The Impact of Anthropogenic Channel Alteration on the Retention of Particulate Organic Matter (POM) in the Third-Order River Ilm, Germany

Dissertation

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Dedication

To my
FATHER (1939-2002)

Für
meinen
VATER (1939-2002)

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1. Introduction – Organic Matter in Stream Ecosystems

Streams are open ecosystems (Fisher and Likens, 1973). They intensively exchange energy and matter with adjacent terrestrial ecosystems. This linkage is highly influenced by climate, stream catchment features and by the hydrological and geomorphological conditions of the stream channel itself. The River Continuum Concept (RCC; Vannote *et al.*, 1980) describes lotic ecosystems as continuous gradients of physical conditions. The structural and functional characteristics of the stream community conform to the most probable abiotic state at any point along the stream continuum (Vannote *et al.*, 1980). Many headwater streams are strongly influenced by riparian vegetation, that reduces in-stream autotrophic production by shading and contributes large amounts of allochthonous detritus (Vannote *et al.*, 1980). Various abiotic and biotic processes (see Pusch *et al.*, 1998 for review) delay the downstream transport of autochthonous and allochthonous organic matter. This retention is caused by the interaction of the antagonistic process fixation and release of organic matter to and from the stream bed (Figure 1). The balance between these processes and the processing of the organic matter in the bed sediment determine the standing crop of organic matter in the benthic zone of streams (Figure 1).

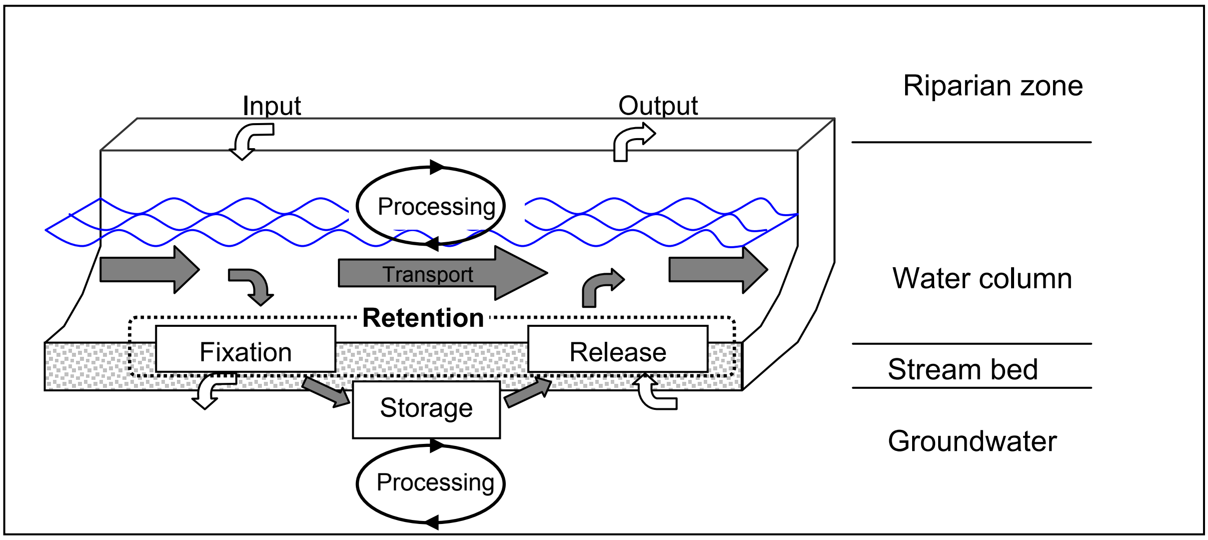


Figure 1: Schematic representation of the retention process of organic matter in stream ecosystems and the sub-processes involved (modified after Mutz, 1997).

Retention includes immediate trapping (short-term retention) and the subsequent long-term storage (long-term retention; Speaker *et al.*, 1984). The time scale for short-term retention is from seconds to minutes (Mutz, 1997) and describes retention in periods of constant in-stream conditions. The time scale for long-term retention is from weeks to years (Mutz, 1997) and considers effects of changing environmental factors (e.g. hydrology, sediment conditions).

The benthic organic matter (BOM) is a major energy source for secondary production in lotic ecosystems (Minshall, 1967). BOM provides habitat for pico-, nano, micro- and macrozoobenthos and fish (Jones, 1997 reference therein). In well-canopied headwater streams (first- to third-order) BOM consists mainly of coarse particulate organic matter (CPOM; particle size >1 mm) entering the stream mostly as leaf litter and dead wood (Fisher and Likens, 1973).

Thus the RCC (Vannote *et al.*, 1980) predicts shredding and collecting invertebrates as dominant functional feeding groups in headwater stream invertebrate communities. In addition to microbial activities, these shredders brake down large organic particles into smaller sizes. This biotic degradation of particulate organic matter follows an ordered series: rapid leaching of soluble components, colonisation of CPOM surfaces by microorganisms and protozoa, and finally the feeding on this preprocessed matter by shredding invertebrates (Cummins, 1974). With increasing stream size, autochthonous primary production and fine particulate organic matter (FPOM) supplied from the upstream reaches become important as energy sources for stream biota. Thus the RCC (Vannote *et al.*, 1980) predicts grazers and collectors dominating the macro-invertebrate assemblages further down stream (streams higher than third-order).

The strong linkage of any point in the stream with the upstream reaches results from the unidirectional water flow causing a permanent downstream transport of matter (Fisher and Likens, 1973). As emphasised in the nutrient spiralling concept (Wallace *et al.*, 1977; Webster and Patten, 1979; Newbold *et al.*, 1982), cycles of nutrients and organic matter are stretched into spirals due to the water flow. The spiralling length for nutrients is defined as the spatial distance that is required for a complete cycle through physical and biological components (Newbold *et al.*, 1982).

Carbon spiralling is more difficult to conceptualise because a permanent exchange of carbon dioxide occurs with the atmosphere at the water − air border. However, when limited to organic carbon, the spiralling length is applicable. An organic carbon atom that is produced in the stream or entering from terrestrial sources is transported a distance down stream, and passes through a number of ecosystem compartments before it is oxidised. Newbold *et al.* (1982) therefore suggest carbon turnover length as adequate measurement for the rate at which ecosystems utilize carbon relative to the rate of its downstream transport. If organic carbon is respired near the location of entry or fixation, turnover length is low. If it is lost rapidly from the local stream reach, turn over length is high.

Material spiralling and turnover is a function of physical and biological processes (Minshall *et al.*, 1983). Their gradients in the stream continuum (Vannote *et al.*, 1980) cause a gradient in turnover lengths along the stream. Headwater characteristics tend to result in long-term accumulation of organic matter (short turnover lengths); proceeding down stream, the system becomes more balanced with regard to its inputs (increasing turnover length; Minshall *et al.*, 1983).

In our anthropogenic formed landscapes, few streams maintained an undisturbed natural river continuum. The serial discontinuity concept of lotic ecosystems by Ward and Stanford (1983) considers alteration of local river regulation over the entire longitudinal stream profile. They point to predictable divergence of altered streams from the natural state in physical parameters and biological phenomena. Organic matter budgets and sediment composition are influenced as well (Thoms and Sheldon, 1997; Wood and Armitage, 1997). So far most studies dealing with impacts of stream channel alterations on the retention of particulate organic matter (POM) focus on large impoundments and their effects on the downstream reaches (e.g. Kimmel *et al.*, 1988; Palmer and Okeeffe, 1990; Perry and Perry, 1991). Few focuses on organic matter storage and transport in the altered stream sections itself and consider the impacts of smaller dams (Wanner *et al.*, 2002) or channel straightening (Petersen and Petersen, 1991; Haapala and Muotka, 1998).

The aim of the present thesis is to investigate the impacts of stream impoundment and channel straightening on organic matter retention in a regulated headwater stream in Germany. The third-order river Ilm, with its series of small impoundments and straightened sites, provided study sites with nearly homogeneous hydrological conditions but heterogeneous stream channel structure. The present thesis focuses on POM transport and storage (Figure 1). These processes both result directly from retention and were used for its quantification. The comparison of short- and long-term retention should reveal whether channel alterations affected both similarly or if time scale differences caused a divergence. Further the role of BOM processing on particle retention and the consequences of impoundment and straightening on the chemical and isotopic composition of BOM were considered. Determining the environmental variables that most affect in-stream retention should reveal major retention mechanisms and provide implications for river restoration.

2. Study Area

The Ilm is a third order (Strahler, 1957), hard water stream in Thuringia, Germany, with a catchment area of 1035 km^2 (Krey, 1995). The water quality can be classified as β-mesosaprobic. The Ilm is characterised by sequences of natural reaches and reaches strongly influenced by straightening or weir impoundments. Over its entire length of 137 km, 58 weirs disturb the natural continuum from the spring to the mouth. The weirs were built originally for water-power-use and more recently for river regulation. This situation is typical for many low mountain range streams in Germany. A 3 km long stream reach located in and nearby the town Stadtilm (11°05´ E, 50° 46´ N, 360 m a.s.l.; Figure 2) in the metarithric zone (slope: 7‰; Schönborn, 1996) contained three 200 m long study sites (Figure 3).

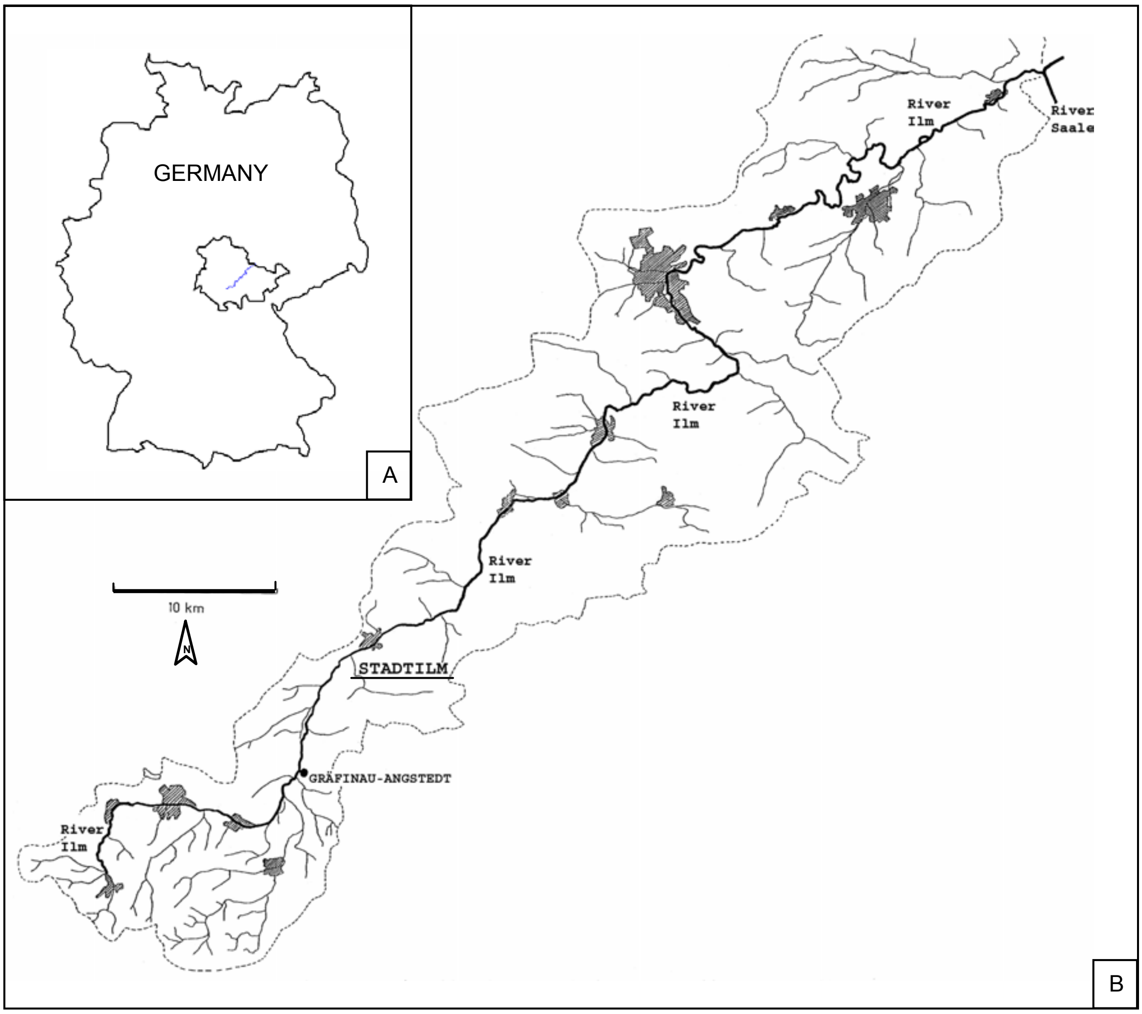


Figure 2: (A) Germany and Thuringia (black outline) with the river Ilm. (B) The Ilm and its catchment with the town Stadtilm where the studies were done.

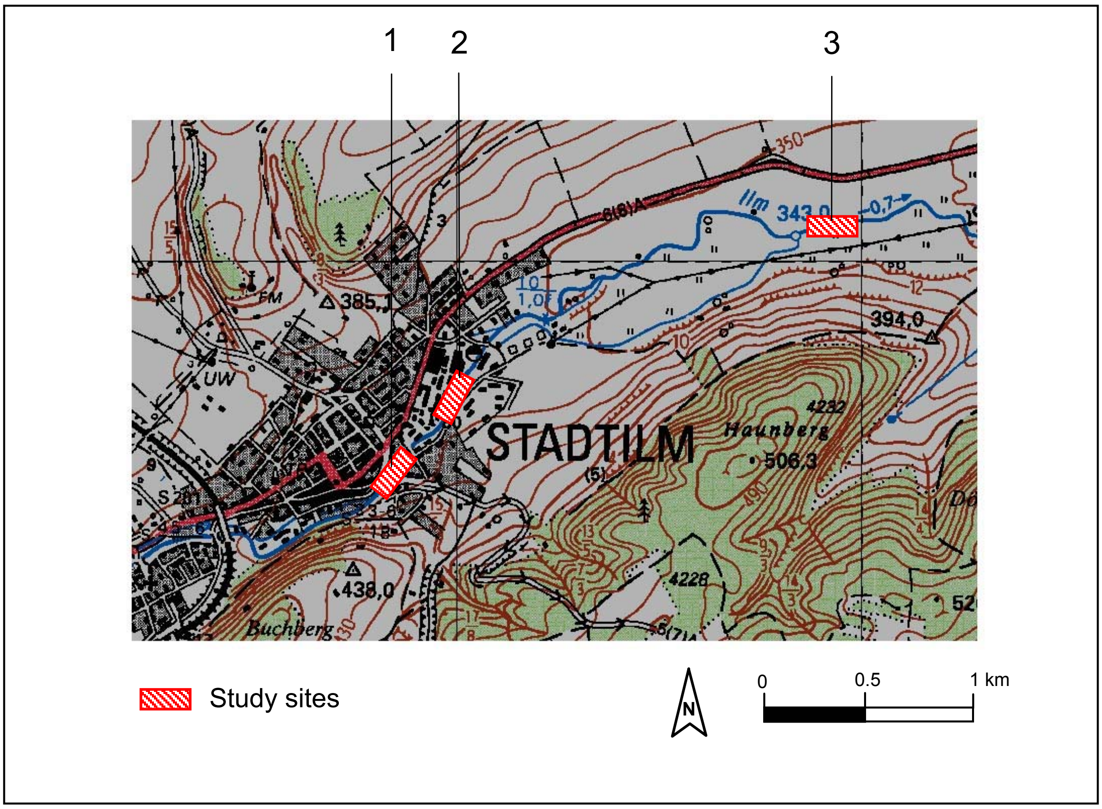


Figure 3: Map of the river Ilm reach containing the three study sites in and downstream of the town Stadtilm. From west to east: (1) impounded site, (2) straightened site and (3) natural reference site.

The first site was situated in an impoundment with reinforced banks (Figure 4) upstream of a 1.9 m high weir, the second in a 400 m long straightened stream section (Figure 5) with natural bed substrate but reinforced banks. Both were located in the town Stadtilm. The third site, almost 2 km downstream of the town, was the natural reference (Figure 6) with natural stream morphology. All sites were free of large debris dams and macrophyte stands. Riparian vegetation consisting mainly of alder (*Alnus glutinosa* L.), ash (*Fraxinus excelsior* L.), mapel (*Acer platanoides* L.) and willow (*Salix* spp.) covers the stream banks.

Figure 4:

Upstream view of the study site in the impounded Ilm section from the bridge in the town Stadtilm.

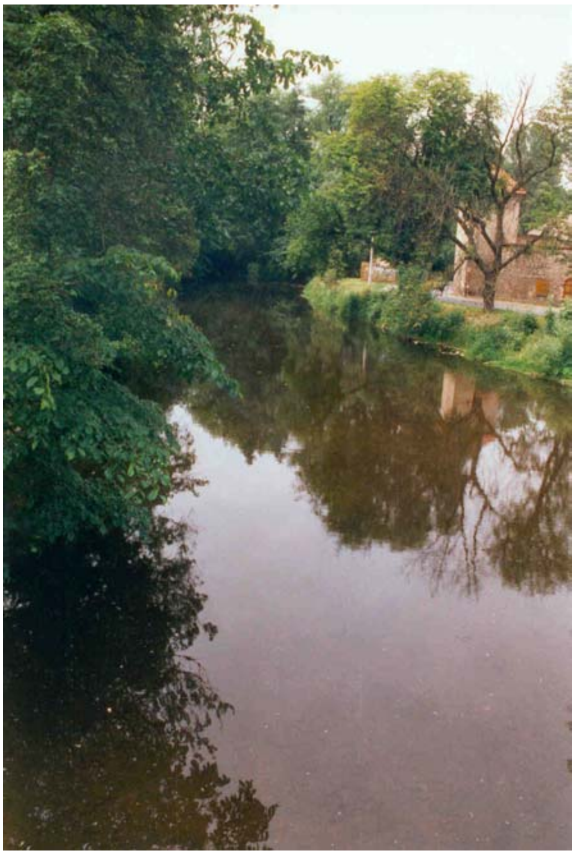


Figure 5:

Downstream view of the study site in the straightened Ilm section in the town Stadtilm.

Figure 6:

Upstream view of the study site in the natural reference section in the river Ilm, downstream of the town Stadtilm.

The absence of inflows in the entire reach containing the sites enabled us to exclude influences of hydrology on the results of the studies. Channel widths varied from 7.5 to 16.5 m. Discharge variations during the study period May 2000 to January 2001 were low after a spate at the end of winter (Figure 7). In other years, discharge is usually more variable during this time period. During the study period, the average discharge from the permanent gauge Gräfinau-Angstedt, 10 km upstream, was 1.134 $m^3 s^{-1}$ (±1.099, S.D.). During the end of winter, annual severe floods occur (Figure 7) with 10 to 20 times the base-flow discharge.

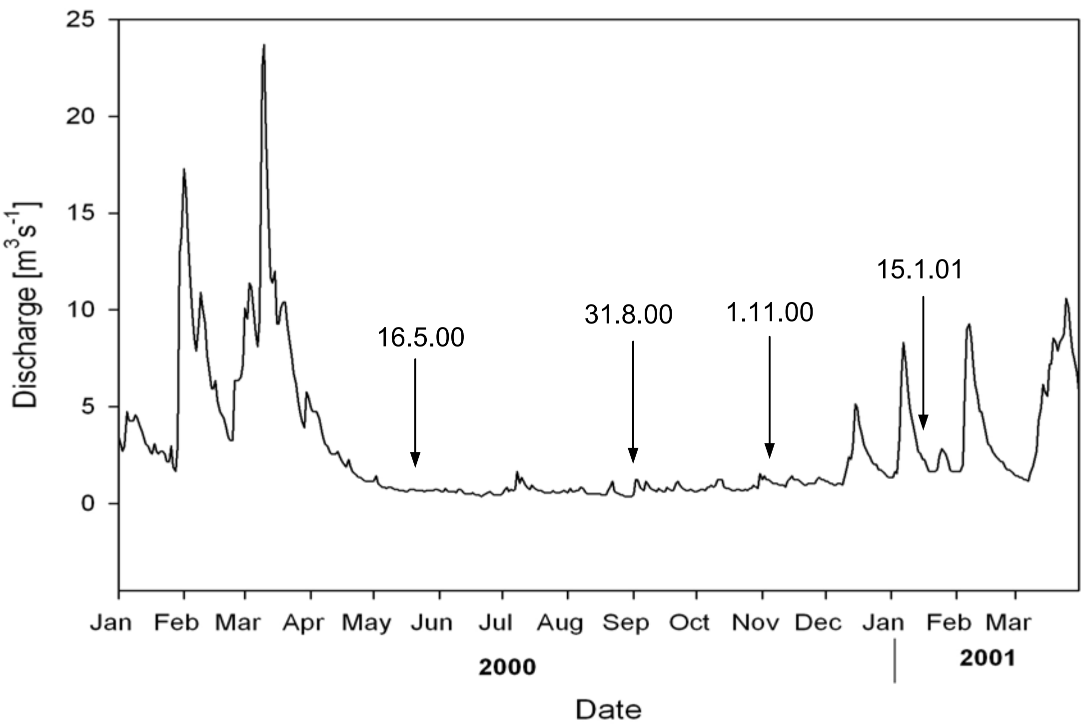


Figure 7: Discharge at the permanent gauge Gräfinau-Angstedt 10 km upstream from the study area from 1 January 2000, to 31 March 2001. Data provided by Umweltamt Erfurt (Erfurt Environmental Agency). Arrows indicate start dates of the four sampling studies for the benthic organic matter.

3. Geomorphologic and Hydrologic Parameters of the Studied Stream Sections

3.1 Introduction

Stream morphology determines a broad set of environmental variables affecting organic matter budgets of stream ecosystems. Thus the standing stock of benthic organic matter (BOM) in a stream reach is not only influenced by the suspended matter load, but also by the local physical and morphological conditions (Newbold, 1992).

Environmental variables constant on a large spatial scale, such as macro climate, general stream catchment features and hydrological conditions, can be assumed to be almost identical for the entire 3 km study reach in the river Ilm. However, different kinds and intensities of human impact on the stream channels (Chapter 2) certainly cause differing physical, small-scale morphological and small-scale hydrological conditions in the three single study sites.

A broad set of environmental variables was measured to characterise these local channel specifics and their consequences for in-stream conditions. This formed the base value upon which we were able to elucidate the effect of channel morphology on retention of particulate organic matter (POM) discussed in Chapter 5 and the following.

3.2 Methods

In a 40 m long stream reach at each site, a 1 by 2 m grid was permanently installed to enable us to measure physical, morphological and bed sediment parameters at given points of the stream channel. The grids comprised the complete stream channel from bank to bank (Figure 8). The numbering of the poles (2 m distances) and points in the stream cross section (1 m distances) defined each cross point. From the 30th to the 31st of October 2001, stream depth and current velocities were measured at every second cross point of the grid both 100 mm above the sediment in the middle depth and 50 mm beneath the water surface. These data enabled channel characterisation and site comparisons during base-flow conditions (discharge at the permanent gauge Gräfinau-Angstedt 0.825 $m^3 s^{-1}$). Hydraulic retention was estimated by measuring the time period required for the concentration peak of an NaCl tracer to pass the 200 m-long study sites of each stream section. Using the mean depths and the corresponding channel positions, we computed a cross section representing the average cross profile of each site and estimated their average hydraulic radius (Gore, 1996).

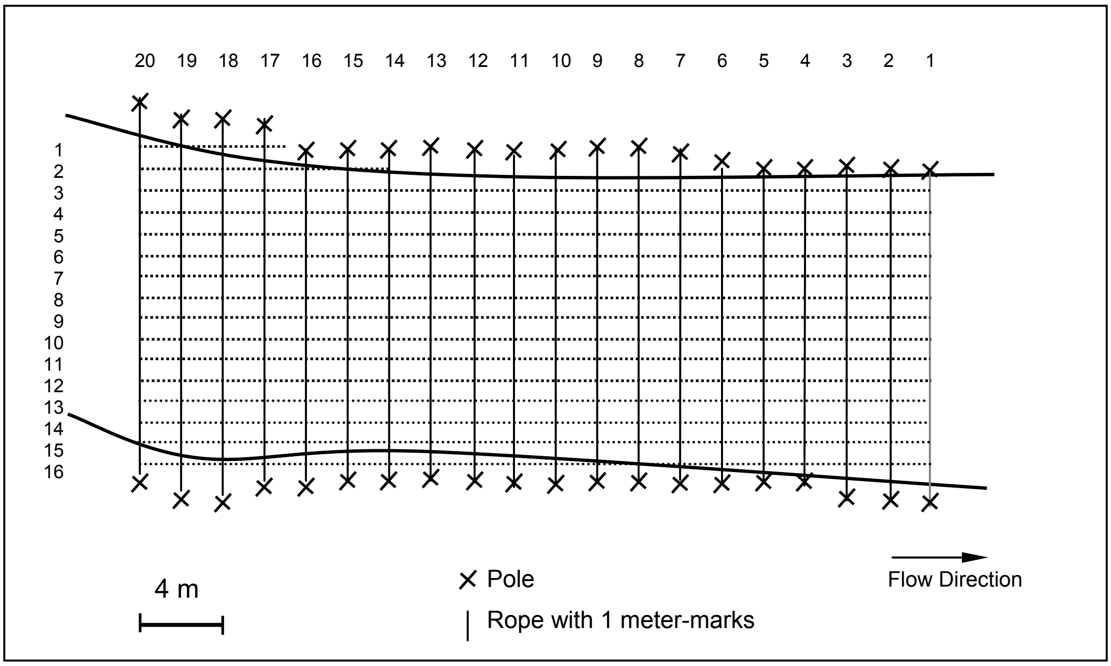


Figure 8: Schematic view of the permanent grid in the impoundment. Ropes were stretched between wooden poles set every 2 m along each bank side. The cells of the grid were 1 m in the cross-section by 2 m along the stream. Measurements and sampling of benthic organic matter (BOM) was done at cross points of the grid.

The sinuosity index, the ratio of the actual channel length to the linear 200 m distance (Moss, 1998), provided estimates for the channel sinuosity of the local stream section. Overhead covers from riparian vegetation in each site were estimated visually on 16 June 2000. During the sampling of BOM, depth and current velocity 100 mm above sediment surface were measured by a Flo-Mate 2000 (Marsh-McBirney Inc., USA) at each sediment sampling point.

For assessing the distribution of substrate types at these points, choriotope-types (Moog, 1994) were used to visually classify the surface sediments. The classification by choriotope-types as suggested by Moog (1994) provides a high resolution in coarse substrates and is therefore more precise than the texture triangle (Gordon *et al.*, 1992). By the relative proportions of the choriotope-types, a choriotope-type index was computed expressing the average substrate type. A high choriotope-type index indicates coarse substrate.

The choriotope-type index (CIX) was computed by the following equation (1).

$$\mathrm{CIX} = \frac{1}{100\%} \cdot \sum_{i=1}^{m} CP_i \cdot CV_i \qquad (1)$$

m = number of choriotope-types (constant: m = 7) (Moog, 1994)
CP = percentage of the particular choriotope-type i [%]
CV = choriotope-value of the choriotope-type i
i = 1, 2, ...7 (Pelal = 1, Psammal = 2, Akal = 3, Mikrolithal = 4, Mesolithal = 5, Makrolithal = 6, Megalithal = 7)

Statistics

To test differences in mean current velocities, choriotope-type indices and depths between the sites, Mann-Whitney U-tests with adjusted significance level (three single comparisons with $p < 0.025$) were used. Data were neither normally distributed, nor did they show homogeneity of variance and were not adjustable with common transformation techniques. The described statistics were calculated with an SPSS computer package (SPSS Inc.).

3.3 Results

The values of overhead cover, hydraulic retention, hydraulic radius, sinuosity indices (Moss, 1998) and mean choriotope-type indices, water depth and mean current velocities in different depths of the three study sites are given in Table 1.

Table 1. Overhead cover, hydraulic radius, hydraulic retention in 200 m flow distance, sinuosity index (Moss, 1998) and means, standard deviation, minima and maxima of the choriotope-type index (CIX), the water depth and the absolute values of the current velocities, 50 mm beneath the water surface (1), in the middle depth (2) and 100 mm above the stream bed (3) in the three study sites. Depths and velocities were measured once at the 30th and 31st October 2001 during base-flow conditions (discharge at the permanent gauge Gräfinau-Angstedt 10 km upstream of the study sites 0.825 $m^3 s^{-1}$).

