chips released were neutrally buoyant, and were transported similarly to other natural pieces of CPOM observed in the Breitenbach. In contrast to transport when macrophytes were present, chips saltated along the stream bottom after macrophytes were removed. Retention of CPOM was increased by the macrophytes rooted in the stream channel and the riparian plants hanging into the stream. Removing macrophytes, but leaving the stream channel otherwise the same, allowed CPOM to travel further downstream than with macrophytes present. Also, few chips were retained in areas where no macrophytes were present, such as the riffle area at site 2. The relationship between instantaneous retention rate and macrophyte biomass equally suggests that the macrophytes are major retentive structures in the Breitenbach. Instantaneous retention in tributaries to Tinker Creek (Georgia, USA) ranged from 0.012 to 0.025 when macrophytes were present in autumn (Koetsier and McArthur, 2000). In contrast, the Breitenbach is a moderate-gradient stream (3.1%). Despite the higher gradient in the Breitenbach (3.1% versus about 0.2%), the average distance traveled was about 1.6 m, which is much less than in other experimental releases (Koetsier and McArthur, 2000). Thus, macrophytes may be more important in CPOM retention in the Breitenbach than in other streams.

Although I did not account for differences in plant architecture and its effects on flow characteristics or retention (Sand-Jensen and Mebus, 1996), it probably was an important factor. The dominant plant species in most reaches, *M. palustris*, can form dense beds in the channel. *M. palustris* have long stems that become entangled among individual plants, and many leaves. In dense patches, *M. palustris* forms a very effective sieve-like structure in the stream. Based on my qualitative observations of where chips were retained, *M. palustris* was more effective at retaining CPOM than other plant species in the channel. Stalk-type emergent species, such as *Sparganium erectum*, and species that did not form dense patches (e.g., *Sium erectum* Huds.) appeared less effective at trapping the particles.

Macrophyte biomass in and along the Breitenbach is substantial. From the experimental sites, macrophyte biomass was as high as 3 kg FW m$^{-2}$ and averaged almost 2 kg m$^{-2}$ across all sites. Most similar studies do not give the biomass of the macrophytes in the stream or experimental channel (e.g., Gregg and Rose (1982)). Sand-Jensen and Mebus (1996) had about 200 g DW m$^{-2}$ standing biomass. If I convert fresh weight to a dry weight (unpublished regression data), then I removed about 180 g DW m$^{-2}$. Koetsier and McArthur (2000) removed around 25 g AFDW m$^{-2}$ of *Sparganium americanum* Nutt. from a stream. Breitenbach regression data are not strong enough to make the fresh weight to AFDW conversion, which makes quantitative comparisons difficult. Still, it seems justified that the Breitenbach had dense stands of vegetation and may represent a retention estimate in the upper range.

Macrophytes were not the only plant biomass in the Breitenbach. Deciduous leaves blown in from the stream margins also accumulated in large numbers, although
their distribution also was very patchy. Deciduous leaves tended to accumulate in areas where emergent and submerged macrophytes were present. I only considered the macrophyte biomass in the analyses, and ignored the biomass of deciduous leaves that had been trapped in the macrophytes at each site. These leaves no doubt contributed to the three-dimensional structure in the reaches, and thus to the retention of particles. Without considering this biomass, I likely am overestimating the retentive properties of the macrophytes alone. However, the macrophytes are certainly essential in initially trapping the deciduous leaves.

In addition to physically trapping particles, macrophytes can reduce the velocity enough to have particles settle out of suspension, thus also increasing retention. Macrophytes reduced the current velocity in the Breitenbach and increased retention of the CPOM released. Other studies have also documented the effects of macrophytes on certain hydraulic characteristics. Changes in bed roughness were associated with seasonal changes in macrophyte biomass, with reduced roughness being associated with times when few macrophytes were present (Dawson and Robinson, 1984). Sand-Jensen and Mebus (1996) found significantly lower flow velocities within patches of macrophytes, and this reduction was both species dependent and biomass dependent. Gregg and Rose (1982) also found reduced velocities in experimentally placed macrophyte beds, but the biomass of plants influenced velocity for only one of two species tested. However, they also recorded increased velocity above the plants as water was “raced” over the macrophyte-bed canopy (Gregg and Rose, 1982). My measurements were not as detailed as other studies (e.g., Sand-Jensen and Mebus (1996), Sand-Jensen and Pedersen (1999)), which makes more rigorous comparisons difficult.

The Breitenbach has experienced a noticeable increase in submerged and emergent macrophytes in the few years leading to this study (Peter Zwick, personal communication, 1997). These changes may have long-term implications for the stream. The role of macrophytes in particle retention creates a positive feedback loop in this stream. For example, if a few macrophyte beds are allowed to establish, they act to trap and stabilize the bottom sediments and particles such as sands, silts and organic matter. Gregg and Rose (1982) measured increased organic matter accumulation in macrophyte beds compared to no-macrophyte controls. These deposited sediments then increase the available area for more macrophytes to take root, which in turn increases sediment deposition. This study was very short-term, so I most probably missed potential long-term effects of macrophytes in the Breitenbach. Long-term changes in streams caused by macrophyte removal includes noticeable increases in depth, velocity and subsequent changes in discharge (Hearne and Armitage, 1993). Analogously, increasing macrophyte biomass in the Breitenbach may cause opposite changes.

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References