	Impounded site		**Straightened site**		**Natural site**	
	mean (±SD)	**min. / max.**	**mean (±SD)**	**min. / max.**	**mean (±SD)**	**min. / max.**
Current velocity 1 [m s^{-1}]	0.08 (±0.04)	0.0 / 0.15	0.46 (±0.26)	0.0 / 1.12	0.53 (±0.43)	0.001 / 1.57
Current velocity 2 [m s^{-1}]	0.07 (±0.03)	0.0 / 0.14	0.51 (±0.13)	0.12 / 0.80	0.45 (±0.36)	0.002 / 1.26
Current velocity 3 [m s^{-1}]	0.01 (±0.02)	0.0 / 0.1	0.24 (±0.16)	0.0 / 0.79	0.22 (±0.23)	0.001 / 1.32
Depth [m]	0.44 (±0.17)	- / 0.90	0.13 (±0.06)	- / 0.30	0.28 (±0.23)	- / 1.04
CIX	3.90 (±0.13)	3.6 / 4.1	5.04 (±0.21)	4.75 / 5.7	4.42 (±0.76)	2.00 / 5.20
Sinuosity index	1.02	-	1.01	-	1.35	-
Hydraulic radius [m]	0.36	-	0.1	-	0.14	-
Hydraulic retention [s]	1650	-	362	-	640	-
Overhead cover [%]	80	-	20	-	80	-

The mean water depth was highest in the impoundment and lowest in the straightened site (Mann-Whitney U-tests, $p < 0.025$, $n = 1424$; Table 1). The current velocities near the water surface ($n = 1028$) and in the middle depths ($n = 562$) were lower in the impoundment than in the other sites (Mann-Whitney U-tests, $p < 0.025$; Table 1). The straightened and natural site did not differ in these current velocities (Mann-Whitney U-tests, $p > 0.025$, Table 1). The current velocity 100 mm above the stream bed again was lowest in the impoundment but higher in the straightened than in the natural site (Mann-Whitney U-tests, $p < 0.025$, $n = 982$; Table 1). The size distribution of the mineral bed substrate expressed as choriotope-type index varied between all three sites. Compared to the natural reference, it was increased in the straightened site and decreased in the impoundment (Mann-Whitney U-tests, $p < 0.025$, $n = 180$; Table 1). Standard deviations of current velocities, water depths and choriotope-type indices were much higher in the reference than in the study sites in the structural altered stream sections. The spatial patterns of the water depths and current velocities in the three study sites are shown in Figures 9, 10 and 11.

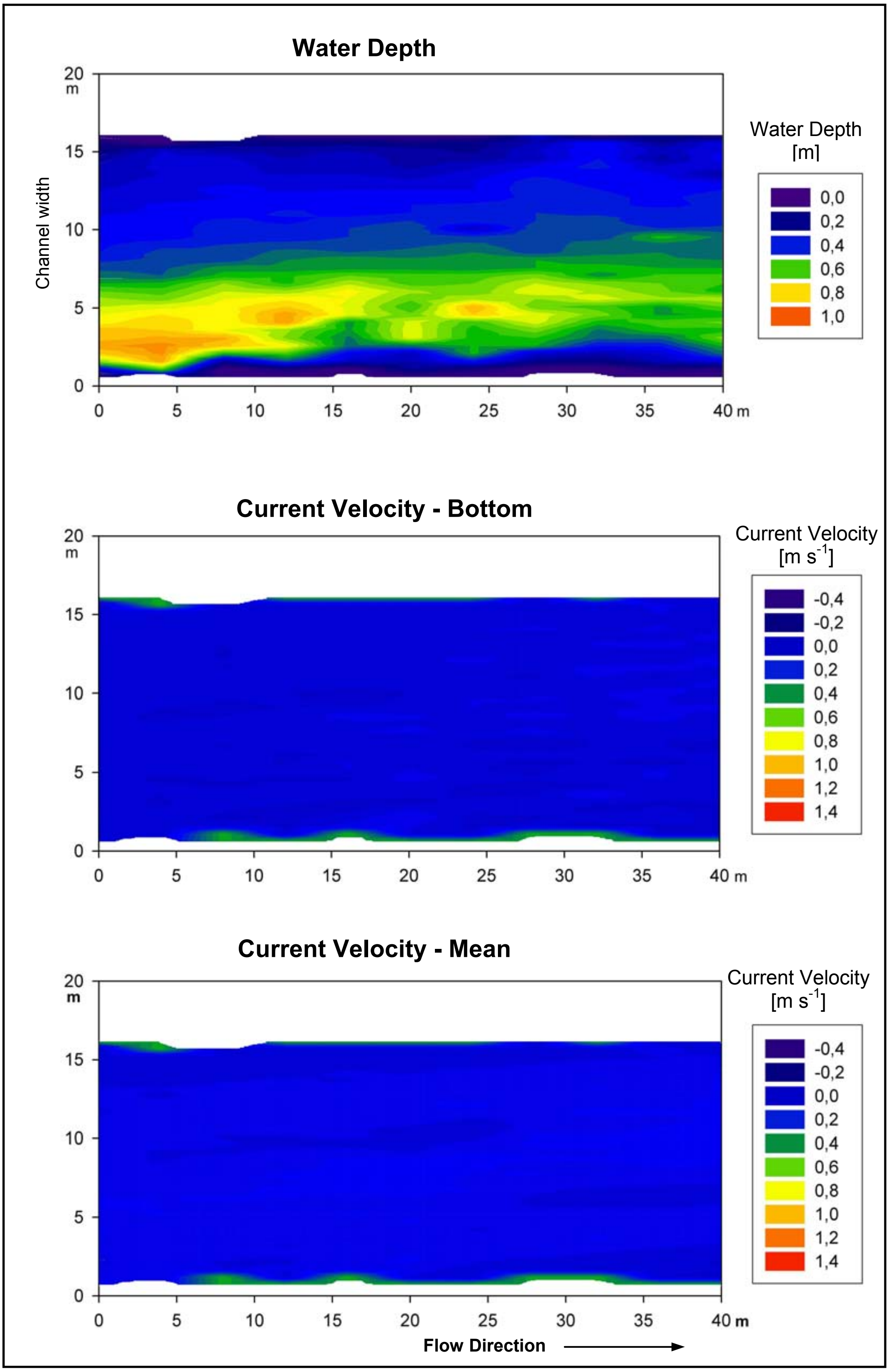


Figure 9: Water depths, current velocities 100 mm above stream bed and mean current velocities over the entire water depth in the 40 m-long stretch covered by the permanent grid in the impounded stream section in the river Ilm.

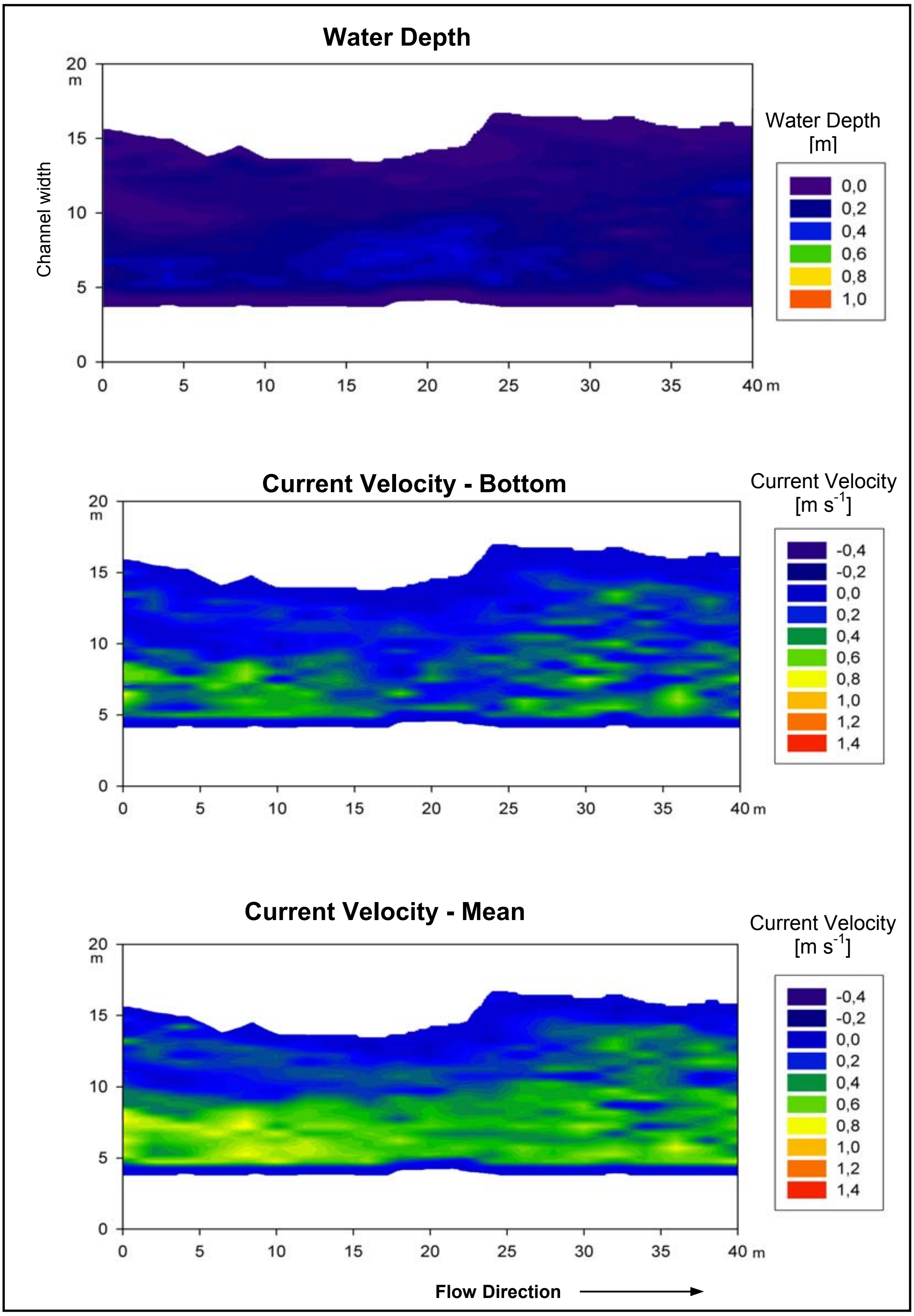


Figure 10: Water depths, current velocities 100 mm above stream bed and mean current velocities over the entire water depth in the 40 m-long stretch covered by the permanent grid in the straightened stream section in the river Ilm.

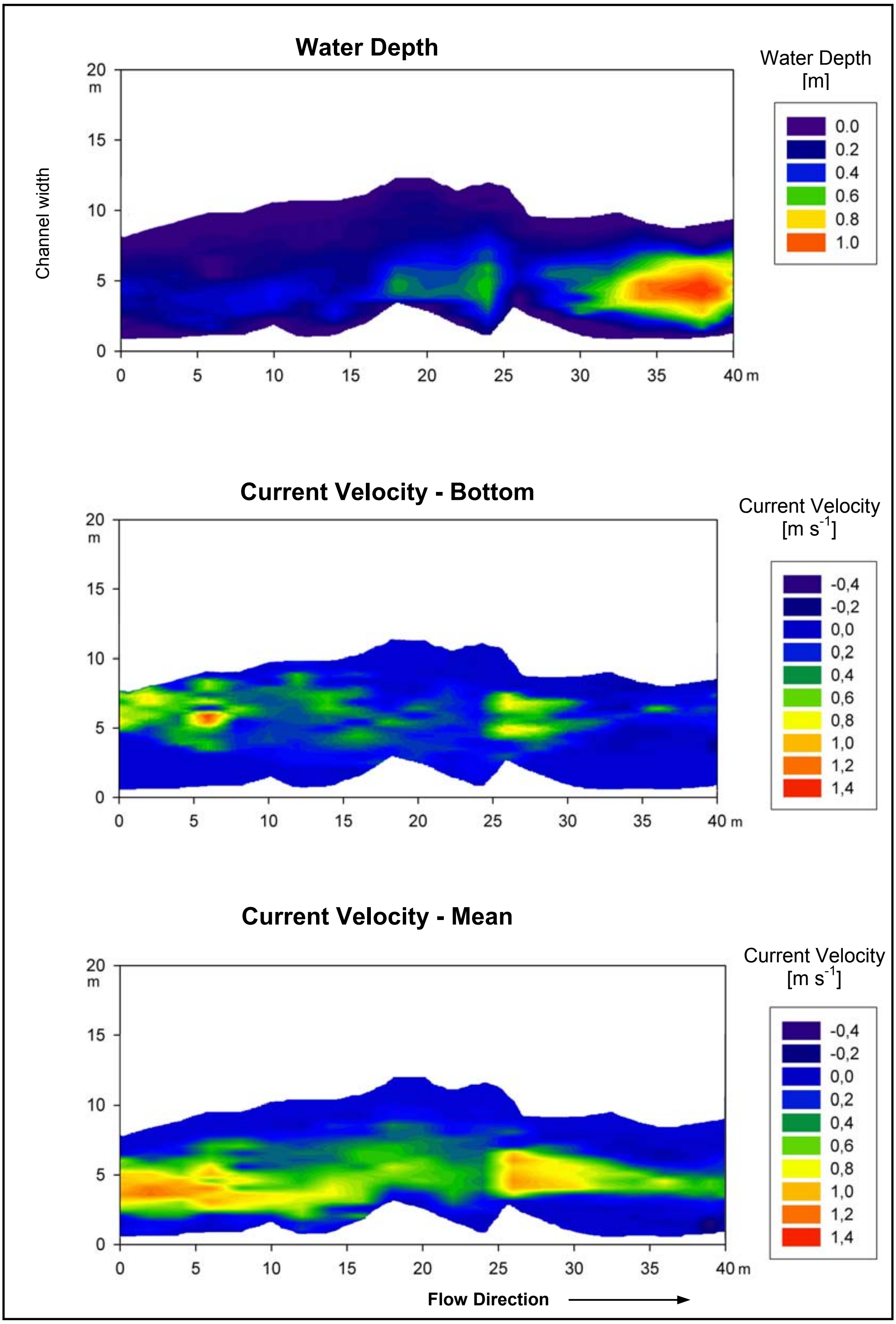


Figure 11: Water depths, current velocities 100 mm above stream bed and mean current velocities over the entire water depth in the 40 m-long stretch covered by the permanent grid in the natural reference section in the river Ilm. Curve of the stream channel to the left (60°) at the 25 m-mark is eliminated for this figure.

3.4 Discussion

The comparison of geomorphologic and hydrologic parameters of the anthropogenic altered and unaltered stream sections in the Ilm highlights their different channel morphologies. The impoundment with its high water depth, low current velocities, fine stream bed substrate and high hydraulic retention (Table 1) corresponds to conditions typical for natural pools. The maximum depth (0.9 m) and maximum current velocity (0.15 m s^{-1}) of the impoundment were in the range of values found in pools of the natural reference site (maximum depth 1.04 m and minimum current velocity 0.001 m s^{-1}; Figure 11). However, the pool conditions in the impoundment stretched over a more than 200 m flow distance and over the entire cross channel. Such spatially extended pools with a similarly high hydraulic radius do not occur naturally in the Ilm.

In contrast, the low water depth (maximum 0.3 m) and high current velocities (maximum 1.2 m s^{-1}; Figure 10) make the straightened site comparable to natural riffles in the reference site (maximum current velocity 1.57 m s^{-1}; Figure 11). The artificial riffle structure in the straightened stream section was spatially equivalently extended as the pool characteristics of the impoundment.

The low channel sinuosity of the study sites in the impoundment and straightened stream section indicate that in both sections the stream does not meander anymore (Table 1). This is linked to a reduced heterogeneity in erosion dynamics resulting in the absence of riffle-pool sequences (Schönborn, 1992) occurring naturally in the reference site (Figure 11). At the reference site, the meandering Ilm causes the formation of distinct riffle-pool patterns and a high water depth variation. Pools and riffles alternate in the natural section within close spatial proximity (Figure 11). These pools are as deep as the impounded stream section and the riffles are as shallow as the straightened stream section (Figure 11). On a smaller spatial scale, the shoreline in the straightened site forms curves and alcoves on the left bank side due to erosion of alluvial material deposited after straightening. A highly curved shoreline is present at both bank sides in the natural reference site as well (Figure 11). These curves and alcoves which are entirely absent in the impoundment (Figure 9) are structures that occasionally cause backwaters and increase the water-land transient zone (Figure 11).

Lower overhead covers in the straightened site may have caused lower lateral leaf inputs than in the other sites (Table 1). However, overhead covers are poor predictors for in-stream leaf biomass (Johnson and Covich, 1997) and upstream reaches contribute to most of the particle input into stream reaches. The amount of leaves in SOM in the Little Washita River, Oklahoma, USA, was best explained by the riparian forest cover of 500 to 1000 m reaches (Johnson and Covich, 1997). The overhead covers in the Ilm reach we studied and those at least 1000 m upstream were almost homogeneous except in the 400 m long straightened section. The SOM input to the study site at the start of this section (Figure 3) is therefore unlikely to differ strongly from the other sites (Chapter 6.3). The high standard deviation of current velocities, water depth and choriotope-type index in the natural reference reflects its diverse channel structure.

4. Problems in Sampling Benthic Organic Matter – Method Comparison

4.1 Introduction

The quality and quantity of benthic organic matter (BOM) is important for the function and structure of lotic ecosystems. Natural or anthropogenic changes in quantity and quality of particulate organic matter (POM) in the benthic zone greatly influence community composition and energy budgets in stream ecosystems as predicted by the River Continuum Concept (Vannote *et al.*, 1980).

This crucial role illustrates the importance of obtaining accurate qualitative and quantitative data on BOM for ecological research and environmental pollution monitoring (Hill, 1999). However, fundamental problems persist in most sediment sampling techniques. This complicates quantitative sediment sampling, especially for fine particulate organic matter (FPOM; Webster and Meyer, 1997).

Thus, traditional sediment sampling techniques (Table 2) were unsuited to obtain quantitatively reliable data for benthic coarse particulate organic matter (CPOM) and FPOM in the Ilm with its hard and coarse bed substrate (Chapter 2). I therefore developed a new technique for sampling bed sediments of streams and shallow lakes (Wagner *et al.*, 2001 submitted, see Appendix II and German Patent No.: DE 100 57 738 A1, see Appendix III). The new method was compared to the Hess-Sampling technique, the traditional sediment sampling method which provides quantitative data under personal and financial constrains and is appropriate for hard and coarse bed substrate (Table 2).

Table 2. Features of different sediment sampling methods, – absent, (+) present to some degree, + present.

	Quantitative	Complete particle range in sample	Applicable in all substrate types	Sample in natural composition and spatial structure	Sample available immediately	Mobile, flexible application	Low personal demands
Hand collecting (Bretschko, 1990)	(+)	–	+	–	+	+	+
Hess-Sampler (Hess, 1941)	+	–	+	–	+	+	+
Corer + pump (Short and Ward, 1981)	+	+	(+)	–	+	+	+
Sediment-corer (Kajak, 1971)	+	+	–	+	+	+	+
Freezing core technique (Stocker and Williams, 1972)	+	+	+	(+)	–	–	–
Bottom-Sampler (Wagner *et al.*, 2001 submitted)	+	+	+	+	+	+	+

4.2 Methods

Bottom-Sampler

The Bottom-Sampler consists of a stamp-shaped sampler (in narrower sense), a closed hollow cooling cylinder (260 mm diameter - sampling area 0.0531 m^2) with an insulated refrigerant pipe and stackable jackets (Figures 12, 13 and 14; detailed description in Wagner *et al.*, 2001 submitted, see Appendix II and German Pat.: DE 100 57 738 A1, see Appendix III).

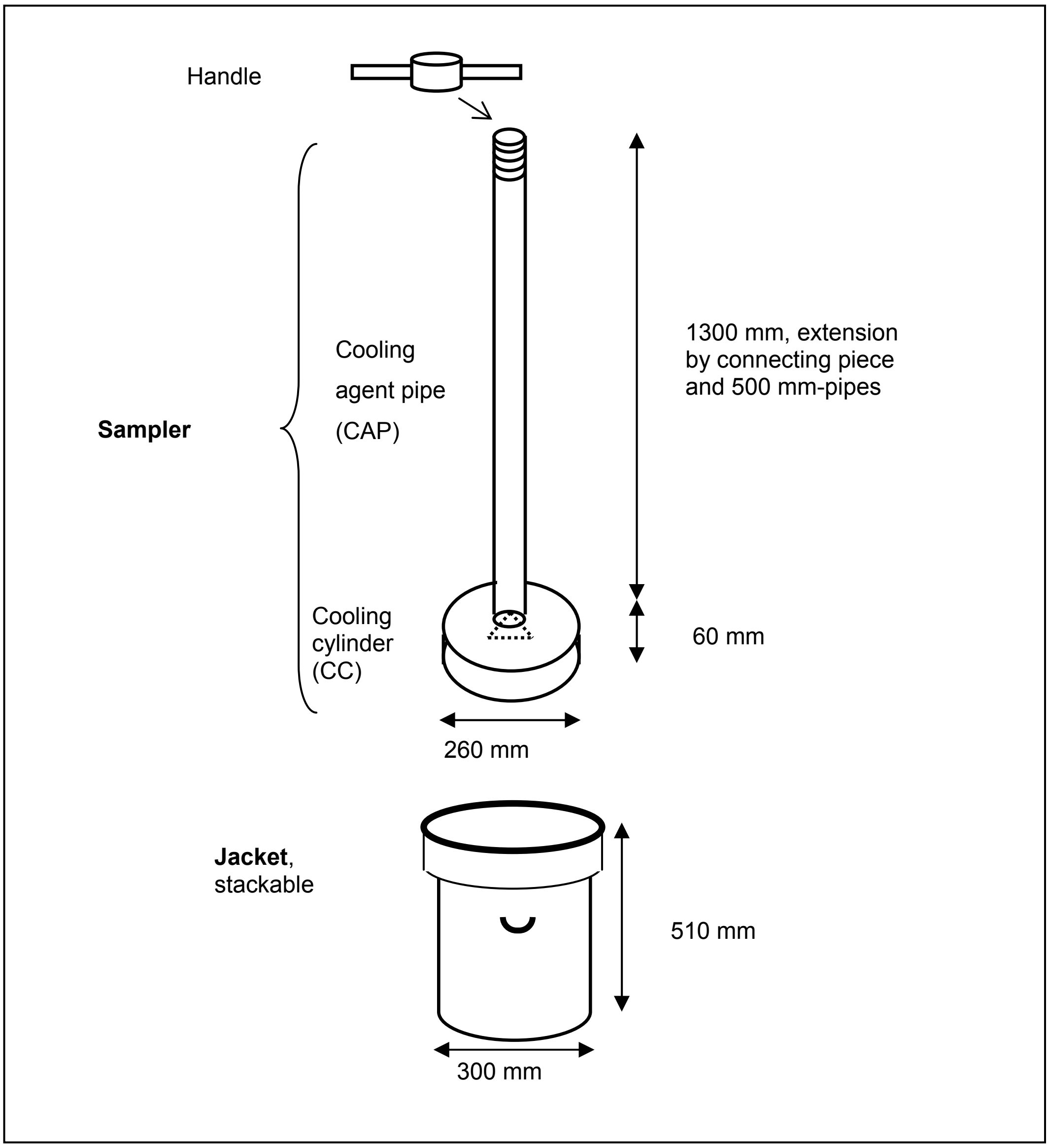


Figure 12: Schematic drawing of the Bottom-Sampler components: in the upper part the sampler, in the lower part the jacket protecting the sampling area from current.

For the sampling process, the jacket (298 mm diameter) is put into the water at the sampling point and lowered until it rests on the sediment surface where it protects the sediment from the current. Next the sampler is put gently on the sediment surface inside the jacket and liquid nitrogen is poured down the refrigerant pipe (Figure 14). This cools down the uninsulated base of the cooling cylinder, causing the upper 80 to 120 mm of the bed sediment to freeze onto the cylinder base. The ice disc thus formed (Figure 15), together with the imbedded sediment, is the sample and is removed and put into a bucket by hitting it with a hammer.

Figure 13: The Bottom-Sampler (left) and two stacked jackets (right).

Figure 14: Freezing process during Bottom sampling: the liquid nitrogen is poured into the refrigerant pipe.

Figure 15: View at the ice-sediment mix disc attached at the Bottom-Sampler basis shortly after removal from stream.

Hess-Sampler (Modified)

A Hess-Sampler (298 mm diameter - sampling area 0.0697 m^2) was used. The traditional Hess-Sampler (Hess, 1941) was modified by fitting flaps closing the windows at the front and rear (Figure 16). This allowed for sampling even the fine particles normally washed out through the net bag. The modified sampler was applied in two successive steps. First, we closed the windows and took a 5 l scoop sample of water and particles suspended by strong turbulence within the sampler. This sub-sample provided data to estimate amounts of FPOM following the method described by Minshall *et al.* (1992). In the second step the flaps were removed and the sampler was used in its traditional way, which is by disturbing again the upper sediment layer to get the total amount of the benthic organic particles larger than 0.4 mm.

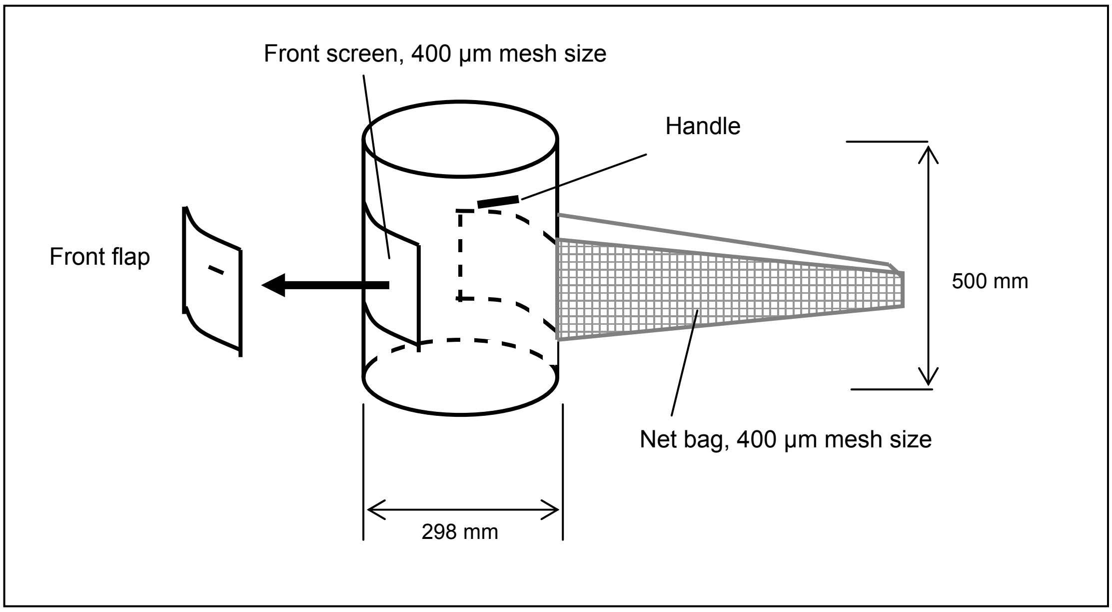


Figure 16: Schematic drawing of the modified Hess-Sampler, removable flaps were used to close the front screen and the opening to the net bag opposite the front screen.

Sampling and Analysis

45 Bottom and 45 Hess samples were taken in Summer and Autumn 2000 and Winter 2001 at randomly chosen cross points of the permanent grids in the three different sites of the river Ilm (Chapter 3.2). Bottom- and Hess-Sampling techniques were applied together at every sampling point. In order to avoid contamination between samples, the second sample was always taken from undisturbed sediment 1 m upstream of the first. The sediment was transferred in buckets to the laboratory and stored at 5 °C in the dark.

The organisms visible under a binocular microscope were removed and the samples subdivided into six particle-size fraction 0.0016 - 0.071 mm, 0.071 - 0.25 mm, 0.25 - 0.4 mm, 0.4 - 1 mm, 1 - 4 mm, >4 mm. To separate the large size classes, the BOM was wet sieved using an analysis sieving machine AS 200 (Retsch GmbH & Co KG, Haan, Germany). The smallest size class was yielded by filtering the water sediment mix remaining after the sieve passages by using pre-ashed, preweighted Whatman GF/A filters. The subsamples were dried at 105 °C to constant weight and ash free dry weights (AFDW) determined (ashed for 5 hr at 500 °C). To ensure that dissociation of magnesium carbonate did not influence the results unpredictably (Bretschko and Leichtfried, 1987), 52 random chosen samples were acidified with 10 % HCl prior total organic carbon (TOC) analyses by a Ströhlein C-mat 550 (JUWE Laborgeräte GmbH, Korschenbroich, Germany). These TOC data were compared with AFDW data of corresponding not acidified subsamples. The linear regression showed a high correlation of the AFDW content of not acidified samples with the TOC content of the acidified samples according to the following equation (AFDM [g m^{-2}] = 2.34·TOC [g m^{-2}]; $R^2 = 0.949$). This indicates a very low variability in magnesium carbonate content between the samples.

Numerical Analysis and Statistics

Bottom-Sampler data of AFDW [g m^2] were standardised for the mean sampling depth (Wagner *et al.*, 2001 submitted) to reduce variability caused by differences between samplings. The mean sampling depth (d) was calculated by the following equation (2):

$$d = \frac{V}{A} \qquad \begin{array}{l} V = \text{sum of pore water and sediment volume } [m^3] \\ A = \text{sampler area } [m^2] \end{array} \qquad (2)$$

The same was impossible for the Hess-Sampler data since this methodology does not provide data for the sampled sediment volume or sampling depth. However, all samples were taken by the same operator using a constant procedure (step 1, sampler closed: turbulence 30 seconds - scooping; step 2, sampler open: turbulence for 150 seconds) to reduce variation. The data for the amount of organic matter as AFDW [g m^{-2}], the organic content [%] and sample dry weight (DW [g]) for both sampling techniques were compared for the single particle-size fractions separated and pooled over all fractions. Original and data transformed by common methods were not normally distributed (Kolmogorov-Smirnov test). Therefore, Mann-Whitney U-tests were used to compare these data. The statistics were computed using the SPSS computer package 10.0.5 (SPSS Inc.).

4.3 Results

The results for the stream sediment characteristics differed strongly between Hess- and Bottom-Sampler technique. Significant differences (Mann-Whitney U-test, $p < 0.001$, $n = 90$) existed in the BOM amount expressed as AFDW per stream bed area [g m^{-2}] between both techniques (Table 3). This was true for the total amounts of BOM (Table 3) as well as for the individual data from the six particle-size fractions (Figure 17). The highest difference in the mean AFDW per stream bed area occurred in the smallest size fraction (87 %) and the lowest in the 0.4 - 1 mm fraction (4 %; Figure 17). The mean amount of BOM per stream bed area obtained by the Bottom-Sampler (65.8 g AFDW m^{-2}) was significantly higher than that for the Hess-Sampler (15.1 g AFDW m^{-2}; Mann-Whitney U-test, $p < 0.001$, $n = 90$), with total BOM in the Bottom-Sampler four times that for the other method. This was linked to method-specific differences in the sample dry weights and sample organic contents (Table 1, Figures 18 and 19). In any fraction, the samples taken by Bottom-Sampler were much larger than the Hess samples (Mann-Whitney U-test, $p < 0.001$, $n = 90$; Figure 18). The mean sample dry weight (DW) per sampled area for the Bottom samples was 3504.9 g DW m^{-2}. The Hess samples measured only 206.4 g DW m^{-2}. This means there was a high significant difference (Mann-Whitney U-test, $p < 0.001$, $n = 90$). This difference was relatively constant in all size classes ranging from the minimum of 70 % in the 0.4 - 1 mm fraction to a maximum of 96 % in the >4 mm fraction (Figure 18). The inter-method difference for the organic content obtained by both methods varied highly between the size classes (Figure 19), with a maximum of 83 % in the 0.25 - 0.4 mm and a minimum of 39 % in the 0.0016 - 0.071 mm sediment-size classes.

Table 3. Means and standard errors of the amounts of benthic organic matter (BOM) expressed as ash free dry weight (AFDW), the organic content in the dry weight [%] and the absolute sample dry weights (DW) in the 90 samples obtained by the two sampling techniques, H = Hess-Sampler, B = Bottom-Sampler. Samples taken in Summer and Autumn 2000 and Winter 2001, n = 45 in each technique.

Particle-size fraction	**AFDW [g m^{-2}]**		**Organic content [%]**		**DW [g]**	
[mm]	**H**	**B**	**H**	**B**	**H**	**B**
0.0016 - 0.071	9.7 (±4.5)	142 (±26.2)	26.2 (±2.3)	19.1 (±0.7)	49.8 (±24.8)	659.1 (±204.5)
0.071 - 0.25	10.7 (±3.2	28.7 (±8.1)	10.3 (±1)	3.7 (±0.4)	95.4 (±28.3)	968.1 (±201.5
0.25 - 0.4	1.2 (±0.3)	11.3 (±1.9)	10.9 (±1.8)	1.9 (±0.3)	21.5 (±7.1)	970.0 (±236.7
0.4 - 1	20.4 (±8.1)	22.2 (±3.5)	5.6 (±1.6)	1.8 (±0.3)	519.3 (±71.4)	2927.0 (±745.2)
1 - 4	20.2 (±4.5)	72.0 (±8.7)	12.3 (±2.2)	3.1 (±0.8)	358.7 (±54.7)	5585.0 (±1527.8)
> 4	28.3 (±7.8)	118.2 (±16.1)	40.1 (±5.1)	6.4 (±2.1)	191.4 (±58.5)	9920.1 (±3181.9)
Total	90.5	394.4	105.4	36	1236.1	21029.3

Because the modified Hess-Sampler technique was used, the data were based on two sampling steps (Chapter 4.2). The data for the particles 0.0016 - 0.25 mm were based on scoop samples whereas the data for particles >0.4 mm were derived from total samples from the net bag. Within both groups, an increasing difference between the Hess- and Bottom-Sampler measures of organic content with increasing particle size was discovered (Figure 19). The mean organic content of the Hess samples (17 %) was significantly higher than for the Bottom samples (6 %; Mann-Whitney U-test, $p < 0.001$, $n = 90$).

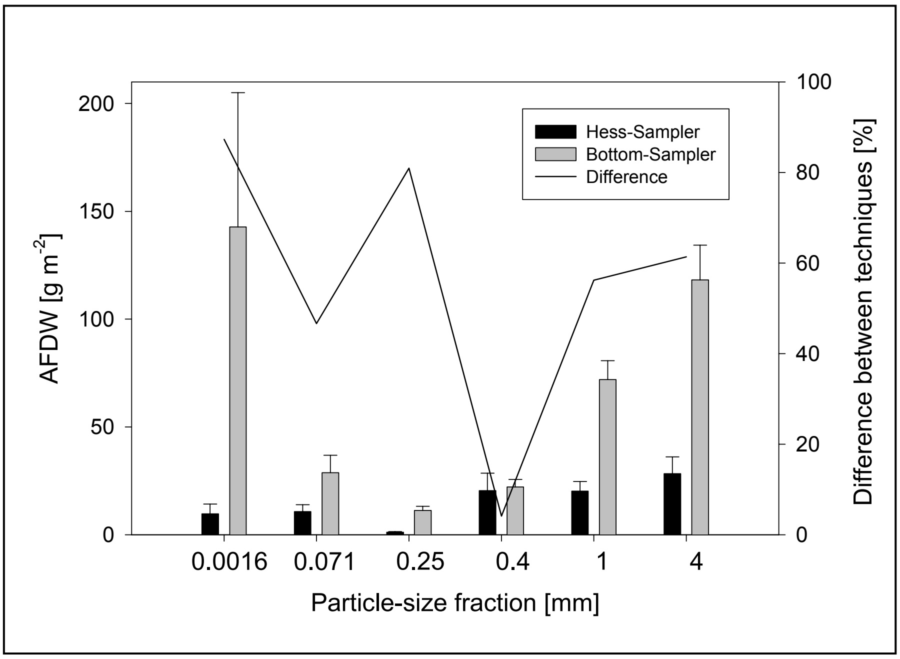


Figure 17: Means of the ash free dry weight (AFDW) of the bed sediment obtained by Bottom- and Hess-Sampler technique ($n = 90$), bars represent standard error, the line represents the difference between methods. All differences in AFDW between methods were significant (Mann-Whitney U-test, $p < 0.001$, $n = 90$). The given particle sizes are the lower bounds of each size class.

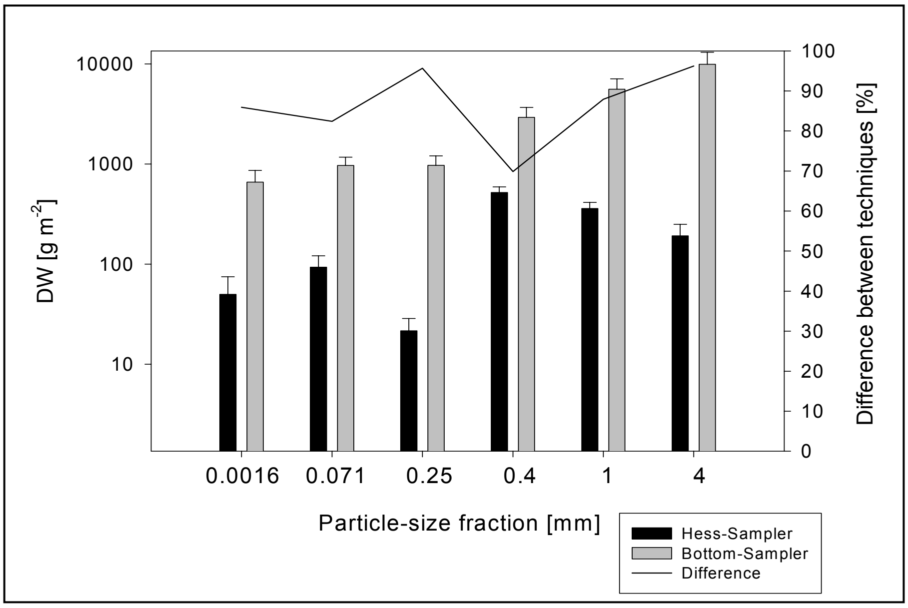


Figure 18: Means of the sample dry weight (DW) per sampled area obtained by Bottom- and Hess-Sampler technique (n = 90); bars represent standard error, the line represents the difference between methods [%]. Bottom and Hess samples in all particle-size fractions were significantly different (Mann-Whitney U-test, $p < 0.001$, n = 90). The given particle sizes are the lower bounds of each size class.

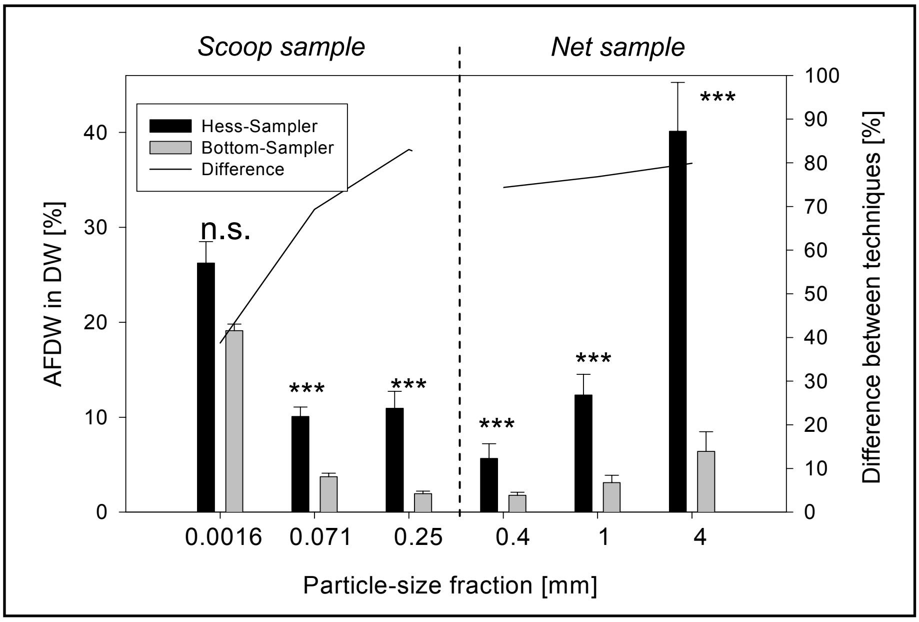


Figure 19: Organic content of the samples obtained by Bottom- and Hess-Sampler technique given as mean proportion (n = 90) of ash free dry weight (AFDW) on dry weight (DW); bars represent standard error; the line represents the difference between both methods [%]. The results from Mann-Whitney U-test for inter-method differences (n = 90) given as follows: *** = $p < 0.001$; n.s. = not significant. Results for first three particle-size fractions in Hess-Sampler technique were based on scoop sample, last three fractions were based on net sample. The given particle sizes are the lower bounds of each size class.

4.4 Discussion

The present comparison of methods for sediment sampling in streams was limited to techniques that produce immediate quantitative sediment samples that are applicable under a broad range of field conditions and low in personal and financial demands (Table 2). These features enable a high number of samples and are required in most research and monitoring programs constrained by finances and time. The comparison of the Hess- and Bottom-Sampler demonstrated that qualitative stream sediment data clearly depend on the sampling method used. The result for mean total amount of BOM obtained by the Bottom-Sampler was four times that of the Hess-Sampler. The inter-method difference was particle-size dependent and lowest in the smallest particle-size fraction.

Due to the technology of the Bottom-Sampler technique, the sediment in the samples retains its natural composition and spatial structure (Wagner *et al.*, 2001 submitted). As in the freeze coring technique (Stocker and Williams, 1972), an exact representative portion of sediment is removed. Previous studies on the accuracy of the freeze coring techniques in hydrogeology confirmed that methods based on sediment freezing provide good quantitative estimation on the real sediment conditions (Thoms, 1992). In contrast to traditional freeze coring techniques, during the entire Bottom-Sampler process the sediment remains almost undisturbed. For certain applications this is a clear advantage. The very low turbulence, which may occur during sampler insertion, is sufficient to suspend only small amounts of very fine particles. If this had had an effect on the present results, we would have expected a lower sample weight of fine sediment in the Bottom samples and thus a reduction of the high inter-method difference with decreasing particle size. But the sample dry weight difference in the 0.4 - 1 mm and 0.071 - 0.25 mm particle-size fraction was lower than the difference in the finest particles (Figure 18).

If we accept that the Bottom samples closely reflect the real BOM conditions, it is reasonable to trace the inter-method differences back to specifics in the Hess-Sampler technique. The main reason for the method-specific discrepancies is that the Hess sampling process involves the suspension of sediment particles, whereas in the Bottom-Sampler technique particle suspension is not needed (Wagner *et al.*, 2001 submitted). The degree of suspension depends on particle size, shape and density. Large particles and those with higher density (e.g. cobbles, processed wood fragments) will either not be suspended or quickly sink back to the bottom. The result is an incomplete sampling of these sediment components. This is confirmed by the differing particle-size distribution and the seventeen times smaller mean dry weight of the Hess samples. However, different method-specific sampling depths may cause some discrepancy in sample weight as well, even when we tried to sample at similar depths in both methods. In the Bottom-Sampler technique, depths were from 80 to 160 mm (Wagner *et al.*, 2001 submitted). It was possible to eliminate effects of varying sampling depths on Bottom-Sampler results, whereas this was not possible for Hess-Sampler data. The Hess-Sampler technique does not allow for determining exact sampling depths.

A convincing argument for the misleading selectivity of the Hess-Sampler for finer- and low-density particles was the almost three times higher mean organic content of Hess samples. Sediment suspension, that is an integral part of the Hess methodology, leads to the over-representation of organic matter in the sample. Organic matter particles with their lower density would remain longer in suspension than mineral particles with their higher density. Mean organic content was thus overestimated in data based on the (modified) Hess-Sampler technique. This was true in all particle-size fractions except in the finest. There, the turbulence was evidently sufficient to keep mineral and organic particles equally suspended. In this single particle-size fraction, the organic content did not significantly differ between techniques. In both steps of the Hess-Sampler process, selectivity increased from finer to coarser particles. This indicates that differences in the particle properties (e.g., shape) become more important with increased particle size because of the increasing heterogeneity in particle settling velocity (Eisma, 1993).

The differences between Hess and Bottom samples, in both organic content and sample dry weight, produced distinctly different results for BOM. This emphasises the fact that stream sediment data based on different sampling techniques must be compared with great care, or might be altogether inappropriate for comparison. Fraser and Williams (1997) came to a similar conclusion for stream invertebrate data that were provided by different benthic sampling techniques. The shortcomings of the Hess-Sampler (modified) resulted in a poor reflection of the BOM conditions in the Ilm. The Bottom-Sampler turned out to be the superior sediment sampling technique for BOM in the upper layers of the bed substrate with mobility and flexibility equal to the Hess-Sampler. Therefore, the use of the Bottom-Sampler can provide much more precise data in a broad range of environmental studies when doing research on stream sediments.

5. Particle Storage - Benthic Organic Matter

5.1 Introduction

In-stream conditions over extended periods of time determine benthic organic matter (BOM) standing crop (Minshall *et al.*, 1992). Thus BOM standing crop characterises long-term retention (Minshall *et al.*, 1992; Webster *et al.*, 1997). Studies on BOM that include fine particulate organic matter (FPOM) are rare (Short and Ward, 1981). This deficiency is related to problems associated with quantitatively sampling the complete particle-size range in streams with both hard and coarse bed substrate (Webster and Meyer, 1997). Many previous studies on BOM standing crop in headwater streams were limited to coarse particulate organic matter (CPOM; e.g. Speaker *et al.*, 1984; Bretschko, 1990; Smock, 1990; Prochazka *et al.*, 1991; Webster *et al.*, 1994; Wallace *et al.*, 1995). Only a few authors considered FPOM completely (Short and Ward, 1981; Newbold *et al.*, 1997; Webster *et al.*, 1997), and some that did consider FPOM were restricted to particles larger than 0.25 mm (Maridet *et al.*, 1995; Haapala and Muotka, 1998). However, FPOM (0.45 µm - 1 mm) can dominate stream seston (Minshall *et al.*, 1992) and stream communities are adapted to this food source.

For the present thesis, it was important to consider both CPOM and FPOM since organic matter storage is presumed to be particle-size dependent (Thomas *et al.*, 2001). Fundamental problems in traditional BOM sampling methods prevented or limited their applicability for the Ilm (Chapter 4). However, in the present study sediment sampling by the new Bottom-Sampler (German Patent No.: DE 100 57 738 A1, see Appendix III) provided quantitatively reliable sediment data for the complete BOM particle-size range.

Former studies on impacts of channel alterations on organic matter retention (Petersen and Petersen, 1991; Haapala and Muotka, 1998; Wanner *et al.*, 2002) suggest the following pattern of BOM standing crop for the anthropogenic altered and unaltered stream channels in the Ilm: impoundment > natural site > straightened site.

The test of this hypothesis should reveal how small-scale impoundment and straightening affect long-term retention of particulate organic matter (POM) in the river Ilm.

5.2 Methods

Sampling and Analysis

FPOM (particle size 0.0016 -1 mm) and CPOM (particle size >1 mm up to sampler diameter) were sampled seasonally from May 2000 to January 2001 to quantify BOM standing crop and particle-size distribution (sampling dates: 16.5.2000, 31.8.-7.9.2000, 1.11.-3.11.2000, 15.1.-16.1.2001) in an impounded, a straightened and a natural stream section of the Ilm. The modified Hess-Sampler provided sediment samples for spring. Starting from summer, the newly developed Bottom-Sampler (Chapter 4) was also used. The parallel application of both methods starting from Summer 2000 allowed comparability to spring data. Bed sediments were randomly sampled in each stream section at the cross points of the 40 m long permanent grid (grid cells 2 by 2 m; Figure 8) following the procedure given in Chapter 4. In spring, 21 Hess samples were taken. In each of the three later campaigns, 15 Hess samples and 15 Bottom samples were taken. The samples were treated as described for the BOM samples in Chapter 4. The amount of BOM is expressed as AFDW (ash free dry weight) per stream bed area.

Statistics

Analysis of Variance (Univariate ANOVA) of the $\ln(x + 1)$-transformed amounts of AFDW, with sampling site and season as factors, was used to test for differences in the BOM standing crops between the three sites. Student-Newman-Keuls Post hoc tests were used to determine differences in the total AFDW and the AFDW in each particle-size fraction. The data based on the Hess-Sampler underestimated BOM standing crop (Chapter 4.3). Therefore, these data were multiplied by a factor compensating for the method-specific error. The correction factor was derived from the inter-method comparison of the Hess-Sampler data and reliable Bottom-Sampler data in each particle-size fraction separately (Chapter 4.3; correction factors were 14.7 for 0.0016 - 0.071 mm; 2.7 for 0.071 - 0.25 mm; 9.5 for 0.25 - 0.4 mm: 1.1 for 0.4 - 1 mm: 3.6 for 1 - 4 mm and 4.2 for >4 mm particle-size fraction).

To detect differences between the sites in the proportions of each particle-size fraction, an Analysis of Variance (Univariate ANOVA) and subsequent Student-Newman-Keuls Post hoc tests of the arcus-sinus-transformed data were computed. The Wilcoxon test for bounded samples was used to test for seasonal differences in BOM standing crops in each site. Data were not adjustable either to normal distribution or homogeneity of variance by common transformation techniques.

Detrended Correspondence Analysis (DCA) indicated that the BOM data fitted an unimodal model and thus required a Canonical Correspondence Analysis (CCA). Therefore, CCA and stepwise Monte Carlo permutation procedure (Jongman *et al.*, 1995) were used to assess the relative importance of the environmental variables influencing BOM standing crop [g ADFW m^{-2}] uncorrected for inter-method difference. Water depth [m], absolute current velocity [m s^{-1}], proportion of the choriotope-types [%], choriotope-type-index at the sampling time and the sampling point in the permanent grid, the sampling technique and hydraulic radius [m] were considered as environmental variables.

A stepwise forward selection with Monte Carlo permutation ($n = 1000$) should reveal which environmental variables explain most of the variability in the BOM. The ordination was computed with CANOCO 4.0 (CPRO-DLO, ter Braak & Smilauer, The Netherlands).

5.3 Results

5.3.1 Spatial Variability of the Benthic Organic Matter

The BOM standing crop varied significantly between the three study sites (Figure 20). These differences were independent of season (ANOVA, interactive effect of factors site and season, $p > 0.05$). Significantly, the highest amounts of BOM were found in the impounded site (maximum: 3830 g ADFW m^{-2}). Straightened and natural sites did not differ significantly (Figure 20). Also, in each particle-size fraction, standing crop differed significantly between the sites. These differences were particle-size dependent. FPOM (particle size 0.0016 - 1 mm) was found in significantly higher amounts in the impoundment than in the other sites (Table 4). No significant differences were found between the straightened and the natural site. Considering CPOM (particle size >1 mm) the standing crop in the impoundment and the straightened site was equal but both higher than in the natural site (Table 4).

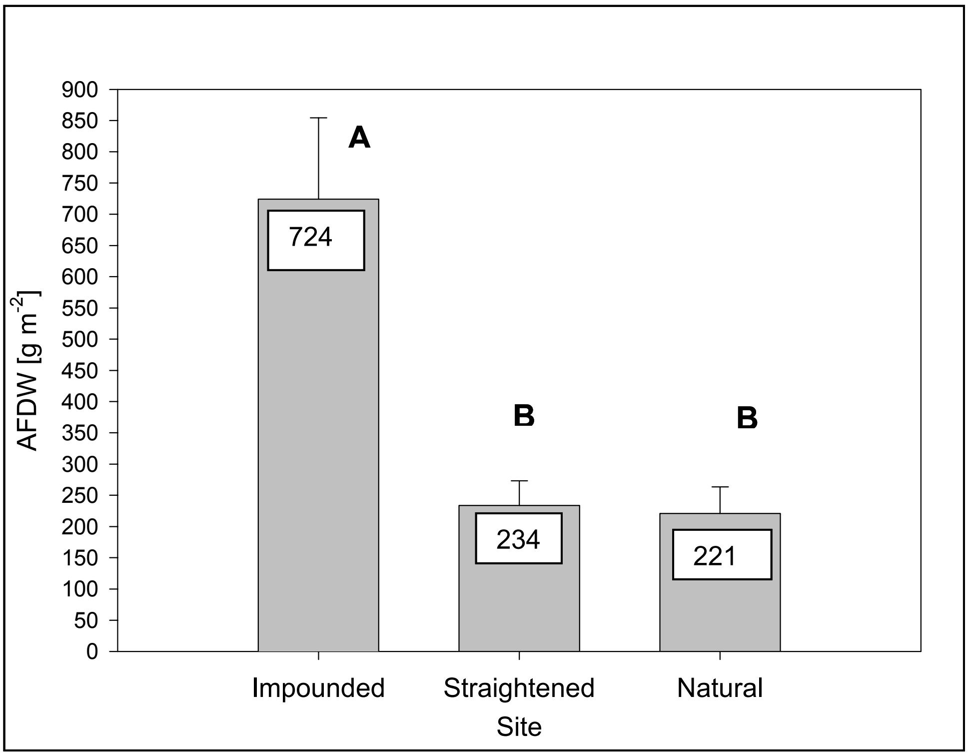


Figure 20: Standing crop of benthic particulate organic matter (BOM) in the three stream sections. Columns represent the means of ash free dry weight (AFDW) in all four seasons and two sampling techniques (n = 111), bars indicate standard errors. Standing crops in the sites are significantly different (ANOVA, $p < 0.001$, n = 111), letters indicate the results from pair-wise comparison by Student-Newman-Keuls Post hoc test.

Table 4. Means and standard errors of benthic organic matter (BOM) standing crop given as ash free dry weight (AFDW) of each particle-size fraction in the three stream sections; I = impounded, S = straightened, N = natural. BOM amounts are in all size fractions significantly different between the three study sites (ANOVA, $p < 0.001$, n = 111). Numbers indicate the ranks from pair-wise comparisons by Student-Newman-Keuls Post hoc tests (S-N-K).

Particles [mm]	**0.0016-0.071**			**0.071 - 0.25**			**0.25 - 0.4**			**0.4 - 1**			**1 - 4**			**> 4**		
Site	**I**	**S**	**N**	**I**	**S**	**N**	**I**	**S**	**N**	**I**	**S**	**N**	**I**	**S**	**N**	**I**	**S**	**N**
BOM [g AFDW m^{-2}]	363	45	75	58	8	14	19	5	8	34	11	16	93	59	44	157	105	63
Std. Error	105.4	5.5	29.9	12.6	1.3	4.2	3	0.8	2.2	10.5	1.3	4.5	18.6	8.3	8.5	26.5	35.5	12.6
S-N-K	2	1	1	2	1	1	2	1	1	2	1	1	2	2	1	2	2	1

These particle size-specific differences in BOM standing crop between the three sites caused variations in BOM size distribution (Figure 21). Significant differences existed between the sites in the stream sections in the proportions of the two smallest particle-size fractions and the 1 -4 mm fraction (Table 5). Compared to the natural reference, the proportion of the 0.071 - 0.25 mm fraction was increased but the 1 – 4 mm fraction was decreased within the impounded site (Table 5). Thus, CPOM : FPOM ratio was 0.5, lower than in the natural site which was 0.9 (Table 6). In the straightened site, the finest particles (0.0016 - 0.071 mm) were underrepresented, whereas the proportion of the 1 – 4 mm fraction was significantly higher than that in the natural site (Table 5). This resulted in a high CPOM : FPOM ratio of 2.4 (Table 6). The overall mean BOM standing crop during the study period amounted to 393 g ADFW m^{-2} (CPOM: 174 g ADFW m^{-2}, FPOM: 218 g ADFW m^{-2}).

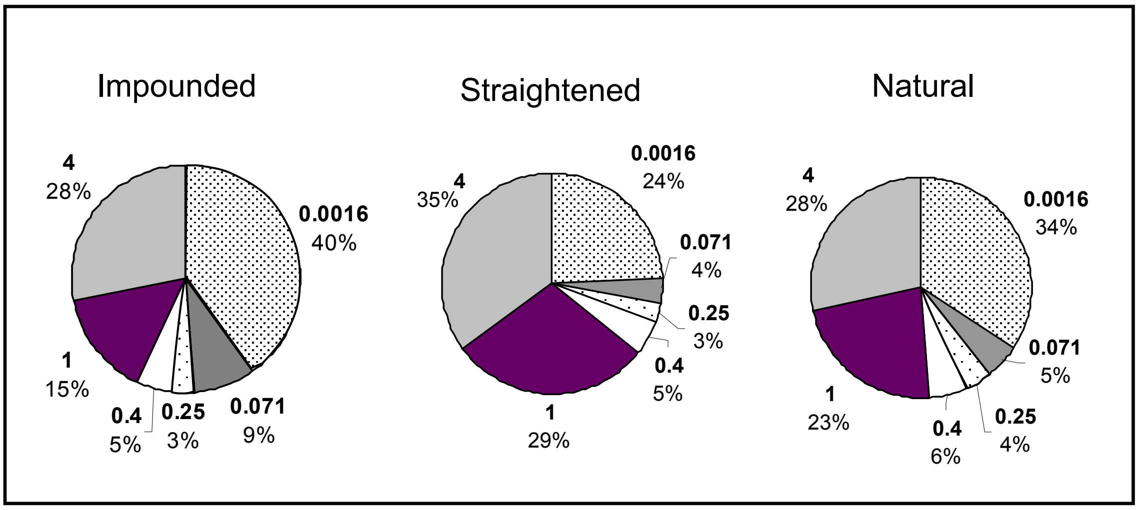


Figure 21: Particle size distributions in the benthic organic matter of the three study sites during the entire study period, given as proportions means of the six particle-size fractions in the samples obtained by Hess- and Bottom-Sampler technique (n = 111).

Table 5. Results from site comparisons of each particle-fraction proportions as ash free dry weight [%]. Numbers indicate the rank of subsets from pair-wise comparisons by Student-Newman-Keuls Post hoc test (S-N-K), p = significance level of the Univariate ANOVA (n = 37).

Particle fraction [mm]	S-N-K - Subsets			p
	Impounded	Straightened	Natural	
0.0016 - 0.071	2	1	2	0.001
0.071 - 0.25	2	1	1	0.000
0.25 - 0.4	1	1	1	> 0.05
0.4 - 1	1	1	1	> 0.05
1 - 4	1	3	2	0.000
> 4	1	1	1	> 0.05

Table 6. Means and standard errors of benthic organic matter (BOM) standing crop given as ash free dry weight (AFDW) [g AFDW m^{-2}] of coarse (CPOM; n = 111) and fine particulate organic matter (FPOM, n = 111), and the CPOM : FPOM ratio in the three stream sections of the river Ilm during the entire study period.

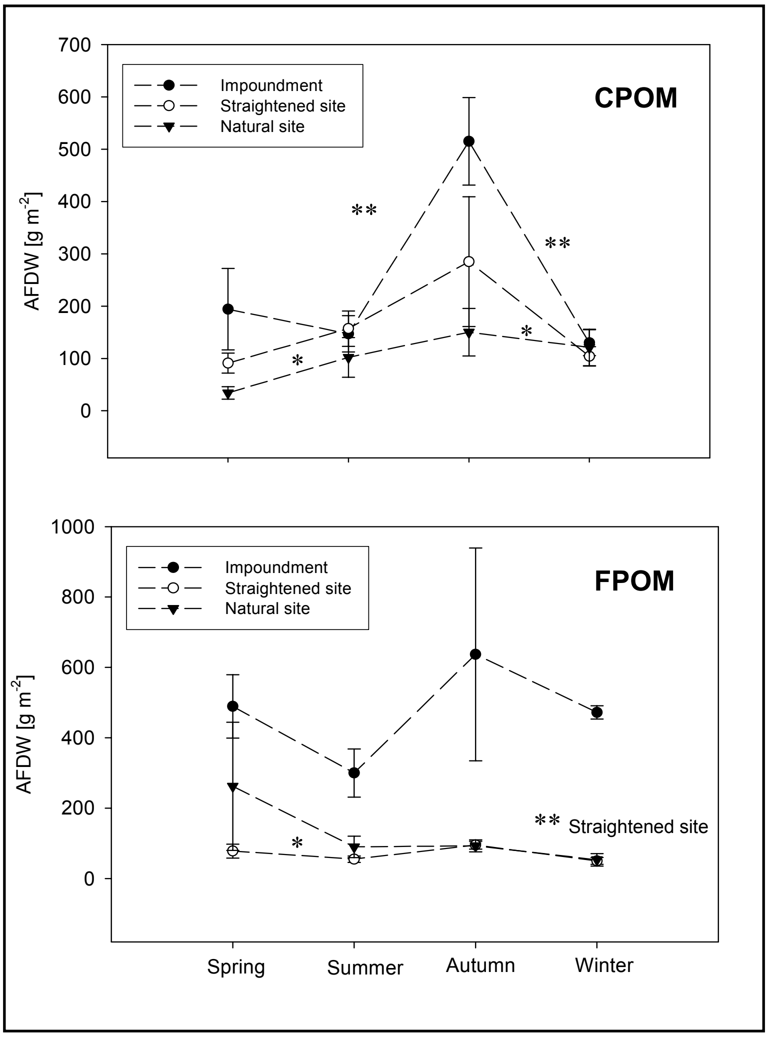
Site	[g AFDW m^{-2}]		CPOM : FPOM
	CPOM	FPOM	ratio
Impounded	251 (±40)	474 (±120)	0.5
Straightened	165 (±36)	69 (±6)	2.4
Natural	107 (±19)	114 (±36)	0.9

5.3.2 Seasonal Variability of the Benthic Organic Matter

In the impoundment, BOM standing crop during the study period was highly variable in time. CPOM standing crop increased significantly from summer to autumn and was reduced strongly from autumn to winter. From the statistical point of view, high variance in the FPOM data in autumn prevented the high difference to summer and winter to be significant (Figure 22). In the straightened site CPOM amount did not significantly vary between seasons. FPOM amount decreased slightly from spring to summer and from autumn to winter (Figure 22). CPOM amount in the natural site increased slightly from spring to summer and decreased from autumn to winter. Although differences of the FPOM amounts between seasons in the natural site seemed higher than in the straightened site, they were not statistically significant due to higher variance in data (Figure 22).

Figure 22:

Seasonal dynamic of mean benthic organic matter (BOM) standing crop in the three stream sections: bars represent standard errors; upper graph shows dynamic of coarse particulate organic matter (CPOM); lower graph of fine particulate organic matter (FPOM). When seasonal differences are significant (Wilcoxon test) they are indicated by: ** = p < 0.01 and * = < 0.05.



5.3.3 Influence of Environmental Factors on the Benthic Organic Matter

The CCA showed the relative importance of the environmental factors. The inflating factors of the remaining variables, a measurement for colinearity of variables, were below 20 (values above this threshold indicate colinearity). The Monte Carlo permutation revealed that the ordination axes were significant (Table 7). The first two canonical axes together explained 94.2 % of the variability in BOM standing crop in the distinguished particle-size fractions (Table 7). This means that there is a high correlation between the BOM standing crop and all environmental variables including sampling technique.

Table 7. Summary of the Canonical Correspondence Analysis (CCA) of the benthic organic matter (BOM) standing crop and the environmental variables, Monte Carlo permutation tests of significance of the CCA axes 1: F = 61.617, p = 0.001; axes 2: F = 16.302, p = 0.001.

Axes	**1**	**2**	**3**	**4**	**Total inertia**
Eigenvalues	0.667	0.268	0.046	0.012	1.533
BOM characteristic-environment correlations	0.924	0.744	0.546	0.325	
Cumulative percentage variance					
of BOM data	43.5	61.0	64.0	64.7	
of BOM data environment relationship	67.2	94.2	98.8	100.0	
Sum of all canonical eigenvalues					0.992

The hydraulic radius was the single variable explaining the highest percentage of variability (52 %), followed by the percentage of the choriotope-type “Akal” (29 %), the sampling technique (24 %), percentage of “Mikrolithal” (16 %), percentage of “Mesolithal” (99 %) and choriotope-type index (44 %; Table 8). Depth and percentage of “Megalithal” explained only 11 % (Table 8). The current velocity during sampling did not explain any variability. Forward selection of the environmental variables revealed that hydraulic radius, sampling technique, water depth and choriotope-type index had significant effects ($p < 0.05$) on BOM. The single choriotope-types explained 22 % or less (Table 8) because these variables were already explained within the model by the choriotope-type index.

Table 8. Ranking of the variables by their effects on benthic organic matter (BOM) standing crop [g ADFW m^{-2}]. Lambda 1 indicates the percentage of variability explained by each variable (marginal effects), Lambda A explains the variability after forward selection, starting with the best variable (conditional effect). P- and F-values indicate the level of significance of each variable obtained by Monte Carlo permutation with 1000 random permutations.

Variable	Lambda 1	Lambda A	p	F
Hydraulic radius	0.52	0.52	0.001	45.31
Akal	0.29	0.02	0.071	2.64
Sampling Technique	0.24	0.25	0.001	28.42
Mikrolithal	0.16	0.02	0.054	3.53
Mesolithal	0.09	0.01	0.253	1.38
Choriotope-type index	0.04	0.05	0.021	6.09
Water depth	0.01	0.12	0.001	16.45
Megalithal	0.01	0.00	0.301	0.73
Current velocity	0.00	0.00	0.705	0.09

The hydraulic radius was strongly positively correlated with the finest particle-size fraction but negatively with the large particles (Table 9). The intermediate particle-size fractions were less influenced by the hydraulic radius. The correlation of the choriotope-type index was positive with the largest particles but negative with the intermediate and small particles (Table 9). The depth at the sampling point was negatively correlated with the 1 - 4 mm and 0.25 - 0.4 mm fraction, but not with the >4 mm fraction and fine particles smaller 0.25 mm (Table 9). The choriotope-types Akal and Mikrolithal showed a shift from a positive correlation with BOM amount in the two largest particle-size fractions to an increasing negative correlation in the smallest. The Mesolithal correlated negatively with the coarse and positively with the amount of fine particles (Table 9). The remaining environmental variables had correlations lower than 0.1.

Table 9. Environment by BOM-size fraction table of the Canonical Correspondence Analysis (CCA), with the correlations between each particle fraction and environmental variables (CIX = choriotope-type index).

Variable	Particle size fraction [mm]					
	> 4	**1 - 4**	**0.4 - 1**	**0.25 - 0.4**	**0.071 - 0.25**	**0.0016 - 0.071**
Hydraulic radius [m]	-0.638	-0.724	0.303	-0.316	0.437	0.835
Water depth [m]	0.091	-0.242	-0.164	0.0161	0.036	-0.010
Current velocity [m s^{-1}]	0.024	0.044	0.019	0.022	0.018	0.035
CIX	0.231	-0.115	-0.492	-0.259	-0.32	-0.145
Megalithal [%]	0.095	-0.055	-0.073	-0.001	0.038	-0.078
Mesolithal [%]	-0.229	-0.362	-0.108	-0.271	0.230	0.347
Akal [%]	0.537	0.331	-0.416	0.214	-0.230	-0.612
Mikrolithal [%]	0.418	0.155	-0.339	0.069	-0.437	-0.431

In the CCA plot, most environmental variables were oriented along axis 1 (Figure 23), but the sampling vector (tech) was oriented strongly along axis 2. Along this axis, two distinct groups of BOM samples were evident, separated by the sampling technique. The upper group contained the samples taken by the Hess-Sampler, the lower group contained those taken by the Bottom-Sampler. Within both groups, a separation of two groups along axis 1 was visible (Figure 23). The first group contained the samples from the impoundment, the second was a group consisting of the samples from the straightened and natural site (Figure 23). The redundancy of this pattern along axis 2 separated by sampling technique confirmed the technique-independent site separation along the first axis.

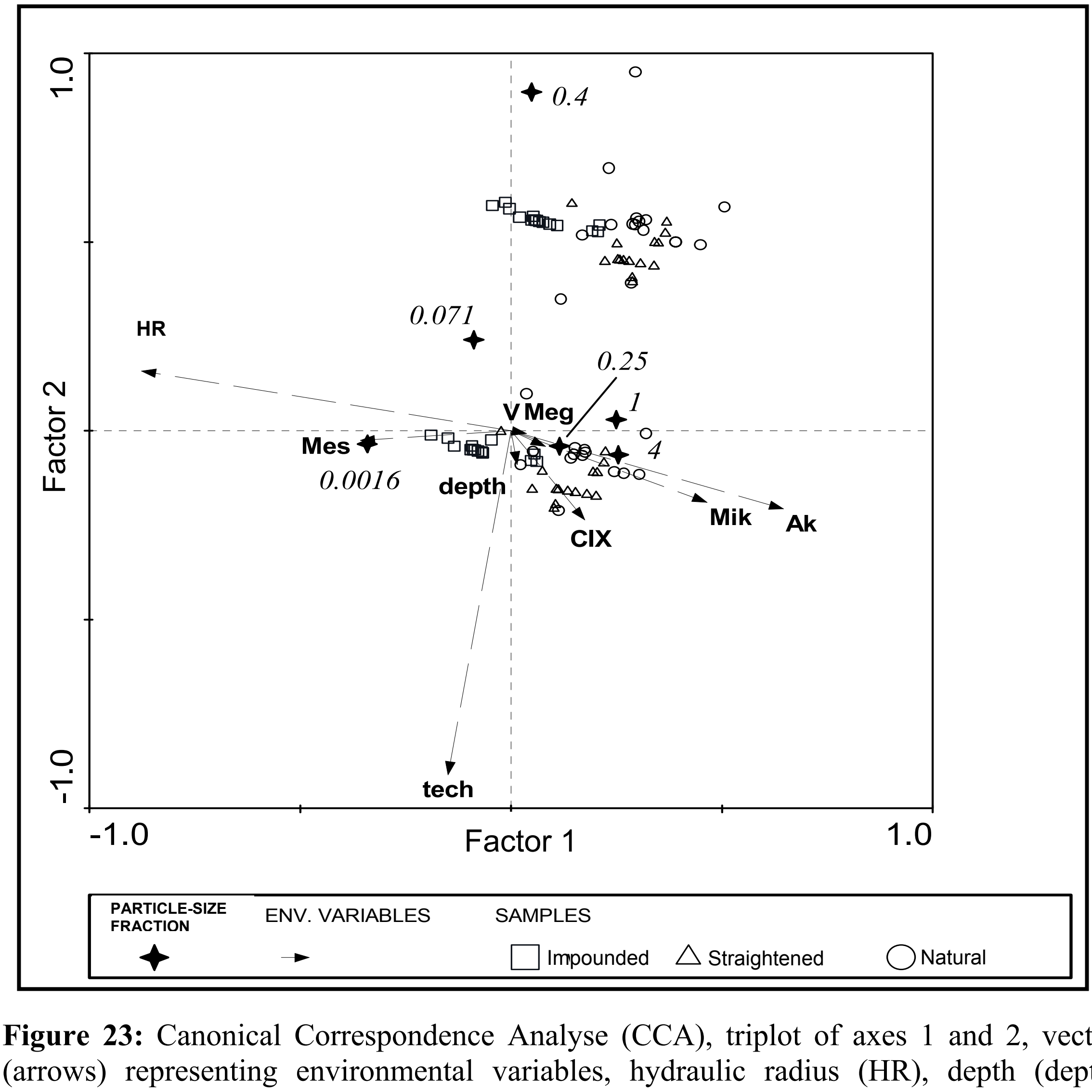


Figure 23: Canonical Correspondence Analyse (CCA), triplot of axes 1 and 2, vectors (arrows) representing environmental variables, hydraulic radius (HR), depth (depth), current velocity (V), choriotope-type index (CIX), sampling method (tech) and the choriotope-types: Mikrolithal (Mik), Akal (Ak), Mesolithal (Mes), Megalithal (Meg); the different symbols represent the three groups of samples taken from impoundment, straightened and natural site; the stars represent the six particle-size fractions.

5.4 Discussion

One important factor affecting stream ecosystem structure is BOM available for stream biota. The mean total BOM standing crop measured during the sampling period in the third-order river Ilm (393 g AFDW m^{-2}) is similar to annual means reported from other rivers, for instance from the Salmon River (Idaho, USA), which is a 2nd- to 8th-order stream (10-350 g AFDW m^{-2}; Minshall *et al.*, 1992), and from the White Clay Creek (Pennsylvania, USA), a 3rd-order stream (319 g AFDW m^{-2}; Newbold *et al.*, 1997). The Ilm standing crop was in the range of those determined in 10 streams in several geographical regions (minimum: 10 g AFDW m^{-2}, Middle Oconee River, Georgia, USA; maximum: 5270 g AFDW m^{-2} Grady Branch, North Carolina, USA; Jones, 1997). But it was lower than that of the German lowland River Spree with 2050 g AFDW m^{-2} in a free flowing section to 3670 g AFDW m^{-2} in an impounded river section (Wanner and Pusch, 2001). However, the mean CPOM standing crop in the straightened site (165 g ADFW m^{-2}, Table 6) was higher than reports from River Rutajoki, a canalised third-order stream in central Finland (23 g AFDW m^{-2}; Haapala and Muotka, 1998).

The results from the Ilm agreed to previous studies on the structural degraded streams Barwon-Darling River (Australia; Thoms and Sheldon, 1997), River Rutajoki (Finland; Haapala and Muotka, 1998) and River Spree (Germany; Wanner and Pusch, 2001), revealing impacts of channel alterations on in-stream organic matter retention. However, the straightening did not affect particle retention in the predicted way. The initial hypothesis assumed that BOM standing crops occur in the following pattern: impoundment > natural > straightened site. This was disproved. In the straightened site with an almost absent channel sinuosity and uniform low water depths (lack of riffle-pool sequences, Chapter 3), retention of POM was in total as high as in the natural site with its stream channel with heterogeneous water depth and stream bed substrate. Surprisingly, not even the retention of FPOM (particle size 1 - 0.0016 mm) was reduced in the straightened site compared to the natural reference. Moreover, CPOM retention actually was higher rather than lower. The straightening in the Ilm did not have as dramatic an effect on POM retention in total, as originally assumed. This contradicts a reduced POM retention observed in the canalised stream River Rutajoki (Finland; Haapala and Muotka, 1998) where major flow obstacles (debris dams, boulders etc.) were removed from the stream channel. The straightened stream section in the Ilm kept its natural bed substrate, which may explain the contrary results to River Rutajoki. Natural (diverse and high) sediment roughness beside the low hydraulic radius was the essential prerequisite for maintaining a natural-like POM retention in the straightened section of the Ilm. The erosions of alluvial sediments deposited after straightening in the stream channel result in a curved left shoreline on a small spatial scale (Chapter 3). Backwaters existing in alcoves are important but unstable retention devices. They certainly increased particle retention of this stream section during low discharge periods. Debris dams were generally unimportant as retention structures. Larger dams (>200 mm) were absent, possibly due to the annual winter spates sufficient to remove woody debris almost entirely from the studied stream reach.

In agreement with my initial hypothesis, BOM standing crop in the impoundment was highly increased in total and in each particle-size fraction. A mud layer consequently clogged the bed substrate and caused sediment conditions that would exist naturally only locally in large pools or in lower order streams. Such increased organic matter storage diminishes the ability of the running water ecosystem for organic matter recycling and affects basic ecosystem functions and structures (Wanner *et al.*, 2002).

The environmental variables highly affecting BOM standing crop were hydraulic radius, as found in former studies (Speaker *et al.*, 1984; Thomas *et al.*, 2001), water depth and particle-size distribution of bed substrate expressed as choriotope-type index. The use of choriotope-type index as a variable to describe the average substrate conditions did not consider the entire complex relationship between substrate and particle deposition. Despite a partial positive correlation to the choriotope-type index, the CPOM content was increased in substrates with higher proportions of the fine choriotope-types Akal and Mikrolithal. Thus, the combination of coarse and fine mineral substrate seems to promote CPOM retention. Mesolithal enhanced the deposition of the finest organic particles (<0.25 mm) whereas the negative correlation to the choriotope-type index indicated a predominant deposition of these particles in regions with a smoother bed surface. This could be attributed to higher depositions in the lee zones of single stones, as described by Proft (1995) for the Ilm. The results from the Ilm confirm that POM retention in streams is not solely based on sedimentation and agree with results of previous studies on retention mechanisms (Petersen and Petersen, 1991; Minshall *et al.*, 2000; Wanner and Pusch, 2001). Positive correlations of the CPOM amount with low hydraulic radius, coarse bed substrate (high choriotope-type index) and with partially shallow water suggest particle entrainment into the permeable bed substrate as an alternative retention mechanism.

In the straightened site, low hydraulic radius enabled an intensive contact of suspended matter with the bed substrate and caused an effective CPOM retention despite high current velocities. Trapping of organic particles on substrate structures is the major retention mechanism in natural riffles (Speaker *et al.*, 1984) and in the straightened stream section as well, since its morphological properties are comparable to these riffles. The particle entrainment can explain the seasonally constant CPOM standing crop of the straightened site. Particles retained in the gaps of the bed substrate are resistant against resuspension (Webster *et al.*, 1987). Thus, minor discharge variations would cause an at most slight particle release.

In contrast, the high BOM storage in the impoundment is probably due to sedimentation, similar to particle deposition in natural pools (Speaker *et al.*, 1984) and backwaters (Ehrman and Lamberti, 1992). Current velocities less than particle fall velocity in these structural elements cause particle sedimentation. FPOM, the dominant BOM particle-size fraction in the impoundment, occurred generally in higher amounts in places of smoother bed surfaces indicating localities of low current velocity over extended time periods. A positive correlation of FPOM standing crop with high hydraulic radius corroborated a retention that is independent from intensive water-substrate contact. This, and the fine, impermeable bed substrate, contradict entrainment and suggest sedimentation as the major retention mechanism in the impounded Ilm section.

Current velocity clearly effects deposition (Minshall *et al.*, 2000) even when there was no evidence for a direct influence on the BOM in the Ilm. This is an artefact of measuring current velocity just before BOM sampling, since deposition is influenced by flow conditions a long time prior to sampling (Wanner *et al.*, 2002). Data on previous flow conditions for the single sites were unfortunately not available. The sedimentation causes a layer of organic matter on the bed surface susceptible for resuspension. Natural slight but frequent discharge variations would result in periods of net particle fixation and net release. This may explain the strong seasonal changes in CPOM standing crops. It seems that the extreme dominance of either sedimentation or entrainment, as in the degraded sections, results in a more effective CPOM retention than the existence of both mechanisms in close spatial proximity, as in the natural site with its resulting transition zones.

Both impoundment and straightening altered BOM size distribution and BOM availability. Proportions of CPOM to FPOM were naturally almost equal. In the straightened site, CPOM dominated BOM. In the impoundment, FPOM dominated BOM. Thus stream biota face altered particle pools as food and habitat (Jones, 1997). The River Continuum Concept (Vannote *et al.*, 1980) predicts CPOM as the major POM component in headwaters, with increasing FPOM proportions downstream. If the balanced

CPOM : FPOM ratio in the reference site is presumed to be the potentially natural state, the BOM size distribution in the impoundment is comparable to that in reaches more downstream whereas the straightened site is comparable to upstream reaches. The stream continuum (Vannote *et al.*, 1980) is interrupted. For the Ilm, the discontinuity concept of lotic ecosystems by Ward and Stanford (1983), predicting a depression of CPOM : FPOM ratio for impoundments, is confirmed.

Another aspect is the seasonal BOM dynamic. Compared to the natural reference the seasonal variation of CPOM and FPOM standing crop in the impoundment was strongly increased, whereas seasonal CPOM variation in the straightened site was decreased. Altered seasonal BOM standing crop dynamic and changed particle-size distribution both ultimately affect stream food webs and species composition (Ward, 1976; Ward and Stanford, 1983; Baekken *et al.*, 1984; Cummins *et al.*, 1984; Haapala and Muotka, 1998; Martinez *et al.*, 1998). The impoundment and the straightening in the Ilm must be considered to represent serious impacts on the stream ecosystem.

6. Particle Transport - Suspended Organic Matter

6.1 Introduction

Fluvial organic matter dynamics are hardly assessed from a single and particular spatial or temporal scale (Pozo *et al.*, 1994). An approach providing information on organic matter retention in streams at a different time scale than benthic organic matter (BOM) is the organic matter transport (Figure 1). This transport is similarly effected by local retention efficiency as particle storage. However, the organic particle transport is influenced by flow regime and stream retentiveness immediately before (seconds to minutes) and during the sampling process, whereas BOM standing crop is influenced by the flow regime of an extended time period (Chapter 5). Thus, the amount of suspended organic matter (SOM) in the water column at the moment of sampling characterises short-term retention. Studies on short-term retention and organic matter transport are either based on measuring the temporary export of natural particles (e.g. Cuffney and Wallace, 1989; Angradi, 1991; Wallace *et al.*, 1991; Young and Huryn, 1997) or on tracer release experiments with artificial or C^{14}-labled particles (e.g. Miller and Georgian, 1992; Cushing *et al.*, 1993; Minshall *et al.*, 2000). The integration of short- with long-term retention results in the present thesis required the measurement of native organic particle transport to ensure comparability to BOM data. Thus, artificial particles were unsuited for the river Ilm. Furthermore, C^{14}- labelling was impossible due to methodological and financial constrains. Therefore for the present study, concentration differences of natural SOM between an upstream and a downstream location in each of the study sites in the three stream sections provided the necessary data on short-term retention that enabled a site comparison.

6.2 Methods

Sampling and analysis

Three drift nets (Johnson and Covich, 1997; 190 x 480 mm, 0.4 mm mesh size) were distributed evenly over the stream width to examine SOM concentration. The nets were set perpendicular to the current at the beginning and end of every stretch in Spring, late Summer and Autumn 2000. In winter, ice transport in the water prevented sampling.

Nets were positioned with their bottom edge at least 40 mm above the substrate surface to avoid sampling bed load and their top edge at the water surface to ensure the sampling of floating material. A hypothetical identical water parcel at up- and downstream points was sampled by submerging the downstream nets at a delay to the upstream nets which corresponded to the flow time. The mean time span necessary for the water from upstream to reach the downstream point was estimated using 10 floats. Drift net exposure time was 10-16 min as adapted to the suspended matter load. The flow rate in each net was recorded (Flo-Mate 2000; Marsh-McBirney Inc., USA) to compute the water volume passed through the net.

The samples were transferred in jars to the laboratory and stored at 5 °C in the dark. Organisms visible by binocular microscope were removed. The material was wet sieved using an analysis sieving machine AS 200 (Retsch GmbH & Co. KG, Haan, Germany) to separate coarse particulate organic matter (CPOM) from fine particulate organic matter (FPOM; particle size 0.4 - 1 mm). The samples were dried at 105 °C to a constant weight and subsequently ashed for 5 hr at 500 °C to determine ash free dry weights (AFDW).

Statistics

Data for SOM (mg AFDW l^{-1}) at the up- and downstream points in each study site at the sampling dates and in the different stream sections were not adjustable to normal distribution and variance homogeneity by common transformation techniques. Therefore, Mann-Whitney tests were used to test for differences in the SOM concentration between up- and downstream points in each site. Mann-Whitney tests with adjusted significance levels ($p < 0.025$) were applied for the multiple tests (triple) on differences between each sampling date. The comparison of the amounts of SOM between study sites was done by Kruskal-Wallis-ANOVA on ranks. The statistics described were calculated with SPSS 10.0 computer package (SPSS Inc.).

6.3 Results

The mean concentration of suspended CPOM (particle size >1 mm) in all sites during the sampling dates was 0.27 mg AFDW l^{-1} (S.E. 0.49) and that of FPOM (particle size 0.4 - 1 mm) was 0.011 mg AFDW l^{-1} (S.E. 0.004). On 200 m flow distance, the concentration of suspended CPOM was reduced significantly by 75 % (Mann-Whitney test, $n = 18$, $p < 0.05$) in the natural stream section and by 87 % (Mann-Whitney test, $n = 18$, $p < 0.005$) in the impoundment (Figure 24). In the straightened site, the concentration of suspended CPOM did not differ significantly (Mann-Whitney test, $n = 18$, $p > 0.05$) between the upstream and downstream points. Concentrations of suspended FPOM did not change (Mann-Whitney test, $n = 18$, $p > 0.05$; Figure 24) in any study site.

The amount of SOM in transport varied between seasonal samplings. In summer and autumn, mean concentrations of CPOM in transport (0.29 and 0.44 mg AFDW l^{-1} respectively) were significantly higher (Mann-Whitney test, $n = 18$, $p < 0.025$) than in spring (0.08 mg AFDW l^{-1}; Figure 25). In contrast, with FPOM the significantly lowest amount of particles in suspension (Mann-Whitney test, $n = 18$, $p < 0.025$) was found in summer (0.003 mg AFDW l^{-1}; Figure 25). The concentration in spring (0.009 mg AFDW l^{-1}) and autumn (0.021 mg AFDW l^{-1}) did not differ significantly (Mann-Whitney test, $n = 18$, $p > 0.025$). Between the sites in the three stream sections, no significant differences were found in the mean SOM concentrations of the three seasonal samplings (Kruskal-Wallis-ANOVA on ranks, $p > 0.05$, $n = 54$).

Figure 24:
Concentrations of suspended coarse particulate organic matter (CPOM; upper graph) and fine particulate organic matter (FPOM, 0.4 - 1 mm; lower graph) in each of the three study sites at the upstream (black bars) and downstream (grey bars) sampling points. Resulting from comparison of these concentrations by Mann-Whitney test ($n = 18$), ** = $p < 0.005$, * = $p < 0.05$, n.s. = $p > 0.05$, columns represent means of ash free dry weight (AFDW) of all samples; bars indicate the standard errors with the proportion of initial suspended CPOM retained or released given in %.

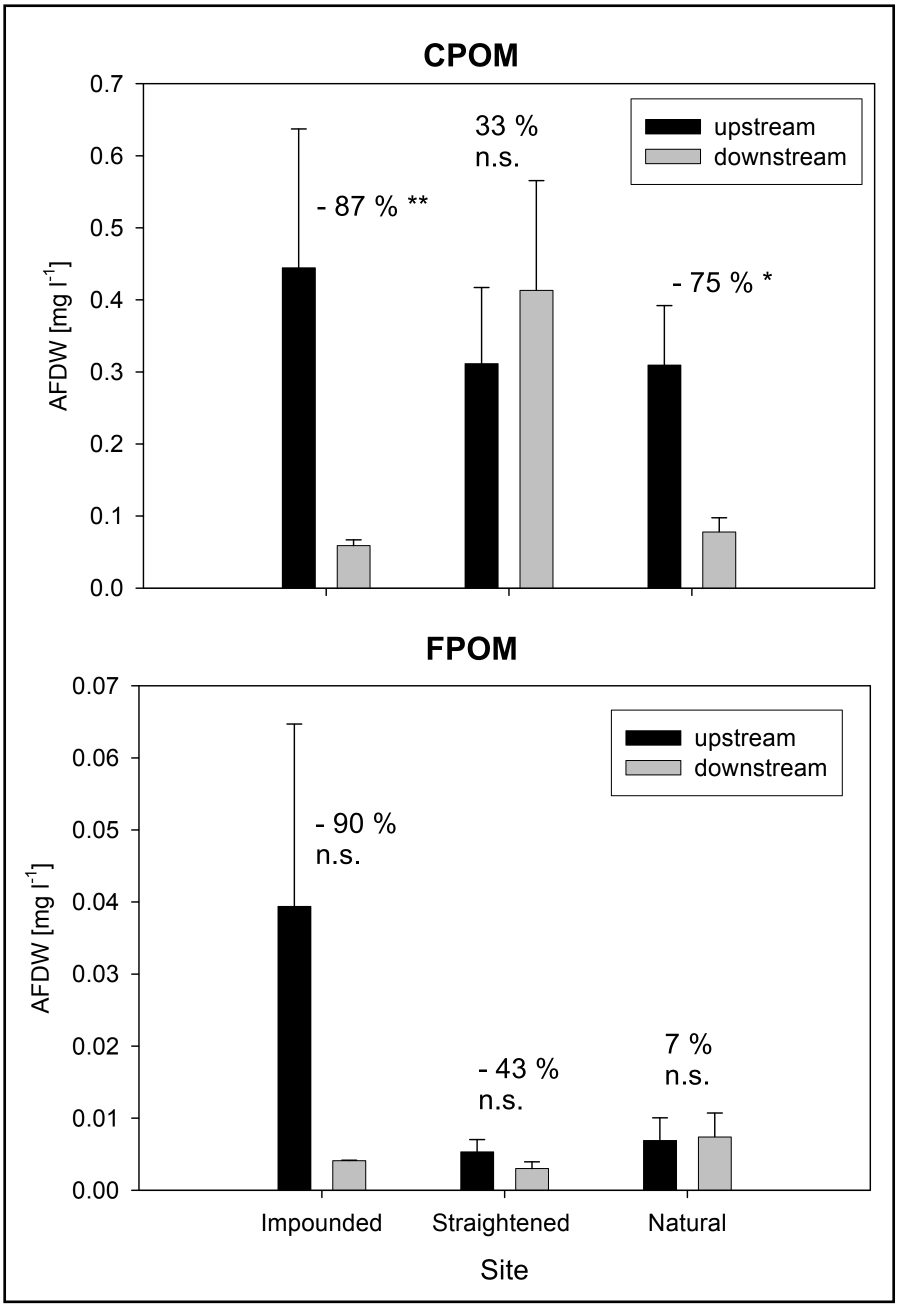
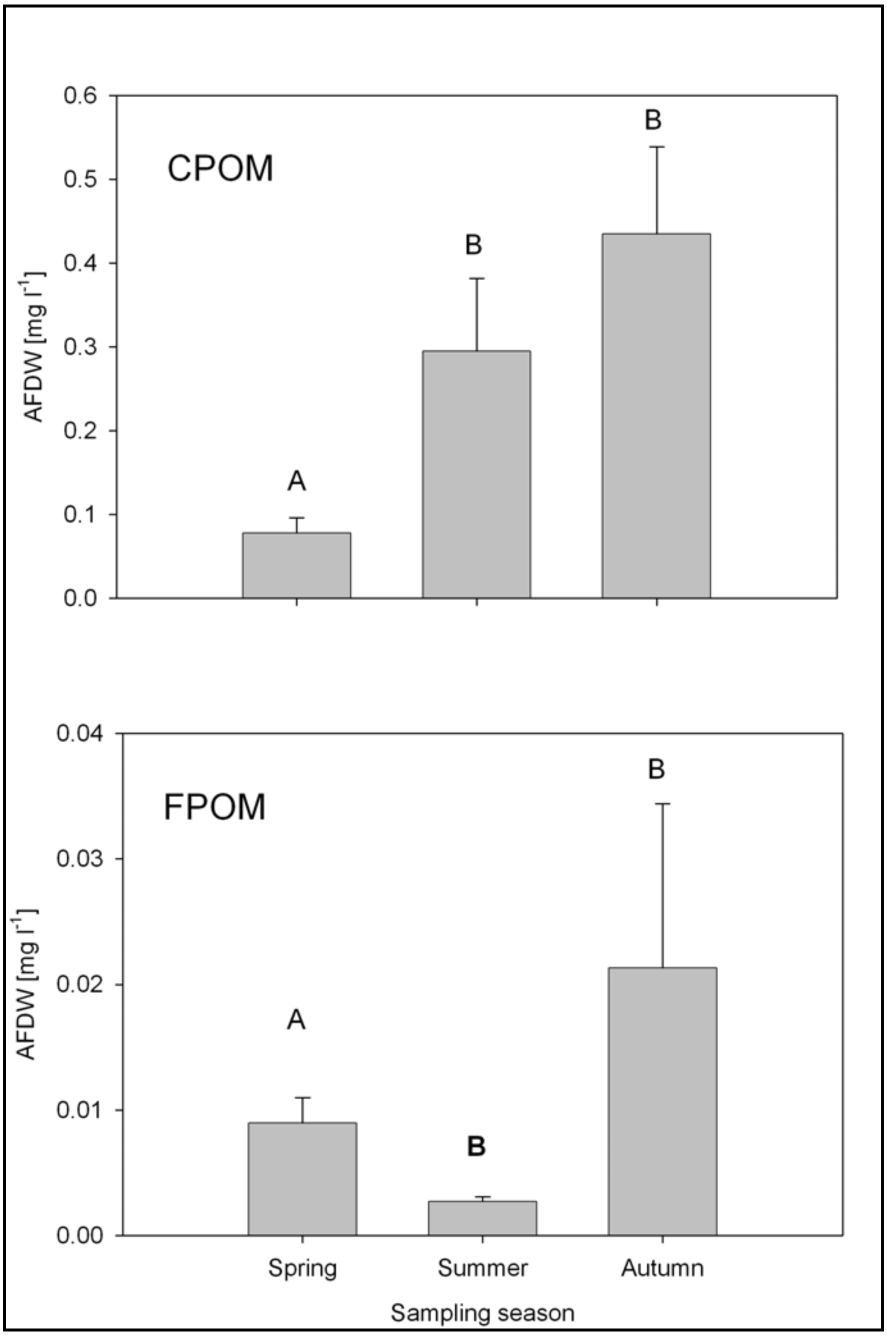


Figure 25:
Mean suspended organic matter (SOM) concentrations (columns), as ash free dry weight (AFDW) and standard errors (bars) during the three sampling dates; upper graph coarse particulate organic matter (CPOM), lower graph fine particulate organic matter (FPOM, 0.4 - 1 mm); letters indicate results from pair-wise comparisons by Mann-Whitney test ($p < 0.025$, $n = 18$) in CPOM and ($p < 0.025$, $n = 8$) in FPOM.



6.4 Discussion

The mean concentration of suspended CPOM in the Ilm (0.27 mg AFDW l^{-1}) at the three sampling dates was almost in the magnitude of average concentrations obtained by permanent sampling in three first-order streams with forested catchments in North Carolina (0.106 - 0.171 mg AFDW l^{-1}; Wallace *et al.*, 1995). SOM concentrations based on seasonal water sampling in the second- to fourth-order Upper Salmon River (0.069 - 0.098 mg l^{-1}; Minshall *et al.*, 1992) are lower than in the Ilm. This may be attributed to the low proportion of forest in the Salmon River catchment. The validity of the results from the Ilm is restricted to the moderate hydrological conditions during the sampling periods, whereas main particle transport occurs during storms. These storm events contribute up to 80 % to the annual export (Cummins *et al.*, 1983). Thus, permanent sampling would be necessary to obtain reliable data on annual mean suspended CPOM concentration or detailed seasonal variations. The present thesis did not focus on seasonal patterns and annual budgets of SOM but on an inter-site comparison of short-term retention. Thus, episodic sampling was appropriate.

The data from the Ilm indicate a significant impact of channel alteration on short-term retention of CPOM but not of FPOM (particle size 0.4 - 1 mm). In the natural and the impounded sites, more than 75 % of the CPOM was retained 200 m along the stream while no net fixation of CPOM existed in the straightened site. We exclude an influence of riparian vegetation inputs. If lateral input had added particles into suspension during the drift measurements, we would have expected values of low retentiveness in the impounded and natural stream sections due to higher overhead covers than in the straightened (Chapter 3). Lacking this phenomenon, it is evident that the site-specific differences in short-term retention in the Ilm are not the consequence of different local riparian vegetation.

Experiments involving the release of artificial leaves into the River Rutajoki (Haapala and Muotka, 1998) and nine Swedish second- to third-order streams (Petersen and Petersen, 1991) show similarly strong decreases in retentiveness for straightened streams as in the Ilm. Haapala and Muotka (1998) explain their results by the lack of retentive elements (boulders, debris dams etc.), similar to Petersen and Petersen (1991), who found leaves captured primarily in unstable retention devices (alcoves and macrophyte stands). In contrast, the Ilm straightened site had uniform but still natural bed substrate that included boulders. Alcoves, present at the left bank side, caused backwaters. Although unstable retention devices (Petersen and Petersen, 1991), these boulders and alcoves may increase short-term retention during stable and low discharge periods in the Ilm. Debris dams as retention structures were unimportant in all stream sections studied. Thus the low short-term retentiveness of the straightened Ilm section cannot be explained by the lack of retentive elements relevant for reduced retentiveness in River Rutajoki (Haapala and Muotka, 1998) and the nine Swedish streams (Petersen and Petersen, 1991). One possible explanation is the complete exploitation of the retentive capacity during the SOM sampling periods. In this case, almost no additional suspended particles can be fixed in the sediment (for further discussion in Chapter 8).

The high short-term retention in the impoundment is probably caused by the low current velocity. The high retentiveness may be restricted to constant base-flow conditions. If discharge increases, the current velocity would exceed particle fall velocity resulting in dramatically reduced retentiveness. In this case, even a resuspension of previously retained particulate organic matter (POM) may occur. Unfortunately, data on short-term retention during high discharge events were not available. The method used for quantifying SOM concentration was restricted to base-flow conditions. The natural stream section contained pools and riffles. Short-term retention typical for conditions at the impoundment (pools-like) and the straightened site (riffle-like) will therefore form a spatial mosaic. This possibly explains the intermediate retentiveness.

7. Detritus Processing Markers - Stable N-, C-Isotopes and C : N Ratios

7.1 Introduction

Beside the balance between fixation and release of organic matter in and from the stream bed, organic matter processing affects standing crop of benthic organic matter (BOM) as well (Figure 1). Detritus mineralization directly reduces organic matter standing crop and the decomposition process alters size, condition and chemical nature of the remaining organic matter while facilitating its export (Cummins *et al.*, 1984; Pusch *et al.*, 1998). BOM is a conglomeration of more or less decomposed organic matter with the attached microbiota community (bacteria, fungi, protozoa).

Dead organic matter undergoes steps of transformation (Pusch *et al.*, 1998) with a series of characteristic stages. C : N ratios of particulate organic matter (POM) decrease whilst it decomposes (Ward and Cummins, 1979; Schönborn, 1992). Additionally, there is a regular change in isotopic composition (Melillo *et al.*, 1989; Finlay, 2001). This suggests C : N ratio and stable isotopes to be markers of organic matter processing. However, most studies focusing on isotopic changes during decomposition are restricted to terrestrial environments (Nadelhoffer and Fry, 1988; Balesdent *et al.*, 1993). The use of stable isotopes in stream study is, up to now, mainly limited to identifying sources of POM (e.g. Hein *et al.*, 2003), whereas C : N ratio is a common tool to assess degradation of organic matter in stream ecosystems (Andrews *et al.*, 1998).

The suitability of C : N ratio and stable carbon and nitrogen isotopes for characterising processing stages of detritus (Pusch *et al.*, 1998) was tested in a field study in which we screened BOM from the study sites in the impounded, straightened and natural stream section of the river Ilm (Chapter 2) for differences in the BOM chemical and isotope composition. Additionally we compared C : N ratio and stable carbon and nitrogen isotope composition of detritus before and after processing in a laboratory experiment to check for changes in detritus during its processing in controlled environmental conditions.

7.2 Methods

Laboratory Experiment

Parts of an experiment primarily designed by Arle (unpublished) to elucidate food preferences of *Gammarus pulex* (LINNÉ) were used for monitoring the processing of leaves and leaf fragments (>2.5 mm and 2.5 - 1 mm) in the presence and absence of macro-invertebrates. The experiment was conducted in Perspex flumes (0.4 m x 0.05 m x 0.1 m) over a four-week period. Particle-size fractions were obtained by grinding and dry sieving dried leaves collected in Autumn 2000 from natural leaf packs in the Ilm. The leaf mix represented the natural input into the river and consisted of alder, ash, maple and willow leaves (Chapter 2). A single particle-size fraction was added randomly to one of 15 flumes containing 1.8 l of a 1:1 mixture of de-ionized water and tap water. The experiment provided 5 replicates for each treatment, two with macro-invertebrates and one control treatment (detritus >2.5 mm) without macrobiota. Initial inoculation with natural microbes and protozoa was assured by adding 5 ml of Ilm water to each flume. We reduced variations of environmental factors with a 12/12 hr light/dark regime, constant temperature of 10 °C in a climate chamber and a constantly circulating water flow of 0.1 m s^{-1} (±0.02 m s^{-1}). Weekly, 50 % of the flume water was replaced by the water mixture used at the beginning. An opaque screen protected the flumes from direct light to reduce autochthonous primary production. Four days after adding the detritus, five to six specimens of *G. pulex* were introduced to each flume in order to enable macro-invertebrates impact on detritus processing. The animals were collected in the Ilm and kept in a large aquarium for a one-week period prior to the experiment, allowing their adaptation to climate chamber conditions. During the experiment, dead specimens and exuviae of invertebrates were removed every second or third day. Animal densities in the flumes remained below those in the Ilm (Arle, unpubl.) to minimize competition and preventing high mortality. Body mass and length of *G. pulex* specimens increased during the experiment, indicating growth. The average survival rate was 86 %. Detritus input and detritus output of the same particle size were each analysed for carbon and nitrogen content and for stable isotope ratios (see Sampling Processing and Analysis). Note that the final detritus material of the replicates of each treatment was pooled prior analysis.

Sampling of Benthic Organic Matter in the River Ilm

BOM from the bed of the Ilm was sampled randomly using a Bottom-Sampler (Wagner *et al.*, 2001 submitted, see Appendix II and German Patent No.: DE 100 57 738 A1, see Appendix III) in September and November 2000. The sediment was transferred in jars to the laboratory and stored at 5 °C in the dark and treated according to the protocol given for BOM samples in Chapter 5.2. The BOM present in the sediment samples was not separated from the inorganic material; rather, the sediment was treated as a whole unit including biofilm on mineral surfaces. Only from the fraction >4 mm stones larger than 20 mm were removed. 46 samples were chosen for elemental and isotope analysis to screen BOM for differences between the study sites in the different stream sections and particle-size fractions (Table 10).

Table 10. Sampling seasons and number of samples used for screening the benthic organic matter (BOM) from the river Ilm for differences in C : N ratio, $\delta^{13}C$ and $\delta^{15}N$ value.

Particle size fraction [mm]	Sampling season	Number of samples
0.0016-0.071	Summer / Autumn	4 / 3
0.071-0.25	Summer / Autumn	3 / 3
0.25-0.4	-	-
0.4-1	Autumn	6
1-4	Summer	6
> 4	Autumn	10

Sample Processing and Analysis

BOM subsamples from the Ilm and detritus from the laboratory experiment were dried at 105 °C to constant weight. Subsequently, samples were ground to a fine powder, acidified (1 M HCl) to remove carbonates, neutralised (0.1 M NaOH) and rinsed (de-ionized water). After freeze-drying, samples according to 150 µg N or 50 µg C were weighed into tin capsules (separately for ^{15}N and ^{13}C). Finally, sample material was combusted in an EA 1110 Elemental Analyser (ThermoQuest, 20090 Rodano, Italy). The resulting gases N_2 and CO_2 were separated by gas chromatography and analysed for ^{15}N and ^{13}C content in a DeltaPlusXL isotope ratio mass spectrometer (Finnigan MAT, 28127 Bremen, Germany). The analytical precision was ±0.2 ‰ for ^{15}N and ^{13}C. Working standards were acetanilide

(δ^{15}N = 1.78 ‰, δ^{13}C = -33.94 ‰) and caffeine (δ^{15}N = -16 ‰, δ^{13}C = -51.80 ‰), calibrated against international standards IAEA-N2 and NBS-22. Accuracy and repeatability of measurements were assured according to Werner and Brand (2001). Isotopic ratios are expressed in conventional delta (δ) notation in parts per thousand: δX [‰] = ($R_{\text{sample}}/R_{\text{standard}}$ - 1) * 1000 ‰, where $X = {}^{15}$N or ^{13}C and $R = {}^{15}\text{N}/{}^{14}\text{N}$ or $^{13}\text{C}/{}^{12}\text{C}$, respectively. Standard was AIR for ^{15}N and V-PDB for ^{13}C.

One-way ANOVAs with subsequent Student-Newman-Keuls tests (S-N-K) were used to test for differences in C : N ratio, δ^{15}N and δ^{13}C between BOM particle-size fractions. The variances of the C : N ratios were not homogeneous between particle-size fractions (Levene test), therefore these data were square-root transformed prior to testing in order to achieve variance homogeneity. The statistics described were calculated with SigmaStat 2.0 (SPSS Inc., 1997).

7.3 Results

7.3.1 Detritus Processing Experiment

All three parameters, C : N ratio, δ^{13}C and δ^{15}N value, changed during the four-week experimental period. Already the C : N ratios of the input material differed markedly between the coarser and the finer fraction (42.0 vs. 32.5; Figure 26). This difference indicates a qualitative differentiation introduced by the sieving procedure in addition to the particle-size fractionation. Detritus C : N ratios were lower at the end than at the beginning of the experiment (Figure 26). While in treatments with macro-invertebrates the decrease in the C : N ratio was more pronounced in the 1 - 2.5 mm particles, the control without macrobiota revealed a higher decrease compared to the >2.5 mm treatment with *G. pulex*. The δ^{15}N and δ^{13}C values of detritus increased in all treatments (Figure 27). Similar to the C : N ratios, the δ^{15}N values also shifted differently in >2.5 mm treatments both with (0.6 ‰) and without *G. pulex* (1.1 ‰), suggesting that, the particular animal species used had an influence on detritus processing. In contrast, δ^{13}C values differed slightly between the >2.5 mm treatments with and without *G. pulex* but the enrichment in ^{13}C was higher in the >2.5 mm fraction than in the 1 - 2.5 mm fraction (Figure 27).

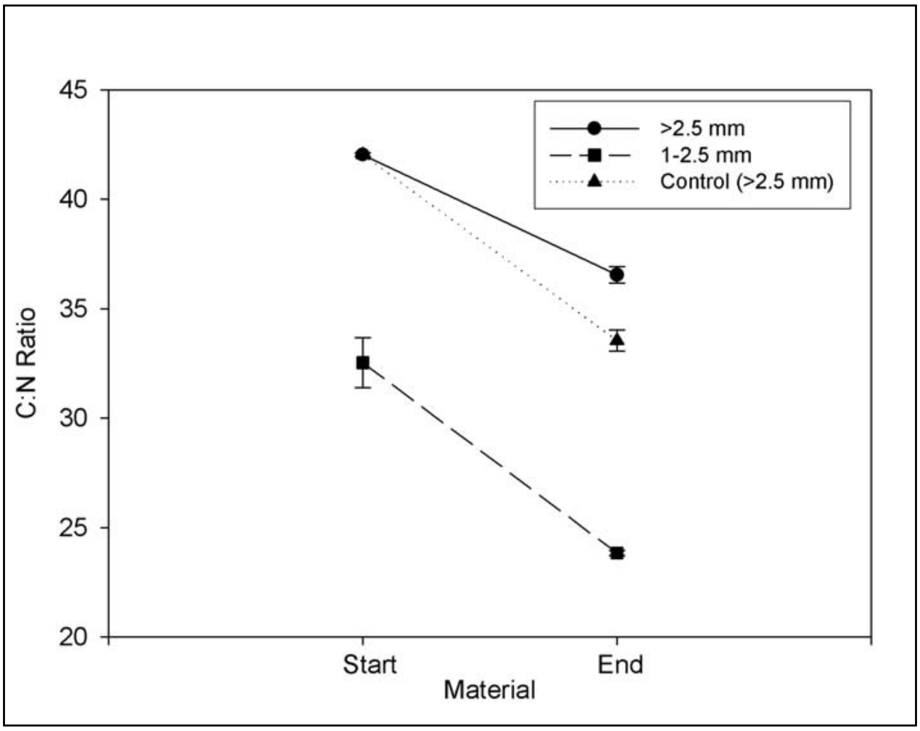


Figure 26: Detritus C : N ratios at the start (introduced organic matter) and at the end (organic matter after four weeks processing) of the experiment for each treatment: points represent medians, bars indicate minima and maxima of two repeated measurements.

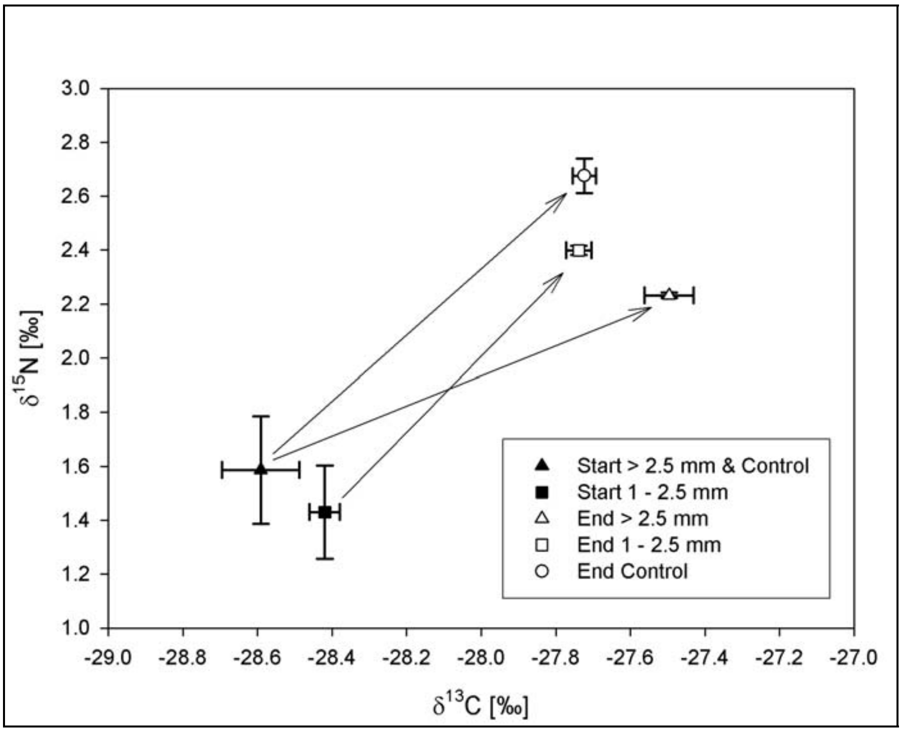


Figure 27: Median, minimum and maximum of two repeated measurements of the detritus $\delta^{13}C$ and $\delta^{15}N$ values during the detritus processing experiment in the two treatments: with animals (>2.5 mm and 1 - 2.5 mm) and the treatment without animals (control); start = introduced organic matter, end = organic matter, processed over four weeks.

7.3.2 Field Study on Natural Benthic Organic Matter

Differences between Particle-Size Fractions

The C : N ratios of BOM sampled from the Ilm decreased almost logarithmically with decreasing particle size from the coarsest (C : N ratios: 41) to the finest material (C : N ratios: 10; Figure 28). The C : N ratios of 0.071 - 0.25 mm and 0.4 - 1 mm fractions did not differ significantly (S-N-K, $p > 0.05$, $n = 18$; Figure 28). Isotopically, the particle-size fraction >4 mm was separated from the others by the low $\delta^{15}N$ value of 4.1 ‰ (One-way ANOVA, $p < 0.001$; S-N-K, $p < 0.001$, $n = 45$; Figure 29). The mean BOM $\delta^{15}N$ values of the smaller fractions ranged from 7.5 to 8.2 ‰ (Figure 29) and did not differ significantly (S-N-K, $p > 0.05$, $n = 35$).

The $\delta^{13}C$ value was statistically identical in all analysed fractions (One-way ANOVA, $p > 0.05$, $n = 40$; Figure 29). However, the four fine fractions, which each had the same ^{15}N signals, showed a certain order along the ^{13}C axis with the highest values in the 1 - 4 mm and the lowest in the 0.0016 - 0.071 mm fraction (Figure 29).

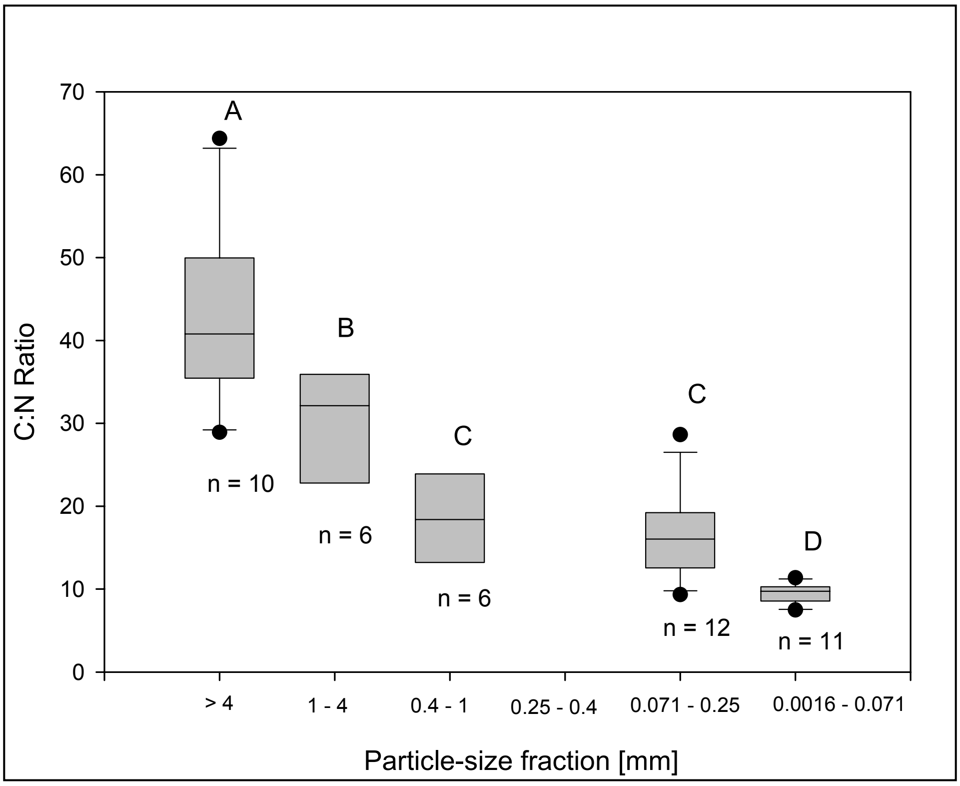


Figure 28: Box plots of the C : N ratio of benthic organic matter (BOM) of five particle-size fractions derived from river Ilm sediments; letters indicate homogeneous subsets from the Student-Newman-Keuls Post hoc test, $p < 0.05$.

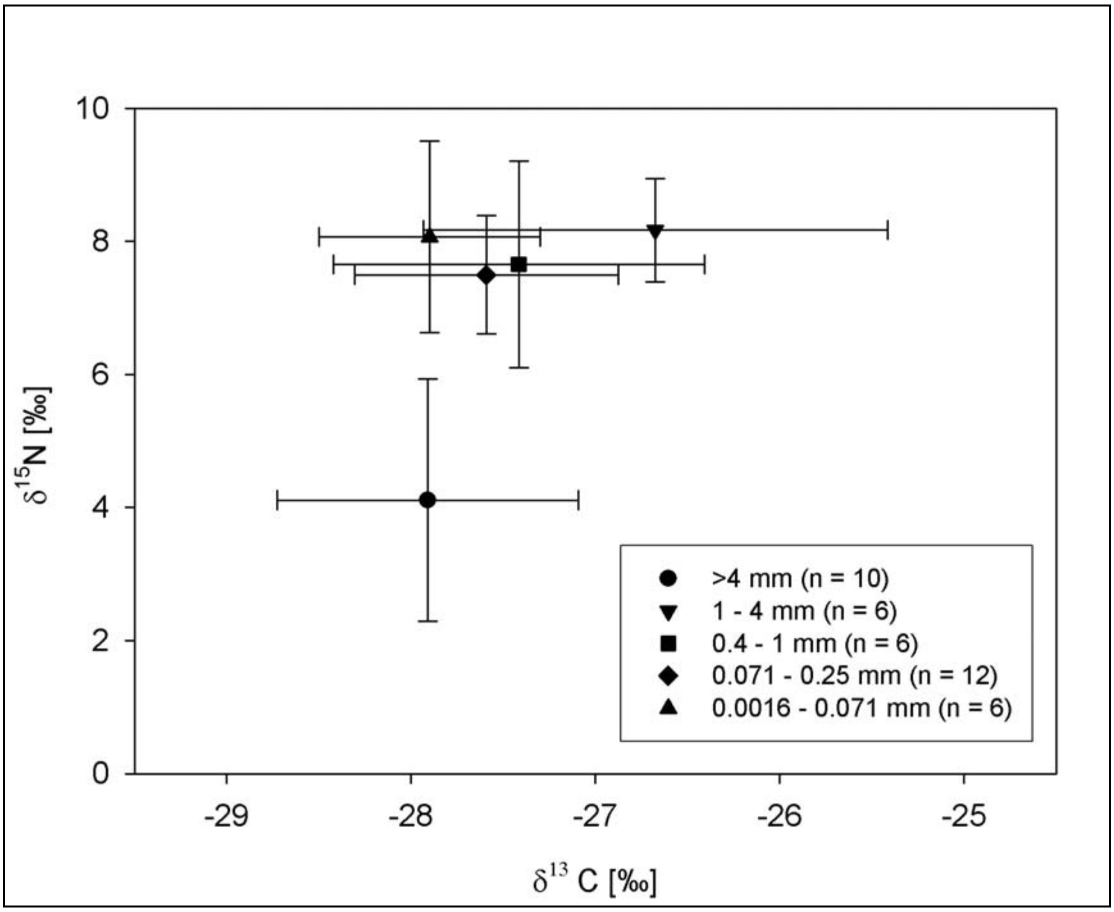


Figure 29: Means and standard deviations of $\delta^{13}C$ and $\delta^{15}N$ values of benthic organic matter (BOM) of five particle-size fractions derived from river Ilm sediments.

Differences between stream sections

No significant differences were found between the sites in the three stream sections in the C : N ratios of BOM. But ^{13}C and ^{15}N patterns varied between study sites. At the straightened site, the material >4 mm revealed lower $\delta^{15}N$ values (n = 3) than in the other stream sections (n = 7). A similar tendency existed in the 1 - 4 mm fraction (Figure 30). Concerning the fine particulate organic matter (FPOM, particle size 0.0016 -1 mm) in the 0.071 - 0.4 mm fraction, $\delta^{15}N$ values were lower at the impoundment (n = 4) than at the natural site (n = 4; Figure 31).

In the other FPOM fractions, $\delta^{15}N$ values were similar at all sites. The variation in the ^{13}C signals between the sites was in the range of 3 ‰ and small with respect to ^{15}N (~9 ‰). In the case of the 0.4 - 1 mm fraction, compared to the natural site, BOM at the impoundment was slightly depleted in ^{13}C. The $\delta^{13}C$ value at the straightened site (-29 ‰) was the lowest in the 0.4 - 1 mm fraction (Figure 31). In the other particle-size fractions, the BOM $\delta^{13}C$ values were very similar at all three sites (Figures 30 and 31).

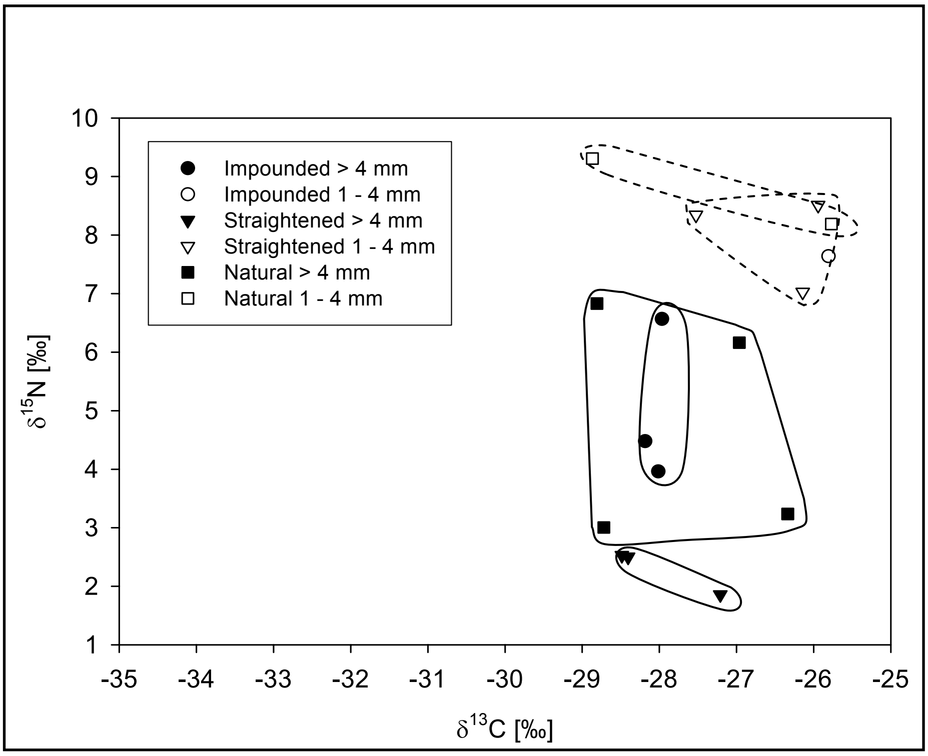


Figure 30: δ^{15}N and δ^{13}C values of the coarse particulate organic matter (CPOM; particle-size fractions >4 mm and 1 - 4 mm) of three stream sections of the river Ilm. Outlines emphasise data points of corresponding particle sizes. Black lines encircle samples of the particle-size fraction >4 mm, dashed lines 1 - 4 mm.

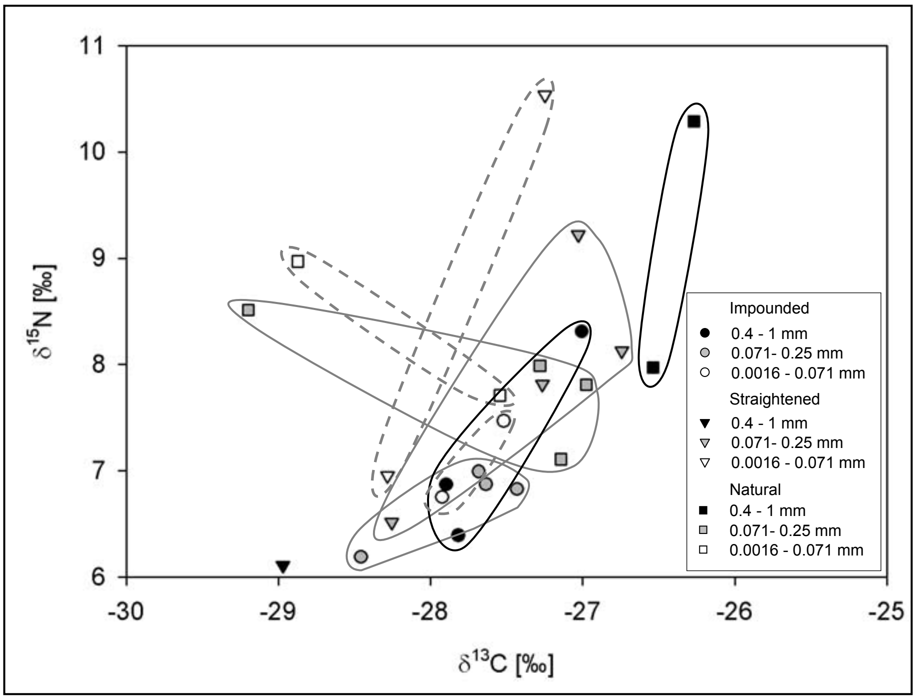


Figure 31: δ^{15}N and δ^{13}C values of the fine particulate organic matter (FPOM; 0.0016-1 mm) of three stream sections of the river Ilm. Outlines emphasise data points of corresponding particle sizes. Black lines encircle samples of the particle-size fraction 0.4 - 1 mm, grey lines 0.071 - 0.025 mm and dashed lines 0.0016 - 0.071 mm.

7.4 Discussion

Experimental results on C : N ratios and on $\delta^{13}C$ and $\delta^{15}N$ values indicate the alteration of the chemical and isotopic composition of detritus during its processing in aquatic environments. Degradation during organic matter processing is combined with an increase in the abundance of microbes in the decaying material which in turn is due to the increasing surface-to-volume ratio. This increasing proportion of microorganisms in the detritus results in a increasing C : N ratio during detritus processing (Schönborn, 1992) which is clearly demonstrated in the experiment (Figure 26). The results suggest that both initial detritus quality (C : N ratio, particle size) and the presence of macro-invertebrates modify the magnitude of the C : N shift. Apart from the contribution of pure chemical leaching, this shift is mainly driven by microbial decomposition activity. Animals grazing on the surface of organic material or biofilms may therefore interfere with the decomposition process by controlling the density of microbiota. This explain a smaller C : N decrease in leaf material >2.5 mm in the experiment with the *G. pulex* treatment compared to the larger decrease in the control.

The overall effect of the interaction between microorganisms and detritivorous animals on decomposition, is hard to predict because it depends on a number of factors. For soils, it was found that the influence of litter-feeding animals is strongest not only in relatively low-quality litter, such as freshly fallen litter with physical and chemical barriers against microbial attack, but also in decayed litter with a low C : N ratio in which carbon content and composition may be limiting for microbial growth (Van Wensem *et al.*, 1993).

In tendency the C : N ratio of organic matter present in the sediments of the Ilm decreased with the particle size of the sediment fraction. This agrees with the experimental results. Based on the fact that the major source of organic matter input to streams such as the Ilm is plant leaf litter from the riparian vegetation (Fisher and Likens, 1973), a decreasing particle size of the detrital material should correlate with the degree of organic matter degradation. Pusch *et al.* (1998) describe POM processing as a series of successive steps in which the reduction of cellulose and hemicellulose with a simultaneous increase of the protein proportion in the detritus cause decreasing C : N ratios in early processing stages. In late stages of decomposition, when POM is compacted into faecal pellets and densely colonised by microbiota, the C : N ratio may rise again (Ward and Cummins, 1979). This corresponds to the successive replacement of rapidly growing organisms with a low C : N ratio by more slowly growing organisms with a slightly higher C : N ratio. This replacement process is observed in soils, reflecting the increase in the fungal contribution to microbial activity (Henriksen, 1999) in the later stage of decomposition. In the field study, the organic material in the smallest of the analysed fractions (0.0016 - 0.071 mm) is unlikely to represent the latest stages of POM processing. In fact, its low mean C : N ratio of 10, which is close to the range (5-10) known from microbial biomass (Friedel and Gabel, 2001; Raubuch and Joergensen, 2002), suggests a still large contribution of microorganisms attached to mineral and organic surfaces (biofilm).

The ^{13}C enrichment in the incubated leaf-litter material was at levels that agree with published data on carbon isotope fractionation during in-stream POM decomposition (Finlay, 2001). A small but consistent ^{13}C enrichment was found in the degradation succession from live foliage to coarse particulate organic matter (CPOM) then to FPOM (Finlay, 2001). This trend was not detectable in the BOM sampled from the Ilm. Although not significantly, the $\delta^{13}C$ values decreased from the 1 - 4 mm to the smallest sediment fraction, in example the 1 - 4 mm fraction was most enriched in ^{13}C (Figure 29). Similarly, in the experiment ^{13}C enrichment, from the initial phase to final detritus, was more pronounced in the material >2.5 mm when compared to the 1 - 2.5 mm material.

The apparent contradiction to the reported trend underlines the complex nature of $^{13}C/^{12}C$ fractionation during detritus processing. Like changes in the C : N ratio, ^{13}C enrichment also depends largely on microbial activity. Microorganisms colonising dead organic matter preferentially use ^{12}C for their respiration (Blair *et al.*, 1985) leading to an enrichment in ^{13}C (Ågren *et al.*, 1996). On the other hand, the amount of slow decomposing plant material low in ^{13}C (O'Leary, 1981) should increase during the decomposition process. This leads to a more rapid loss of ^{13}C from the organic matter (Ågren *et al.*, 1996) and causes ^{13}C depletion. The microbial preferences for organic matter compounds high in ^{13}C and the preferential respiration of ^{12}C drive $\delta^{13}C$ values in opposite directions. Their effects partially cancel each other out.

The $\delta^{13}C$ values from five particle-size fractions were found to be not sensitive enough either to differentiate between organic matter per se or to differentiate between the three study sites in the Ilm. Instead, $\delta^{15}N$ values seemed more promising as POM processing markers in streams. In the course of decomposition, the ^{15}N content of the remaining, more and more degraded material (including bacteria and fungi) should increase mainly as a consequence of the colonisation with microbes that rely on the input material as food source. The relative N accumulation in microbes in the form of chemical compounds, which are more easily available to animal consumers than the original material, is combined with the enrichment of the ^{15}N isotope. Caused by the preferential excretion of the lighter ^{14}N isotope, this enrichment is equivalent to the known isotopic shift between consumer and its diet along the food chain (Minagawa and Wada, 1984). The measured ^{15}N signals provided sufficient resolution to find differences in the Ilm BOM composition both between the particle-size fractions and between the study sites. Detritus ^{15}N data clearly separated the largest particles (>4 mm) from the smaller ones.

Moreover, in two particle-size fractions based on $\delta^{15}N$ values, differences in detritus composition between the three study sites were detectable. The lower $\delta^{15}N$ value of the BOM >4 mm separated the straightened site from the others. The ^{15}N enrichment in the experiment indicates less processed detritus in the straightened site. However, a reduced processing rate in this stream section is unlikely. The high current velocities in this section (Chapter 3) would rather speed up the decay. For example, hyphomycets play an important role in leaf litter breakdown and depend on nutrient supply from the surrounding water (Robinson and Gessner, 2000). High current velocities increasing nutrient and oxygen supply of stream organisms would therefore facilitate microorganism activity. A better explanation is entrainment-based retention (Chapter 5.4). Further processed leaves are soft due to their stronger disintegrated plant tissue. More than fresh leaf litter, these softer leaves will be easily washed through the pores of the bed substrate (Chapter 8). This will result in a preferential removal of further-processed leaves and will cause an increased proportion of fresher leaves and leaf fragments in the BOM of the straightened site.

The lower ^{15}N enrichment, that was observed during the experiment comparing the detritus >2.5 mm to the 1 - 2.5 mm detritus, can be interpreted as a result of a lower processing rate due to the reduced performance of microbes on larger particles (Van Wensem *et al.*, 1993). A comparison of the experimental results and river BOM data was appropriate since both POM >4 mm from the stream and the detritus input used in the experiment consisted of freshly fallen leaves and leaf fragments from the same location and the same season. The similarity of these materials was corroborated by their almost identical C : N ratios (Figures 26 and 28).

In FPOM of 0.071 - 0.25 mm the low $\delta^{15}N$ values distinguished the impoundment from both the natural reference and the straightened site. However, our experimental results cannot explain these low $\delta^{15}N$ values in the FPOM from the impounded stream section. Particle-size reduction in streams results from several biotic and abiotic processes

(Pusch *et al.*, 1998) which may alter organic matter characteristics differently. Therefore to properly interpret stable isotope data from field samples, further experimental studies on detritus processing are required that will be carried out both with and without detritivorous macro-invertebrates considering the finest particles.

The present attempt of using leaf litter material >2.5 mm to describe the influence of macrobiota on the decomposition of detritus in aquatic environments indicated that, apart from different changes of the C : N ratios the isotopic signals individually responded to the presence of a macro-invertebrate species. The experiment showed a lower shift in detritus ^{15}N, but a higher shift in ^{13}C when treated with *G. pulex* compared to the treatment without it. This indicates that *G. pulex* exerted at least some control on the decomposition performance of microbes on the surface of the organic particles. Reduction of the number of microbes leads to both reduced ^{15}N enrichment in the detritus and to a reduced release of easily degradable compounds enriched in ^{13}C relative to the bulk material (O'Leary, 1981). This can explain the lower δ^{15}N values but higher δ^{13}C values of the processed detritus in the treatment with *G. pulex* compared to the treatment without it.

The resolution provided by C : N ratios was too low for detecting differences in the chemical nature of BOM between the stream sections of the Ilm. However, stable N isotopes indicated different chemical compositions of the BOM at the degraded sites when compared to the natural reference site. Combining ^{15}N and ^{13}C data can further improve the resolution and allow separating the impoundment from the natural reference in the 0.4 - 1 mm fraction as well (Figure 31). The combination of stable carbon and nitrogen isotopes is therefore a promising approach to characterise stream detritus in different processing stages and a useful tool to investigate impacts of channel alteration on BOM.

8. General Discussion

Time Scale and Retention

As stressed in Chapter 1, benthic organic matter (BOM) standing crop (storage) is a marker for long-term (weeks to years) retention but suspended matter (transport) is a marker for short-term (seconds to minutes) retention. Short-term retention is influenced by the present flow regime whereas long-term retention is influenced by the flow regime of an extended time period. Therefore differences between short- and long-term retention measurements can certainly be found in most streams depending on the respective sampling design. According to the particular study aim, sampling periods have to be adjusted carefully to the time periods relevant to long- or short-term retention, respectively. For inter-study comparisons, it is necessary to conscientiously consider these time-scale-dependent differences.

In the straightened site of the river Ilm, a decreased short-term retention of coarse particulate organic matter (CPOM), when compared to the natural reference, contradicts an increased long-term retention. CPOM standing crop of the straightened site was as high as that in the impoundment, whereas suspended CPOM (short-term) was retained much more efficiently (Chapters 5 and 6).

Despite the inherent time scale difference between detritus storage (long-term) and transport (short-term), Minshall *et al.* (1983) integrated both by means of an index describing the local retentiveness of a stream reach. They express the relationship between both processes as reach retention (RR). This RR is the relative ratio of stored BOM to organic matter in transport after multiplication with the average depth (*d*) of the stream section (equations 3 and 4).

$$RR = \frac{BOC}{TOC \cdot d} \quad \text{(Minshall } et\ al.\text{, 1983)} \qquad (3)$$

BOC: benthic organic carbon

TOC: transported organic carbon

d: water depth [m]

Adapted to the current thesis:

$$RR = \frac{BOM}{SOM \cdot d} \qquad (4)$$

BOM: benthic organic matter [g ADFW m^{-2}]

SOM: suspended organic matter [g ADFW m^{-3}]

In the current thesis, as in other studies (Minshall *et al.*, 1983; Minshall *et al.*, 1992), transport was measured episodically for short time periods (Chapter 6.2). So RR can be estimated by reasonable sampling effort. Based on our measurements of the suspended organic matter (SOM) in combination with BOM data, the average RR for CPOM amounts to 5056 (±2457 S.D.) in the impoundment, 1772 (±1298 S.D.) in the natural reference and 1707 (±1940 S.D.) in the straightened site. The very high RR for CPOM in the impoundment confirms its more retentive nature compared to the natural reference, whereas the RR in the straightened site was almost equal to the natural. This shows that the straightening of the studied section in the Ilm had almost no affect on CPOM retentiveness. It is necessary to emphasise that the validity of this RR is limited to the hydrological and physical conditions during the short sampling period of for instance SOM. High temporal dynamics in organic matter transport are not reflected by the short SOM sampling. Although the comparison of storage and instantaneous transport provide useful insights on retention, they should be viewed with caution (Minshall *et al.*, 1992) since they consider different time scales. For purposes of comparison, the transport might be better expressed as an amount of matter passing over a unit area per day or some longer periods (Minshall *et al.*, 1992), corresponding to time periods assessed by BOM sampling. This would provide conformity of time scales but increase methodological efforts tremendously. However, it was exactly this time scale difference that was useful for attempting to assess storage dynamics in the Ilm lacking continuous transport or storage measurements.

Storage Dynamics and Retention Mechanisms

In the straightened site, low hydraulic radius (corresponding to low depths) and coarse permeable bed substrate probably result in hyporheic entrainment as the major CPOM retention mechanism (Chapter 5.4) as Smock (1990) and Minshall *et al.* (2000) found for natural streams as well. The presence of stable nitrogen isotopes in the straightened site, indicating less processed BOM (>4 mm) further corroborate the entrainment dominance. The processing stage of particulate organic matter (POM) affects organic particle retention. Thus, retention by entrainment is more effective for fresh, stiff leaves and leaf fragments (Chapter 7.4) than for further processed leaves. Progressive disintegration of the plant tissue makes leaves susceptible to removal from the pores of the bed substrate and to export out of the local reach. Sedimentation would not be affected strongly by the condition of the leaf tissue. The processing state of the organic matter may influence sedimentation weakly due to the alteration of shape and density of the particles, even though there is no direct evidence from the present study.

Entrainment results in an effective and stable fixation of particles within the stream bed (Speaker *et al.*, 1984; Webster *et al.*, 1987). Moderate variations in current velocity and turbulence therefore cause only weak POM resuspension. The low variation of the CPOM standing crop during the study period (Chapter 5.3.2) confirms this stable fixation. Most of the time BOM standing crop probably stays approximately at the level of the input-dependent maximum storage capacity (Figure 32). Almost no matter will be additionally retained and transitory SOM will remain in transport. This can explain the lack of CPOM fixation during the periods of quantifying short-term retention (Chapter 6.3). This illustrates that a low short-term retention does not inevitably imply a low BOM standing crop.

As stressed above (Chapter 5.4), sedimentation is probably the major retention mechanism for CPOM in the impoundment. This and the fine impermeable bed substrate will cause a loose detritus layer to form on the streambed surface. However, neither in natural pools nor on banks of the Ilm did we find, the specific anaerobic backwater sediments consisting of silt and clay mixed with organic particles that were described by Proft (1995). One exception was a very small patch at transect 20 of the study site in the straightened stream section (Figure 10). The loose layer of POM in the impoundment is susceptible to resuspension by increased current velocity and water turbulence (Jones and Smock, 1991) comparable with conditions in natural pools (Malmqvist, 2002). The stored CPOM is therefore less resistant to the frequent minor hydrological variations between April and January in the Ilm (Figure 7) in the impoundment than in the straightened site. Even slight discharge increases (maximum five times; Figure 7) result probably in resuspension and export of BOM. After the current velocity decreases again, the particle loss will be compensated by the fixation of new SOM. Consequently, CPOM standing crop should be subject to strong variations (Figure 32), which is confirmed by the BOM standing crop data from the Ilm (Chapter 5.3.2). Wanner *et al.* (2002) found a reduced seasonal variability of BOM amount in an impoundment compared to a free-flowing section of the river Spree. This contrary result is probably caused by the higher spatial extent of the Spree impoundment and the more constant hydrological conditions in this lowland stream.

There is no direct evidence from short-term retention data for alternating periods of net releasing and fixation predicted for the impoundment. This is an artefact due to SOM sampling (Chapter 6.4). Temporal net releasing periods must have occurred in the impoundment and the natural site since CPOM standing crops were not higher than in the straightened site (Chapter 5.3.1).

The heterogeneous channel structure of the natural stream section forming a spatial mosaic of pools and riffles (Chapter 3) causes physical parameters and hydrological conditions similar to those in the impoundment (pools) and the straightened section (riffles) within a single stream stretch. Analogous retention mechanisms, such as those found in the impoundment and the straightened stream section, will occur in close spatial proximity. Therefore, overall storage dynamics of this section will be a mixture between dynamics of the impoundment and the straightened site (Figure 32).

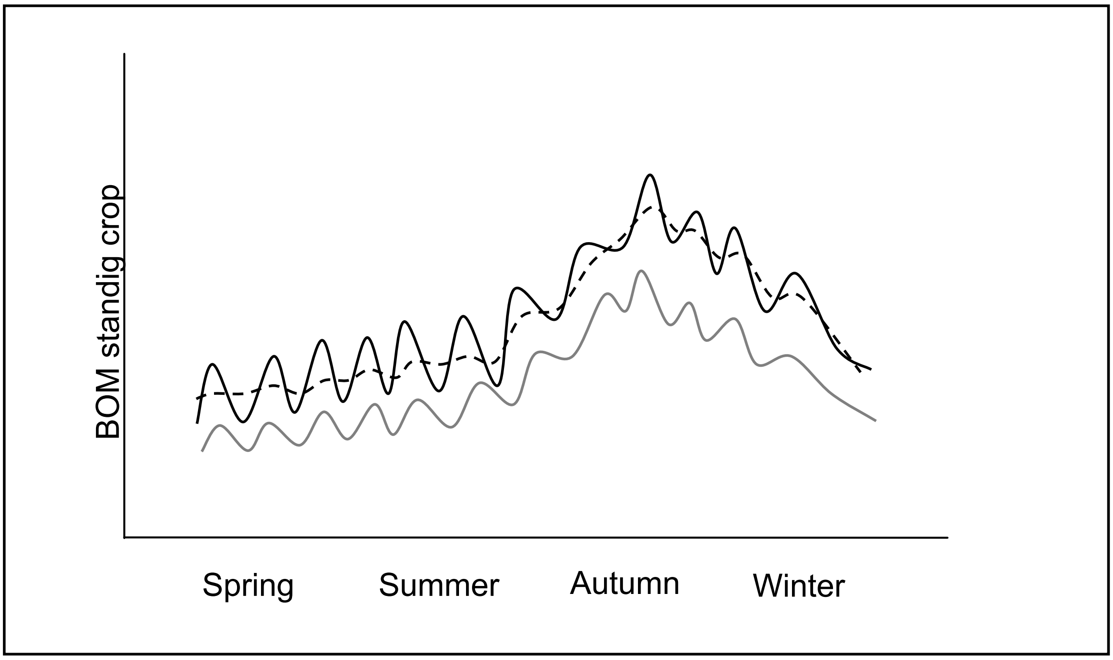


Figure 32: Hypothetical benthic organic matter (BOM) dynamic within the three morphologically different stream sections; the black line represents the standing crop in the impoundment with high BOM fluctuation, the grey line the standing crop in the natural site with intermediate fluctuation and the dashed line the straightened site with its low standing crop variability.

The relationship between retention mechanism and BOM dynamic in the Ilm suggests general predictions for streams. In shallow streams with coarse bed substrate and particle entrainment based retention (Smock, 1990 and Minshall *et al.*, 2000), BOM amounts should remain seasonally more constant than in deeper streams with fine bed substrate and sedimentation-based retention, presuming similar hydrological conditions. Further research is needed to test this prediction, by comparing retention and POM storage dynamic between low-order streams dominated by entrainment-based retention and high-order streams dominated by sedimentation-based retention.

The validity of CPOM retention mechanisms and CPOM storage dynamics suggested for the Ilm is limited to the time period between spring and the end of autumn. During winter, annual large spates remove almost the entire BOM at least from upper sediment layers. Data of standing crop shortly after these spates were not available, due to methodological constrains preventing sampling BOM during high discharge. In all sites however, detritus particles were not visible in spring after these spates in Winter 2000. Bed substrate appeared polished by water flow and ice. The amount of BOM standing crop might have experienced a reset to a similar low level in each stream section.

The Sponge Model – Channel Dependent Storage of Coarse Particulate Organic Matter

Derived from the storage dynamic stressed in the previous paragraph, I suggest water storage in sponges of different material as model to illustrate in-stream particle storage in the impounded and straightened stream sections. Maximum organic matter storage capacity and storage stability in the streams depend on their channel properties. In sponges, the material determines the water storage capacity and the stability of the water held within. In streams, particles are released from stream bed when discharge increases. In sponges, pressure from outside causes water release (Figure 33). Beside the magnitude of the impact (discharge for streams, pressure for sponges) the storage stability (resistance) in both systems determine the amount of POM or water released (Figure 33).

Consider the straightened site as a sponge made of a hard, pressure-resistant material. If this sponge, filled with water to its maximum water storage capacity, is squeezed, the stable sponge structure would allow the release of only small amounts of water (Figure 33). After the pressure stopped, the same low volume of water would be reabsorbed. Temporary and moderate pressure would affect the water storage only slightly. The sponge would contain a relative constant water volume, even when squeezed from time to time. Considering the stream in this context, the low seasonal variation in BOM standing crop confirms a particle storage dynamic in the straightened stream section (entrainment dominated retention) that corresponds to the water storage dynamics of this hard sponge. In contrast, a soft sponge, much less pressure resistant than the previous sponge but with an identical storage capacity, might represent the impoundment. This soft sponge, when filled to its maximum water storage capacity as well, would release a much higher water volume when the same pressure acts on it as acted on the hard sponge (Figure 33). When the pressure stops, this high water volume would be reabsorbed. The water volume within the sponge would vary highly between the periods with pressure and the periods without. This corresponds with the high variations found for CPOM standing crop in the impoundment, with sedimentation as the major retention mechanism.

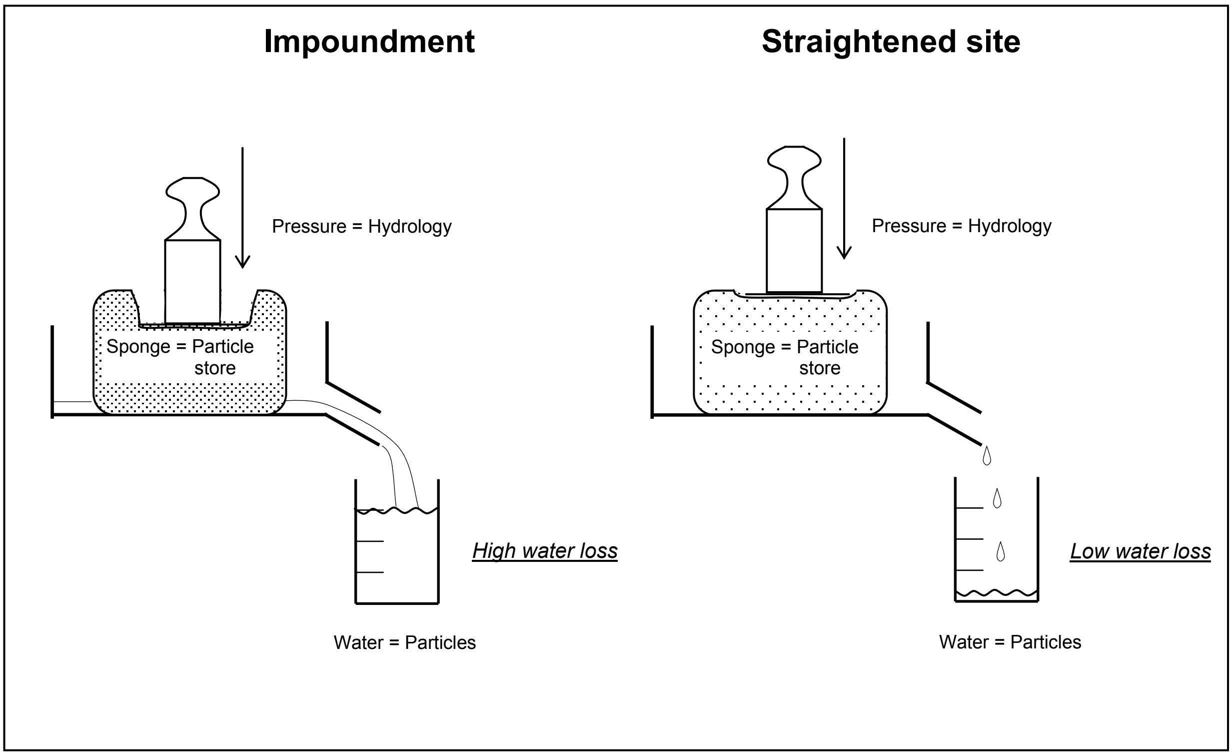


Figure 33: The sponge model for organic particle storage in the impoundment (left side) and the straightened site (right side) studied in the river Ilm.

Impacts of Straightening and Impoundment in the River Ilm and Implications for River Restoration

The almost equal proportions of CPOM and fine particulate organic matter (FPOM) occurring naturally in the third-order river Ilm agreed with the BOM size distribution predicted by the River Continuum Concept (Vannote *et al.*, 1980) for the transient zone from headwater to midsize streams. Stream communities are adapted to local conditions (Vannote *et al.*, 1980) and will therefore respond sensitively to the alteration in storage dynamics and availability of BOM (Cummins *et al.*, 1989) in the degraded Ilm sections.

Increased seasonal CPOM standing crop variation and a decreased CPOM : FPOM ratio (Chapter 5) in the Ilm impoundment will certainly affect species composition. Ecosystem stability in streams may be achieved by a dynamic balance between forces contributing to stabilisation (e.g. retention mechanism) and those causing its instability (e.g. major discharge variations; Vannote *et al.*, 1980). The physical and morphological conditions (low current velocity, high hydraulic radius and water depth) in the impoundment, similar to downstream reaches of midsize streams (Chapter 3), would inevitably result in lower stability compared to that of the natural headwater state (Minshall *et al.*, 1983). On the other hand, such sections are less sensitive to anthropogenic disturbances such as bed substrate alterations (Minshall *et al.*, 1983).

In contrast, the straightened site maintained a high stability in organic matter storage. Thus, predicable food resources are available for stream biota. But the straightening will certainly influence the proportions between functional feeding groups. The increased CPOM proportion will favour shredders (Vannote *et al.*, 1980) and a dominance of less-processed CPOM at least during autumn will alter species composition and ecosystem structure.

It is important to emphasise that effective CPOM retention and the stable storage in the straightened site of the Ilm resulted mainly from its natural stream bed substrate and cannot be generalised for straightened streams with strongly altered bed substrate or particularly concreted stream channels. A reduced stream bed roughness will inevitably reduce retention dramatically. Combinations of stream straightening and stream bed pavement may reduce retention almost to zero.

The present study is one of the first considering the effects of straightening and impoundment on FPOM and CPOM retention in a headwater stream. From the key environmental factors for retention and their effects on BOM composition and dynamic, we can deduce general recommendations for restoration of headwater streams.

The impoundment's high hydraulic radius and high water depth result in sedimentation as the almost exclusive retention mechanism. This causes an unnatural FPOM dominance and high seasonal variation of BOM amounts. This finding certainly is valid generally for impoundments in headwater streams with a significantly increased hydraulic radius. Weir removal would be the essential first step to re-establish natural sediment conditions.

The validity of results from the straightened section may be limited to the section studied and similar sections in the metarithric zone of the Ilm. The results cannot be easily transferred to other streams since the bed substrate, one key environmental factor for retention, is highly variable between streams. However, the results from the Ilm confirm that the maintenance of the natural bed substrate is essential for stream channel restoration. Recovering or introducing the natural or natural-like bed substrate is able to improve retention in straightened headwater streams, with retention primarily based on entrainment. Studies in Finland revealed a reduced restoration success by the unintentional removal of aquatic mosses during stream-bed restoration activities (Muotka and Laasonen, 2002). Beside bed substrate, aquatic mosses are key retentive structures in these Finish streams. In the Ilm, aquatic mosses are rare but, although not present in the studied stream sections, macroalgae (e.g. *Cladophora* spp.) partially affect retention in the Ilm (Schönborn, 1996) similar to mosses in the Finish streams. Further important retention structures are the stream banks and alcoves (Bretschko and Moser, 1993). Although, unstable retention devices (Petersen and Petersen, 1991), these might temporarily increase retention in the straightened Ilm section. The development of a natural-like left bank by secondary alluvial depositions increased the retention capacity during low discharge periods when alcoves, including backwaters, are formed. Generally, the maintenance of locally important retention structures such as macrophytes or highly-structured shore lines are necessary to increase restoration success.

A major negative feature of the impounded and straightened Ilm sections and most engineered streams, which are hardly possible to remedy other than by giving the stream back the entire riparian zone, is their spatial homogeneity resulting from suppressing the natural bank erosion and meander formation. The development of pools and riffles is tightly linked to the erosion dynamics of the meandering streams (Schönborn, 1992). Natural streams, as visible in the natural reference in the Ilm (Chapter 3.3), are characterised by a spatial mosaic of (impoundment-like) pools and (straightened site-like) riffles.

The resulting patch dynamics (Pringle *et al.*, 1988) are important for stream ecosystem function and structure. Inter-patch differences in retention mechanisms and storage dynamics (Chapter 5) supply stream organisms with heterogeneous food resources. Frequent series of resuspension and fixation in pools (impoundment-like storage; Malmqvist, 2002) would constantly supply the benthic community with fresh organic matter and at least temporally with FPOM in high amounts. In contrast, the amount of the organic matter in riffles, that is resistant to the minor discharge variations from spring to autumn, remains relatively constant. Riffles might therefore provide a predictable food source for organisms feeding on CPOM. The establishment of riffle-pool patterns during stream restoration is therefore a further step to supply stream biota with natural, diverse POM.

In the Ilm, both impoundment and straightening in the present state seriously affected BOM as the major energy source for the stream community. Any anthropogenic alteration of natural stream channel morphology must be judged on its far-reaching consequences for the trophic interactions and the energy flow in stream ecosystems linked to the alteration of POM retention.

Summary

1. Biotic communities of headwater streams with forested riparian zones depend highly on allochthonous organic matter. In temperate regions, autumn-shed leaves entering the detrital stream food web are the major energy source for secondary production. Beside the litter input, the retention of organic particles in and onto the stream bed determine the availability of detritus for stream biota. This thesis focuses on the impact of stream straightening and impoundment on the retention of particulate organic matter (POM) in the third-order river Ilm (Thuringia, Germany).

2. Long-term retention was quantified in an impounded, a straightened and a natural stream section by measuring the amount and size distribution of the benthic organic mater (BOM). A new sampling device, the Bottom-Sampler, was developed for sampling the bed sediments in the Ilm with its hard and coarse bed substrate which was impossible to sample by traditional sampling techniques. This new technique instantly provides sediment samples for quantitative analysis and is applicable in a broad range of bed substrate conditions. The sampled sediment keeps its natural composition and spatial structure. The comparative use of the traditional Hess-Sampler (modified) and the Bottom-Sampler revealed the superior performance of the latter and reveals sampling effects on stream sediment data inherent in the traditional technique.

3. As expected, an increased deposition of coarse (CPOM; particle size >1 mm) and fine particulate organic matter (FPOM, particle size 0.0016 - 1 mm) resulted in a much higher amount of BOM in the impoundment (724 g AFDW m^{-2} ±130 S.E.) compared to the natural reference (221 g AFDW m^{-2} ±43 S.E.). But, the straightening did not result in a decreased BOM amount (234 g AFDW m^{-2} ±40 S.E.) as originally assumed. Moreover, a significantly increased CPOM long-term retention in this section was found. This was due to its low hydraulic radius, low water depth and coarse bed substrate promoting an efficient particle entrainment into the bed substrate. A Canonical Correspondence Analysis (CCA) revealed that these environmental factors explain most of the variability in the BOM data. In the impoundment the low-current velocities and high water depth favoured sedimentation as the dominant retention mechanism.

4. Both anthropogenic channel alterations resulted in a shift of the CPOM : FPOM ratio. Whereas in the natural section it was 0.9, FPOM dominance in the impoundment resulted in a ratio of 0.5. In contrast, the increased CPOM retention in the straightened site caused a CPOM : FPOM ratio of 2.5.

5. The results on short-term retention derived from three sampling studies in spring, summer and autumn in the identical stream sections did not entirely correspond to the results on long-term retention. Short-term retention in the natural and impounded sites was high. In the natural site, 75 % (min. 30 %, max. 93 %) and in the impoundment 87 % (min. 52 %, max. 82 %) of the suspended organic matter (CPOM only) was retained within 200 m flow distances. Surprisingly, despite high long-term retention, short-term retention in the straightened site was very low. We did not detect a net fixation of CPOM from the water column to the bed substrate.

6. This contradiction in CPOM retention based on different time scales suggests the dominance of two distinct retention mechanisms in the impounded and the straightened sites that were predicted from the morphological and physical conditions in these channels. In the impoundment, the particles retained by sedimentation form a loose layer on the stream bed surface. They are susceptible to resuspension by discharge variations. The particle losses during increasing discharge will be compensated when discharge decreases. This results in a high temporal variation of BOM standing crop reflected in the high seasonal variability observed in the Ilm. The method used for measuring suspended organic matter in transport is limited to low discharge periods. Short-term retention was therefore quantified most likely during these particle refill periods with high particle fixation.

In the straightened section, the particles retained in the pores of the bed substrate are resistant against moderate increases of current velocity. Except in winter with its spates, the storage capacity is probably almost continuously exhausted due to the low export of POM. No additional material can be retained. This could explain the lack of net fixation of organic particles from the water column. The weak seasonal variation in the straightened stream section confirms constant POM storage.

7. The impact of the site-specific retention mechanisms on the CPOM storage and its temporal dynamic can be illustrated by a sponge model. The particle storage in the impoundment is like the water storage in a soft sponge. If this sponge is squeezed slightly (stream: discharge increase), then a high volume of water will be released (stream: particles). After the pressure from outside has vanished, the same volume will be reabsorbed. In contrast, a hard, resistant sponge corresponds to the straightened stream section. Only a small water volume will be released under squeezing. Consequently, a low volume will be reabsorbed afterwards. Assuming identical squeezing (stream: discharge variations), water volume would vary more highly in the soft than in the hard sponge.

8. Detritus processing experiments in the laboratory revealed general patterns of chemical and isotopic alteration during the processing of organic matter in the aquatic environment. The C : N ratio of the detrital material decreased during the experiment by 5 to 8 and the processed final material was enriched in ^{13}C (max. δ^{13}C increase: 0.8 ‰) and ^{15}N (max. δ^{15}N increase: 1.1 ‰) compared to the initial organic matter. In the BOM from the stream, a decreasing C : N ratio was observed with decreasing particle size. But the C : N ratio was not sufficient to discriminate between the three stream sections of different channel structure. The measured ^{15}N signals from the Ilm BOM provided sufficient resolution to find a lower δ^{15}N in the largest particles (>4 mm) than was the case in other size fractions. The isolated δ^{13}C values did not provide this high resolution but combined with δ^{15}N values, the isotopic composition of BOM separated the impoundment and straightened stream section from the natural reference. Stable isotopes turned out as promising markers for organic matter processing in stream ecosystems.

9. Both impoundment and straightening affected organic particle retention in the Ilm. The unexpectedly low impact of the straightening on the total amount of BOM in the Ilm resulted from the natural bed substrate and the locally low hydraulic radius. Thus, canalisations linked to strong stream substrate alteration or artificial stream bed pavement would highly reduce the POM amount retained. The maintenance or re-establishment of the natural bed substrate, therefore, is the minimum demand for stream channel reconstructions.

Despite the natural bed substrate, the particle size distribution of BOM in the straightened section also differed from the virtually natural state. Further, the isotopic composition of the BOM in the straightened section indicated less microbial processed detritus than in the other sections, linked to a decreased food quality for detritivores. Solely establishing a natural bed substrate will therefore not be sufficient for stream restoration. Promoting riffle pool patterns seems necessary as well for re-establishing a natural POM storage dynamic and quality to which the native stream biota are adapted. A restoration of the impounded section seems completely impossible as long as the weir exists. Both impoundment and straightening of the Ilm in the present state alters the amount, temporal dynamic and quality of BOM, the major energy base for stream biota. This has far-reaching consequences for trophic interactions and the energy flow in stream ecosystems.

Zusammenfassung

Die Oberläufe der Fließgewässer (Gewässer 1.-3. Ordnung) mit bewaldeten Auen sind stark durch den Eintrag allochthonen partikulären organischen Materials (POM) geprägt. Es bildet die energetische Basis für die Bach-Biozönose. Die Verfügbarkeit des POM für die Fließgewässer-Organismen wird durch den Eintrag und durch die Retention des Materials im Gewässer bestimmt. Anthropogenen Änderungen der Gewässerstruktur, wie Begradigung und Stauung, wird ein starker Effekt auf Partikelretention in Fließgewässern nachgesagt. Detaillierte Untersuchungen dazu fehlten bisher. Die vorliegende Dissertation widmet sich dieser Thematik am Beispiel eines Staubereichs und eines begradigten Abschnitts in dem Mittelgebirgsbach Ilm (Thüringen).

1. Durch den Einsatz des von mir entwickelten Bottom-Samplers zur Sediment-Beprobung konnte die Zusammensetzung der Bachsedimente wesentlich genauer bestimmt werden als mit der traditionell genutzten Hess-Sampling-Technik. Durch das neue Verfahren wird das Sediment in seiner natürlichen Zusammensetzung und räumlichen Struktur entnommen. In einem Methodenvergleich wichen die auf Hess-Sampling beruhenden Ergebnisse zur Sediment-Zusammensetzung deutlich von den realen Verhältnissen ab.
2. Im Staubereich der Ilm fand sich wie erwartet auf der Gewässersohle eine verstärkte Ablagerung grob (CPOM; Partikelgröße >1 mm) und fein partikulären organischen Materials (FPOM; Partikelgröße 0,0016 - 1 mm). Die Gesamtmenge benthischen organischen Materials (BOM; 724 g AFDM m^{-2} ±130 S.E.; Mittelwert für alle vier Jahreszeiten) war gegenüber dem natürlichen Referenzabschnitt (221 g AFDM m^{-2} ±43 S.E.) signifikant erhöht. Eine deutliche Auswirkung der Begradigung war dagegen nicht festzustellen. Im Vergleich zum naturnahen Bereich war im begradigten Abschnitt keine signifikante Reduktion der Gesamt-BOM-Menge (234 g AFDM m^{-2} ±40 S.E.) nachweisbar. Unerwartet gab es sogar eine stärkere CPOM-Ablagerung (165 g AFDM m^{-2} ±36 S.E.) als im Referenzabschnitt (107 g AFDM m^{-2} ±19 S.E.).
3. In beiden degradierten Bach-Abschnitten wich das Verhältnis von CPOM zu FPOM von dem im naturnahen Abschnitt ab. Im Referenz-Abschnitt existierte ein nahezu ausgewogenes CPOM : FPOM-Verhältnis (0,9), im Staubereich dominierte FPOM (CPOM : FPOM = 0,5), im begradigten dagegen CPOM (CPOM : FPOM = 2,5).
4. Die Umweltfaktoren mit dem größten Einfluss auf Menge und Zusammensetzung des BOM waren hydraulischer Radius, Gewässertiefe und die Korngrößenverteilung des

Sohlensubstrates am Punkt der Probenahme. Ergebnisse früherer Studien bestätigen einen starken Einfluss dieser drei Faktoren auf die Partikel-Retention.

5. Während der Messungen (Dauer: je 10-16 min) im Frühling, Sommer und Herbst 2000 wurden im naturnahen Abschnitt im Mittel 75 % (min. 30 %, max. 93 %) und im Stauberreich 87 % (min. 52 %, max. 82 %) des CPOM aus der Wassersäule zurückgehalten. Im begradigten Bereich wurde keine signifikante Änderung der Konzentration des transportierten CPOM gemessen. In keinem der Abschnitte änderte sich auf der betrachteten Fließstrecke während der Messungen die FPOM-Konzentration in der Wassersäule. Das heißt, es wurde kein FPOM aus der fließenden Welle fixiert bzw. aus der Gewässersohle freigesetzt.
6. Während die Ergebnisse zur Kurz- und Langzeitretention im naturnahen und angestauten Abschnitt übereinstimmten, widersprachen sie sich im begradigten Abschnitt. Eine geringe Kurzeitretention (Konzentrationsänderung von transportiertem CPOM) stand einer erhöhten Langzeitretention (CPOM-Lagerung) gegenüber. Die Betrachtung von Partikel-Retention auf verschiedenen Zeitskalen kann unterschiedliche Ergebnisse für identische Flussabschnitte hervorbringen. Der Grund liegt im starken Einfluss der hydrologischen Langzeit-Bedingungen auf die Lagerung von BOM (Langzeitretention), die jedoch die Konzentrationsänderung des suspendierten organischen Material während der Messung (Kurzzeitretention) nicht beeinflussen.
7. Aus dem Widerspruch zwischen Lang- und Kurzzeitretention im begradigten Abschnitt und der lokalen Ausprägung der retentions-relevanten Umweltfaktoren lassen sich folgende Haupt-Retentions-Mechanismen für die degradierten Ilm-Abschnitte postulieren:
   - Sedimentation im Staubereich
   - Filtration (entrainment) durch das Lückensystem des Sohlensubstrates im begradigten Abschnitt.
8. Aus den Retentions-Mechanismen resultieren spezifische zeitliche Schwankungen der BOM-Mengen. Durchfluss-Schwankungen bewirken bei sedimentations-basierter Retention (Staubereich) eine Resuspension und den Export größerer Mengen der lose abgelagerten organischen Partikel. Dieser Verlust wird regelmäßig durch neu fixiertes Material ausgeglichen. Das durch filtrations-basierte Retention fest zwischen dem anorganischen Substrat eingelagerte BOM (begradigter Abschnitt) ist resistenter gegenüber Durchfluss-Schwankungen. Wenige Partikel werden bei Erhöhung des

Durchflusses und damit der Fließgeschwindigkeit ausgewaschen, kaum neues Material kann eingelagert werden. Die maximale Speicherkapazität ist fast permanent ausgenutzt. Aus diesem Grund konnte hier keine Netto-Fixierung von Partikeln aus der Wassersäule gefunden werden.

9. Starke saisonale Schwankungen der BOM-Menge im Staubereich und relativ konstante BOM-Mengen im begradigten Abschnitt bestätigten die postulierten Retentions-Mechanismen. Im naturnahen Referenzbereich lassen Riffel-Pool-Strukturen ein räumliches Mosaik von Bedingungen ähnlich denen im Stau (Pool) und denen im begradigten Abschnitt (Riffel) entsteht. Die saisonalen Unterschiede in der BOM-Menge lagen darum zwischen denen im Stau und im begradigten Abschnitt.
10. Zur Veranschaulichung des Zusammenhangs zwischen Retentions-Mechanismen und zeitlicher Dynamik der CPOM-Mengen auf der Gewässersohle dient ein Schwamm-Modell (Sponge-model). Die Speicherung im Staubereich entspricht darin der Wasserspeicherung in einem weichen Schwamm. Bei geringem Druck (Fluss: Durchflusserhöhung) von außen gibt er große Mengen des gespeicherten Wassers (Fluss: Partikel) ab. Lässt der Druck nach, kann dieselbe (große) Wassermenge erneut aufgenommen werden. Der begradigte Abschnitt hingegen wird durch einen festen, widerstandsfähigen Schwamm repräsentiert. Druckeinwirkung führt nur zu einer geringen Freisetzung gespeicherten Wassers, so dass danach nur wenig Wasser erneut aufgenommen werden kann. Wird auf beide Schwämme der gleiche Druck ausgeübt (Fluss: Durchflussschwankungen im Jahresverlauf), unterliegt der Speicherinhalt des weichen Schwamms weit stärkeren Schwankungen als der des harten. Das entspricht den Beobachtungen der BOM-Mengen in den beiden degradierten Ilm-Abschnitten.
11. Experimentell waren während des Detritus-Abbaus Veränderungen der chemischen und der isotopischen Zusammensetzung nachweisbar. Das C : N-Verhältnis verringerte sich um 5 bis 8, und die Anteile der schweren Isotope ^{13}C und ^{15}N stiegen im Detritus an (max. Anstieg von δ^{13}C um 0,8 und δ^{15}N um 1,1 ‰). Über das C : N-Verhältnis waren in der Ilm weder Unterschiede im Abbaugrad des BOM zwischen den einzelnen Partikelgrößen-Fraktionen noch zwischen den verschiedenen Abschnitten nachweisbar. Der im Vergleich zu den anderen Fraktionen geringere ^{15}N-Anteil in den größten Partikeln (>4 mm) und der niedrige ^{15}N-Anteil in der BOM-Fraktion >4 mm im begradigten Abschnitt deuten auf einen verminderten Abbaugrad dieser Detritus-Komponenten hin. Die 0.4 - 1 mm-Fraktion wies in beiden degradierten Abschnitten

geringere δ^{13}C-Werte auf als im naturnahen Abschnitt. Dieses Resultat kann durch die vorliegenden experimentellen Ergebnisse noch nicht interpretiert werden.

12. Die vorliegende Arbeit liefert neue Hinweise für die Fließgewässer-Renaturierung. Die erstaunlich geringe Änderung der POM-Langzeit-Speicherung im begradigten Abschnitt der Ilm war eine Folge des natürlichen Sohlensubstrates und ist nicht auf begradigte Fließgewässer mit stark verändertem Sohlensubstrat oder gar betoniertem Bett übertragbar. Dies zeigt jedoch, dass eine natürliche Gewässersohle das Potential zur Erhaltung einer annähernd natürlich hohen Partikel-Retention besitzt. Trotzdem verursachte die Begradigung genau wie die Anstauung in der Ilm eine Veränderung der Größenzusammensetzung und des Abbaugrades des BOM. Die damit verbundene Verminderung seiner Nahrungsqualität für die abschnittsspezifischen Detritivoren muss unweigerlich zum Umbau der lokalen Lebensgemeinschaft führen. Allein die Wiederherstellung der räumlichen Heterogenität alternierender Riffel-Pool-Strukturen könnte die Bereitstellung der natürlichen Nahrungsressourcen gewährleisten. Eine Renaturierung des Staubereiches kann nur nach vorherigem Rückbau des Wehres erfolgen.

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Appendices

Frequently Used Abbreviations

AFDW	Ash Free Dry Weight
BOC	Benthic Organic Carbon
BOM	Benthic Organic Matter
CCA	Canonical Correspondence Analysis
CIX	Choriotope-type index
CPOM	Coarse Particulate Organic Matter
FPOM	Fine Particulate Organic Matter
POM	Particulate Organic Matter
RR	Reach Retention
S.D.	Standard Deviation
S.E.	Standard Error
S-N-K	Student-Newman-Keuls Post hoc tests
SOM	Suspended Organic Matter
TOC	Total Organic Carbon, exception in equation (3) for RR after Minshall *et al*. (1983), in this case: TOC = Transported Organic Carbon

Manuscript

"The Bottom-Sampler – a new technique for sampling bed sediments in streams and lakes"

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The Bottom-Sampler – a new technique for sampling bed sediments in streams and lakes.

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Abstract

This paper describes a new, easy to handle, liquid nitrogen sampler for the upper layer (80-160 mm) of water sediment and associated benthic organisms in streams and lakes up to 1.2 m depth. The 0.0531 m^2 sediment sample keeps its natural composition and spatial structure. The 15 kg total weight of the two sampler components enables use by hand even in not easily accessible rural areas. A successful two year test period in several first and second order streams demonstrated the applicability of the sampler for sediment textures from fine clay to cobbles and velocity up to 1 m s^{-1}.

Introduction

Detritivore primary consumers are the basis of the main ecosystem energy pathway in streams and benthic zones of lakes. Changes in detritus quantity and quality influence community composition and energy budgets highly as predicted for streams by the River Continuum Concept (Vannote et al., 1980). Thus "processing of materials in stream channels and retention or export of residuals has been recognised as a basic property of streams and rivers" (Fisher, 1998) which is closely bounded to the sediment.

This knowledge recently led to a great interest in investigation of the benthic zone. Studies of this kind as whereas for environmental pollution (Hill, 1999) inevitably make quantitative sampling of the sediment and associated organisms necessary and require appropriate sampling techniques, supplying samples containing all particle sizes and the natural sediment composition. The sampling expense should be low allowing for high sample numbers and should be practicable in a broad range of sediment conditions. Beyond this an instant sample supply for analysis is often important in monitoring.

Traditional sampling techniques are inadequate to cover all these demands. Hand picking (Bretschko, 1990) and net sampling methods as well as the traditional Hess-Sampler (Hess, 1941) fail to collect the fine sediment fraction. In addition the results of hand picking can be subjectively affected. The Shapiro-core-freezer (Shapiro, 1958) and tube corers (Kajak, 1971) are not suited for hard, coarse sediment where driving the tubes into the sediment is impossible. The spatial structure of the sediment sample is not entirely maintained, which is also a problem in hand picking and Hess sampling. Traditional freeze core techniques (Stocker & Williams, 1972; Bretschko, 1985) are to excessive for many sampling purposes and alter the sediment structure during tube insertion.

Waiting periods of several days are necessary to re-establish natural sediment conditions before taking samples. Thus instant sampling following pollution accidents is impossible. Newer freeze-core techniques, excluding these disadvantages described by Hill (1999) and Niederreiter (1999), are either limited to water depths up to 0.3 m and are time-consuming (approx. 48 min freezing time for each sample) or need heavy equipment preventing quick mobile application.

This paper describes a new sampling technique which immediately produces sediment samples including organisms from pure water saturated sediment to water depths up to 1.2 m and deeper and overcomes the problems of the methods mentioned above.

Description and operation of the Bottom-Sampler

Description and operation of the Bottom-Sampler

The Bottom-Sampler (BS) consists of two components: the stamp shaped hollow sampler and a jacket (Fig. 1). The sampler itself is 1.3 m high. The hollow cooling cylinder (CC) is welded from 2 mm thick steel and is closed except the connection to the coolant agent pipe (CAP). A perforated cone at the centre of the CC bottom evenly spread the cooling agent which is led in by the CAP (Fig 2). The sampler is insulated to prevent heating effects. Polyurethane foam for insulation and a Polyester layer preventing mechanical damages cover the CC except the bottom and a 20 mm fringe at the side (Fig. 2). A Polyethylene foam coat insulates the CAP. A thread on the top of the CAP enables the attachment of handles or expands the CC for use in deeper water (>1.2 m). The jacket which prevents the sampling area from heating effects and the loss of sediment and organisms is a part of a water pipe (Omniplast) with two handles attached (Fig. 1).

Several jackets are stackable to adjust to the water depth via the connecting piece at the top. The 15 kg total weight of the of the BS (sampler 10 kg, one jacket 5 kg) makes handling easy even in cases of steep-sided banks and enables in terrain transport by researchers up to few 100 m distance. The sampler covers an area of 0.0531 m^2 (diameter 0.26 m).

To operate the sampler the operator(s) wades into the water and inserts the jacket if possible a few centimetres in to the bed. Than he / she wraps a piece of polyethylene foam around the jacket base held in place by an elastic cord to make sure the sampling area is well protected from the flow. If the water is deep and the flow weak the foam could be attached before the insertion of the jacket or spared under fine sediment conditions. In the next step, the sampler is put gently into the jacket on the bed surface. Then for between eight to ten minutes approximately 15 l liquid nitrogen are carefully poured into the CAP using a high density polyethylene beaker and funnel. The nitrogen demand depends on the water temperature (minimum 13 l in 2 °C and maximum 17 l in 20 °C) and the sample amount needed (mean sample wet mass: 8 kg). After waiting two minutes allow the nitrogen to evaporate completely, the sampler with the jacket is lifted out of the water and transported to the a tub at the bank to remove the sample ice disc from the CC bottom using a hammer or by letting the sample warm up and fall off of its own account. Then the whole sample is transferred into a bucket for later analysis in the laboratory. The BS is immediately ready for the next sampling. Using the sum of pore water and sediment volume (V) and the sampler area (A) it is possible to calculate the mean sampling depth (d) by the equation: $d = \frac{V}{A}$

This sampling depth (d) can be used to standardise the results of the sediment analysis. In shallow water up to 0.4 m depth a single operative is able to handle the equipment.

In deeper water the sampler tends to float and does not stand stably and a second operative is necessary hold the jacket and sampler in position. Movements of the sampler must be kept to a minimum to prevent suspension of sediments.

During a two year test period we took by the BS more than 80 samples in six different first and second order streams in Thuringia (Germany) featuring sediment grain sizes up to 0.2 m and maximum depths of 1.2 m. The successful use in very coarse sediment (grain sizes >0.2 m) seems uncertain since large cobbles make fitting the jacket to the bed surface problematic. Nevertheless all our samples were sufficient for sediment analyses. Sediment disc heights of between 8o to 160 mm were achieved. In six sample sites, high velocity (> 1.0 m s^{-1}) and coarse sediment (0.15 - 0.2 m) caused a remaining flow inside the jacket, leading to incomplete ice discs. This can be avoided by careful sealing of the jacket base by a piece of polyethylene foam which was not yet used in four of these six cases. In the incomplete ice discs we estimated the proportion of the sampler area obtained and fitted the results to a complete sample. The average time needed for one sample was 15 min. The BS is an improvement over traditional methods (Bretschko, 1985; Hess, 1941; Hill, 1999; Shapiro, 1958; Stocker & Williams, 1971) by being mobile, supplying samples instantly and containing organisms and the bed sediment in its natural composition and spatial structure in a broad range of sediment conditions. Although the first tests were limited to sampling streams the use in shallow lakes and the littoral region promises to be successful as well. For this reason the Bottom Sampler is an appropriate method for use in research and applied studies or environmental monitoring.

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Figure captions

Fig. 1 Schematic drawing of the of Bottom-Sampler components

Fig. 2 Detail view of the Bottom-Sampler basis with the insulating visible

Figure 1

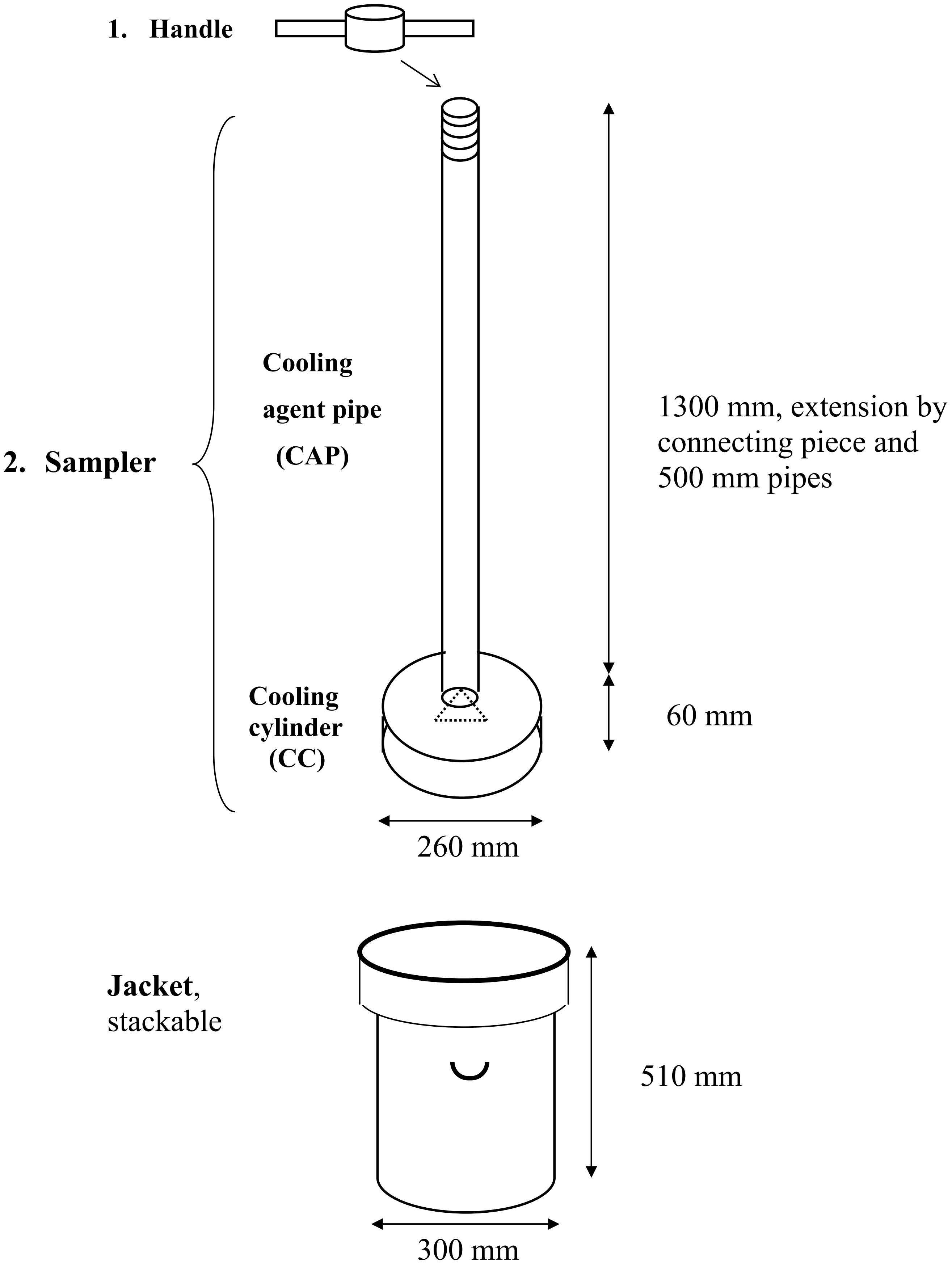
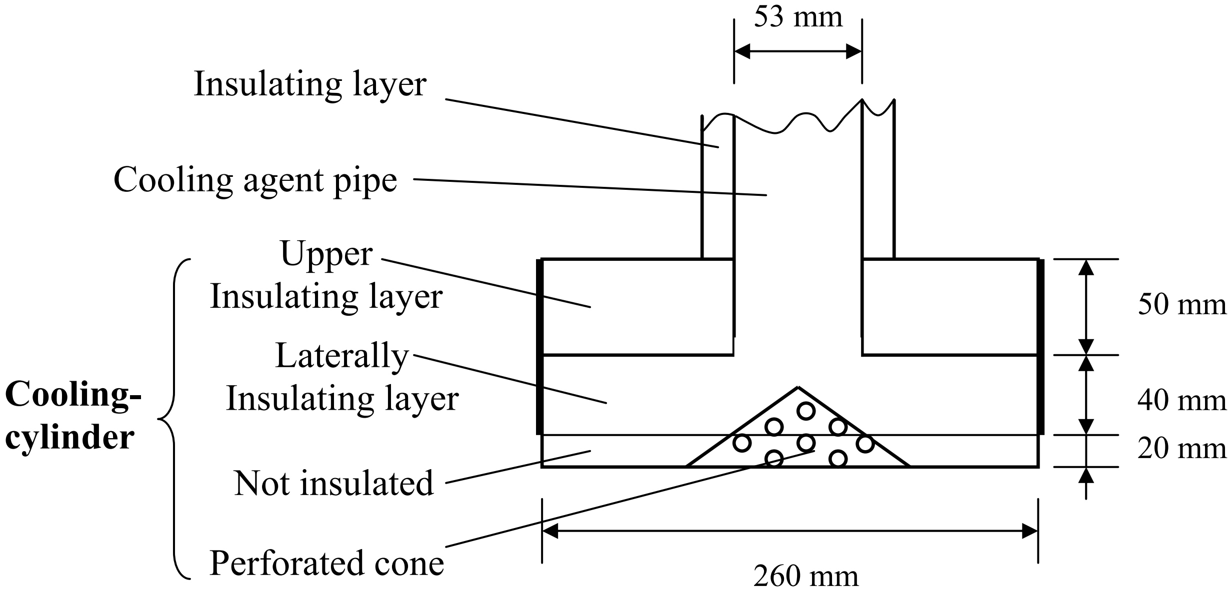

1. Handle
2. Sampler
Cooling agent pipe (CAP)
1300 mm, extension by connecting piece and 500 mm pipes
Cooling cylinder (CC)
60 mm
260 mm
Jacket, stackable
510 mm
300 mm

Figure 2


53 mm
Insulating layer
Cooling agent pipe
Upper
Insulating layer
Laterally
Insulating layer
Cooling-
cylinder
Not insulated
Perforated cone
50 mm
40 mm
20 mm
260 mm

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⑲ **BUNDESREPUBLIK DEUTSCHLAND**

DEUTSCHES PATENT- UND MARKENAMT

⑫ **Offenlegungsschrift**

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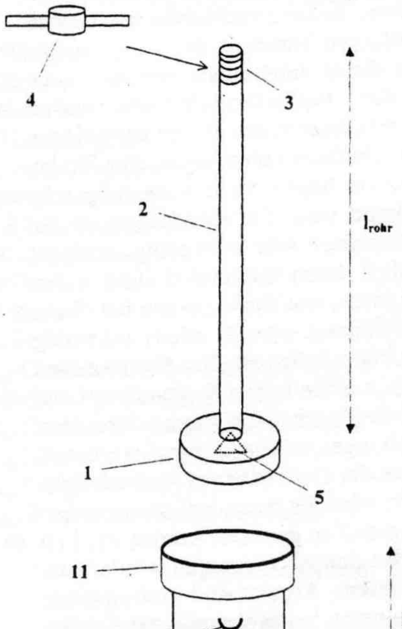
Die folgenden Angaben sind den vom Anmelder eingereichten Unterlagen entnommen

㊿4 Sampler zur Entnahne von Bodensedimenten in fließenden und stehenden Gewässern

㊿7 Aufgabe war es, einen Sampler zu schaffen, mit dem aus stehenden und fließenden Gewässern alle Bodensedimente des jeweils zu untersuchenden Probenvolumens, einschließlich kleinster Fraktionen, gut handhabbar und insbesondere mit möglichst geringem Kraftaufwand, in kürzester Zeit sowie in ihrer natürlich vorhandenen Zusammensetzung zur umfassenden Analyse entnommen werden können.

Erfindungsgemäß wird ein Sampler vorgeschlagen, dessen metallischer Hohlkörper (1) zum Aufstellen auf den Gewässerboden vorgesehen ist. In diesen Aufstell-Hohlkörper (1) wird ein Kühlmittel (flüssiger Stickstoff) eingeleitet, wodurch das Wasser und die Bodensedimente des Probenvolumens in ihrer Gesamtheit kompakt und flächenhaft an der Unterfläche des Samplers anfrieren und mit dem Sampler auf einfache Weise zur Analyse entnommen werden können.

Der Sampler findet Anwendung bei der Probenentnahme für Sedimentanalysen von stehenden und fließenden Gewässern.



DE 100 57 738 A 1

Beschreibung

[0001] Die Erfindung betrifft einen Sampler zur Entnahme von Bodensedimenten in fließenden und stehenden Gewässern, mit dem die Sedimente des Gewässerbodens durch Anwendung von flüssigem Stickstoff, der über eine thermoisolierte Zuführung in den Sampler eingeleitet wird, an metallischen Bestandteilen des Samplers angefroren und gemeinsam mit diesem vom Gewässerboden entnommen werden können.

[0002] Es ist allgemein bekannt, Proben der obersten Sedimentschichten in Gewässern innerhalb eines Rahmens manuell abzusammeln (z. B. G. Bretschko: The dynamic aspect of coarse particulate organic matter (CPOM) on the sediment surface of a second order stream free of debris dams (Ritrodat-Lunz study area), Hydrobiologia, 203, 1990, 15–28). Andere Möglichkeiten bestehen im Auffangen des Materials nach Aufwirbeln durch künstliche Turbulenzen oder mit Hilfe eines Hess-Samplers (A. D. Hess: New limnological sampling equipment. Limnol. Soc. Of Amer., Spec. Publ. 6, 1941, 5 pp.).

[0003] Mit allen diesen Methoden ist es nicht möglich, alle Sedimentfraktionen in ihrer Gesamtheit zu erfassen. Die Handaufsammlung bleibt auf die größeren Fraktionen (meist größer als 4 mm) beschränkt, da die kleineren Partikel nicht mehr alle per Hand entnommen werden können. Damit sind aber exakte Sedimentanalysen, beispielsweise das Verhältnis von organischen zu anorganischen Partikeln nicht möglich. Beim Einsatz von Netzen werden alle Partikel, die kleiner als die Maschenweite sind, ausgespült. Ein weiteres Problem dieser Verfahren besteht darin, dass keine Aussagen über Bodensubstrat (Korngrößenverteilung der anorganischen Anteile) getroffen werden können, weil sich das als Probe vorliegende Material nicht lageexakt dem an dieser Stelle vorhandenen Substrat zuordnen lässt.

[0004] Eine andere Möglichkeit besteht in der freezing core Technik (H. S. J. Stocker and D. D. Williams: Freezing core methode for describing the vertical distribution of sediments in a streambed. Limnol. Oceanogr. 17, 1972, 136–138). Hierzu wird eine Lanze in den Gewässerboden geschlagen, in welche flüssiger Stickstoff eingeleitet wird. Dadurch frieren die oberen Sedimentschichten des Gewässerbodens an der metallischen Wandung der Lanze an und können gemeinsam mit dieser entnommen werden. Allerdings werden nicht nur die Oberflächensedimente, sondern infolge des Eintreibens der Lanze in den Boden auch die tiefer gelegenen Sedimentschichten entnommen, die für bestimmte Untersuchungsziele häufig nicht notwendig oder möglicherweise gar störend sind. Darüber hinaus ist die freezing core Technik technisch sehr aufwendig, weil der core mit Kraft (gewöhnlich durch Hammerschläge) in den Boden gerammt werden muss, was insbesondere bei Grobsubstrat, wie Felsen und Steinen, oftmals relativ schwierig oder mitunter auch gar nicht möglich ist. Das Herausziehen des cores erfordert ebenfalls einen hohen Kraftaufwand und wird in der Regel mit einen Flaschenzug durchgeführt. Außerdem sind die Untersuchungen zeitintensiv und problematisch, da beim Einschlagen der Gefrierlanzen das natürliche Sediment erheblich gestört wird. Es muss deshalb nach dem Einbringen der Lanze längere Zeit gewartet werden, bis sich die natürlichen Verhältnisse der Ablagerungen wieder ausgebildet haben. Unter diesem Aspekt sind insbesondere kurzfristige Bodenbeprobungen, beispielsweise bei Gewässerverunreinigung in einem Störfall, hinsichtlich exakter Bodensediment-Auswertungen so gut wie nicht oder zumindest nur sehr eingeschränkt möglich.

[0005] Eine weitere Methode ist das Zylinderverfahren zur Sedimentprobennahme (DE 197 54 564). Hierbei wird ein Rohr, meist aus Plexiglas, in das Sediment eingetrieben und nach Verschließen der Öffnungen herausgezogen. Allerdings werden auch hier wie bei der freezing core Technik infolge des Eintreibens in das Bodensubstrat die tiefer gelegenen Sedimentschichten mit entnommen. Das Einrammen des Rohres in den Boden ist bei Grobsubstrat, wie Felsen und Steinen, oftmals nicht möglich, ohne den Zylinder dabei zu beschädigen. Die Anwendung dieses Verfahren bleibt darum auf Weichsedimente begrenzt. Das Einbringen des Rohres verursacht ähnlich wie bei der freezing core Technik Störungen des natürlichen Sedimentes. Außerdem ist es durch den relativ kleinen Innendurchmesser des Rohres schwer, repräsentative Proben von Laubablagerungen zu erlangen, da die Größe einzelner Blätter schon den Durchmesser des Rohres übersteigen kann, was einen eindeutigen Flächenbezug der Probe unmöglich macht.

[0006] Der Erfindung liegt deshalb die Aufgabe zu Grunde, einen Sampler zu schaffen, mit dem aus stehenden und fließenden Gewässern mit Hart- oder Weichsubstrat alle Bodensedimente des jeweils zu untersuchenden Probenvolumens, einschließlich kleinster Fraktionen, gut handhabbar und insbesondere mit möglichst geringem Kraftaufwand, in kürzester Zeit sowie in ihrer natürlich vorhandenen Zusammensetzung zur umfassenden Analyse entnommen werden können.

[0007] Erfindungsgemäß besteht der Sampler aus einem metallischen Aufstell-Hohlkörper, dessen Unterfläche zum Aufsetzen auf dem Gewässerboden vorgesehen ist. In diesen Aufstell-Hohlkörper wird ein Kühlmittel (flüssiger Stickstoff) eingeleitet, welches an sich bekannt ist, um Sedimente an Metall anzufrieren. Im Gegensatz zur bekannten freezing core Technik wird jedoch kein lanzenförmiges Sampler-Element in den Boden gerammt, sondern der Sampler-Hohlkörper, beispielsweise in zylindrischer Form, wird in relativ einfacher Handhabung und wenig krafterforderlicher Weise auf den Gewässerboden aufgesetzt. Durch das besagte Kühlmittel erfolgt ein kompaktes, flächenhaftes Anfrieren des Wassers mit den Bodensedimenten an die Unterfläche des Hohlkörpers, wobei der erfasste Bereich der Sedimentoberfläche als Ganzes und mit allen kleinsten Bestandteilen, vor allem in seiner natürlichen Beschaffenheit, zur Untersuchung entnommen wird. In den Sedimentproben sind damit sämtliche Bestandteile in allen Größenfraktionen an organischen und anorganischen Material in ihrer natürlichen, lagerelevanten Zusammensetzung enthalten, was für gewässerökologische Untersuchungen häufig von großem Interesse ist und sowohl eine qualitative als auch quantitative Sedimentanalyse ermöglicht. Der organische Sedimentanteil lässt sich dem anorganischen eindeutig zuordnen und ermöglicht damit ökologisch relevante Aussagen zur Rauhigkeit und Substratzusammensetzung. Aus der gefrorenen Gesamtheit der Probe lassen sich noch zusätzliche Eigenschaften des Substrates ermitteln, wie beispielsweise die Erfassung des Porenvolumens vom Sediment über den Wasseranteil in der Probe.

[0008] Da kein nennenswerter Kraftaufwand zum Einbringen erforderlich ist (wie vergleichsweise bei einzuschlagenden Bodenlanzen), kommt es auch nicht zu größeren Bodenverwirbelungen, die sich erst über längere Zeit beruhigen müssen, ehe überhaupt Proben eingefroren werden. Auf diese Weise können quasi sofortige Bodenproben entnommen werden, was beispielsweise bei akuten Situationen, wie Unwetter oder plötzlichen Gewässerverunreinigungen, aus wissenschaftlichen, technischen oder auch rechtlichen Gründen erforderlich sein kann. Im Vergleich zu den Bodenlanzen und zur Zylindermethode ergibt sich außerdem eine größere Fläche für das Anfrieren der oberen Sedimentschicht, die in der Ebene der Bodenoberfläche liegt. Die tieferen Sedimentschichten werden im Boden belassen. Ein Einbringen einer Lanze oder eines Rohres ins Bodensubstrat findet nicht statt, so daß auch bei groben und harten Substraten eine einfache und schnelle Sedimententnahme möglich ist.

[0009] Auch die Entnahme des Samplers ist wenig kraftaufwendig. Vorteilhaft ist ein zu diesem Zweck am oder auf dem Aufstell-Hohlkörper angebrachtes transportstabiles vertikales Rohr als Handhabeelement, über welches unter Thermoisolierung nach außen der flüssige Stickstoff in den Aufstell-Hohlkörper zugeführt wird.

[0010] In den Unteransprüchen sind weitere Ausführungsmerkmale aufgeführt. Beispielsweise kann das vorgenannte transportstabile vertikale Rohr an seinem oberen Ende Befestigungselemente, wie ein Gewinde, zum Ansatz eines Haltegriffes oder einer Rohrverlängerung aufweisen. Von Vorteil ist auch, wenn nicht nur das transportstabile vertikale Rohr, sondern auch der obere Bereich des Aufstell-Hohlkörpers nach außen thermoisoliert ist und das Kühlmittel über ein vorzugsweise lochkegelförmiges Verteilungselement in den Aufstell-Hohlkörper eingeleitet wird, damit sich das Kühlmittel möglichst gleichmäßig über den Bodenbereich im Innern des Aufstell-Hohlkörpers ausbreitet.

[0011] Zum Schutz vor Gewässerströmung bei der Sedimententnahme und/oder zum Rückhalt von Partikeln, die ggf. beim Aufsetzen des Samplers suspendieren, ist ferner eine Aufstellhülse für den Gewässerboden zweckmäßig, deren Innenabmessungen größer als die Abmaße des Aufstell-Hohlkörpers sind und durch welche hindurch der Hohlkörper auf den Gewässerboden aufgesetzt wird.

[0012] Die Erfindung soll nachstehend anhand eines in der Zeichnung dargestellten Ausführungsbeispiels näher erläutert werden.

[0013] Es zeigen

[0014] **Fig.** 1 Gesamtansicht des Samplers mit Aufstellhülse und anschraubbarem Haltegriff;

[0015] **Fig.** 2 Ansicht des Sampler-Hohlzylinders;

[0016] **Fig.** 3 schematische Darstellung des Sampler-Hohlzylinders mit Rohransatz, mit einem Lochblechkegel zur Verteilung des Kühlmittels sowie mit Thermoisolierung.

[0017] **Fig.** 1 zeigt den Sampler in seiner stempelförmigen Gestalt als Gesamtansicht. In einen geschlossenen Hohlzylinder **1** aus Stahl mit einem Durchmesser $d_{zyl} = 260$ mm und einer Höhe $h_{zyl} = 60$ mm (vgl. **Fig.** 2) führt an der Oberseite ein Rohr **2** aus Stahl mit einem Innendurchmesser $d_{rohr} = 53$ mm (vgl. **Fig.** 3). Das Rohr **2** ist transportstabil und dient zur Handhabung des zur Probenentnahme auf den Gewässerboden aufzusetzenden Hohlzylinders **1**. Zu diesem Zweck besitzt das Rohr **2** mit einer Länge $l_{rohr} = 1200$ mm an seinem oberen Ende ein Gewinde **3**, auf welches ein Transportgriff **4** aufschraubbar ist. Für den Einsatz in größeren Gewässertiefen kann auf das Gewinde **3** auch eine in der Zeichnung aus Übersichtsgründen nicht dargestellte Rohrverlängerung geschraubt werden.

[0018] Gleichzeitig wird über das Rohr **2** flüssiger Stickstoff als Kühlmittel in den Hohlzylinder **1** eingeleitet, wodurch die Bodensedimente des zu untersuchenden Probenvolumens gemeinsam mit dem Wasser in ihrer Gesamtheit kompakt und flächenhaft an der mit dem Gewässerboden in Berührung stehenden Unterfläche des Hohlzylinders **1** anfrieren sowie mit diesem zur Analyse entnommen werden können. Damit sich das in den Hohlzylinder **1** aus dem Rohr **2** ausströmende Kühlmittel möglichst gleichmäßig im Innenraum des Hohlzylinders **1** über dessen Bodenfläche verteilt, ist konzentrisch unter der Einmündung der Rohres **2** auf der Bodenfläche eine Lochblechkegel **5** angeordnet (siehe **Fig.** 3).

[0019] Um thermische Verluste bei der Kühlmittelzufuhr möglichst gering zu halten, ist das Rohr **2** von einem thermischen Isolationsmantel **6** umgeben. Zur weiteren Verbesserung des thermischen Wirkungsgrades und zur Minimierung des Kühlmittelbedarfs ist der obere Bereich des Hohlzylinders **1** ebenfalls thermoisoliert. Auf diese Weise kann sich nur unmittelbar in einem unteren und nach außen metallischen Bereich **12** mit einer Höhe von 20 mm eine Vereisung ausbilden. Zu diesem Zweck weist der Hohlzylinder **1** eine obere Isolationsschicht **7** mit einer Schichthöhe von 50 mm und eine seitliche Isolationsschicht **8** mit einer Schichthöhe von 40 mm aus Polyuretan und/oder Polyester auf (siehe **Fig.** 3).

[0020] In **Fig.** 1 ist ferner eine zylindrische Aufstellhülse **9** mit einem Durchmesser $d_{hül} = 300$ mm und einer Höhe von $h_{hül} = 510$ mm dargestellt, in welcher der Sampler mit seinem Hohlzylinder **1** auf den Gewässerboden aufgestellt wird. Damit dient die Aufstellhülse **9** zum Schutz vor Gewässerströmung bei der Sedimententnahme bzw. zum Rückhalt von Partikeln, die ggf. beim Aufsetzen des Samplers vom Boden suspendieren. Zur Handhabung der Aufstellhülse **9** besitzt diese seitliche Griffe **10**. Durch einen wulstartigen oberen Rand **11** ist die Aufstellhülse **9** stapelbar ausgebildet und kann je nach erforderlicher Anwendungshöhe in der Höhe kaskadiert werden.

[0021] Für die Bodenbeprobung wird der Sampler (ggf. innerhalb der Aufstellhülse **9**) auf den Gewässerboden aufgesetzt. Durch das in den Hohlzylinder **1** über das Rohr **2** eingeleitete Kühlmittel gefriert das Wasser im unteren nicht thermoisolierten Bereich **12** des metallischen Hohlzylinders **1** an diesem an. Mit dem Gefriervorgang werden alle in diesem Bereich befindlichen Bodensedimente in ihrer vorhandenen Zusammensetzung kompakt an der auf dem Gewässerboden aufsitzenden Unterfläche des Hohlkörpers **1** gebunden und können mit dem Sampler entnommen sowie anschließend durch Abklopfen von diesem separiert werden.

[0022] Die benötigte Kühlmittelmenge ist abhängig von der Beschaffenheit des Bodensedimentes sowie der Wasser- und Lufttemperatur. Für eine Probenentnahme mit dem beschrieben Sampler wurden jeweils 15 bis 20 Liter flüssiger Stickstoff verbraucht.

Aufstellung der verwendeten Bezugszeichen

1 Hohlzylinder
2 Rohr
3 Gewinde
4 Transportgriff
5 Lochblechkegel
6 Isolationsmantel
7, 8 Isolationsschicht
9 Aufstellhülse
10 Griffe
11 Rand
12 Bereich
d_{zyl} Durchmesser des Hohlzylinders **1**
h_{zyl} Höhe des Hohlzylinders **1**
$d_{hül}$ Durchmesser der Aufstellhülse **9**
$h_{hül}$ Höhe der Aufstellhülse **9**
l_{rohr} Länge des Rohres **2**
d_{rohr} Innendurchmesser des Rohres **2**

Patentansprüche

1. Sampler zur Entnahme von Bodensedimenten in fließenden und stehenden Gewässern, bei dem die Sedimente des Gewässerbodens durch Anwendung eines Kühlmittels, insbesondere flüssigem Stickstoff, das über eine thermoisolierte Zuführung in einen geschlos-

senen metallischen Hohlkörper eingeleitet wird, an der Wandung desselben angefroren und gemeinsam mit dem Sampler vom Gewässerboden entnommen werden, **dadurch gekennzeichnet**, dass der Hohlkörper aus einem beispielsweise in Zylinderform ausgeführten Aufstell-Hohlkörper (**1**) mit Handhabeelementen (**2**, **4**) besteht, dessen metallische Unterfläche zum Aufsetzen auf dem Gewässerboden vorgesehen ist.

2. Sampler gemäß Anspruch 1, dadurch gekennzeichnet, dass die Handhabeelemente aus einem an der Oberfläche des Aufstell-Hohlkörpers (**1**) angebrachten transportstabilen vertikalen Rohr (**2**) bestehen.

3. Sampler gemäß Anspruch 2, dadurch gekennzeichnet, dass das transportstabile vertikale Rohr (**2**) an seinem oberen Ende Befestigungselemente, beispielsweise ein Gewinde (**3**), zum Ansatz eines Haltegriffes (**4**) oder einer Rohrverlängerung aufweist.

4. Sampler gemäß Anspruch 2, dadurch gekennzeichnet, dass die Wandung des transportstabilen vertikalen Rohrs (**2**) thermoisoliert ist (**6**) und gleichzeitig zur Zuführung des Kühlmittels in den Aufstell-Hohlkörper (**1**) dient.

5. Sampler gemäß Anspruch 4, dadurch gekennzeichnet, dass im Aufstell-Hohlkörper (**1**) zentrisch unter der Einführung des transportstabilen vertikalen Rohrs (**2**) ein vorzugsweise lochkegelförmiges Verteilungselement (**5**) zur möglichst gleichmäßigen Ausbreitung des Kühlmittels im Bodenbereich des Aufstell-Hohlkörpers (**1**) vorgesehen ist.

6. Sampler gemäß Anspruch 1, dadurch gekennzeichnet, dass die Wandung im oberen Bereich des Aufstell-Hohlkörpers (**1**), beispielsweise durch Polyuretan und/oder Polyester, thermoisoliert (**7**, **8**) ist.

7. Sampler gemäß Anspruch 1, dadurch gekennzeichnet, dass zum Schutz vor Gewässerströmung bei der Sedimententnahme und/oder zum Rückhalt von durch das Einbringen des Samplers ggf. suspendierten Partikeln, eine Aufstellhülse (**9**) für den Gewässerboden vorgesehen ist, deren Innenabmessungen größer als die Abmaße des Aufstell-Hohlkörpers (**1**) sind und innerhalb welcher der Aufstell-Hohlkörper (**1**) zur Probenentnahme auf den Gewässerboden aufgesetzt wird.

Hierzu 2 Seite(n) Zeichnungen

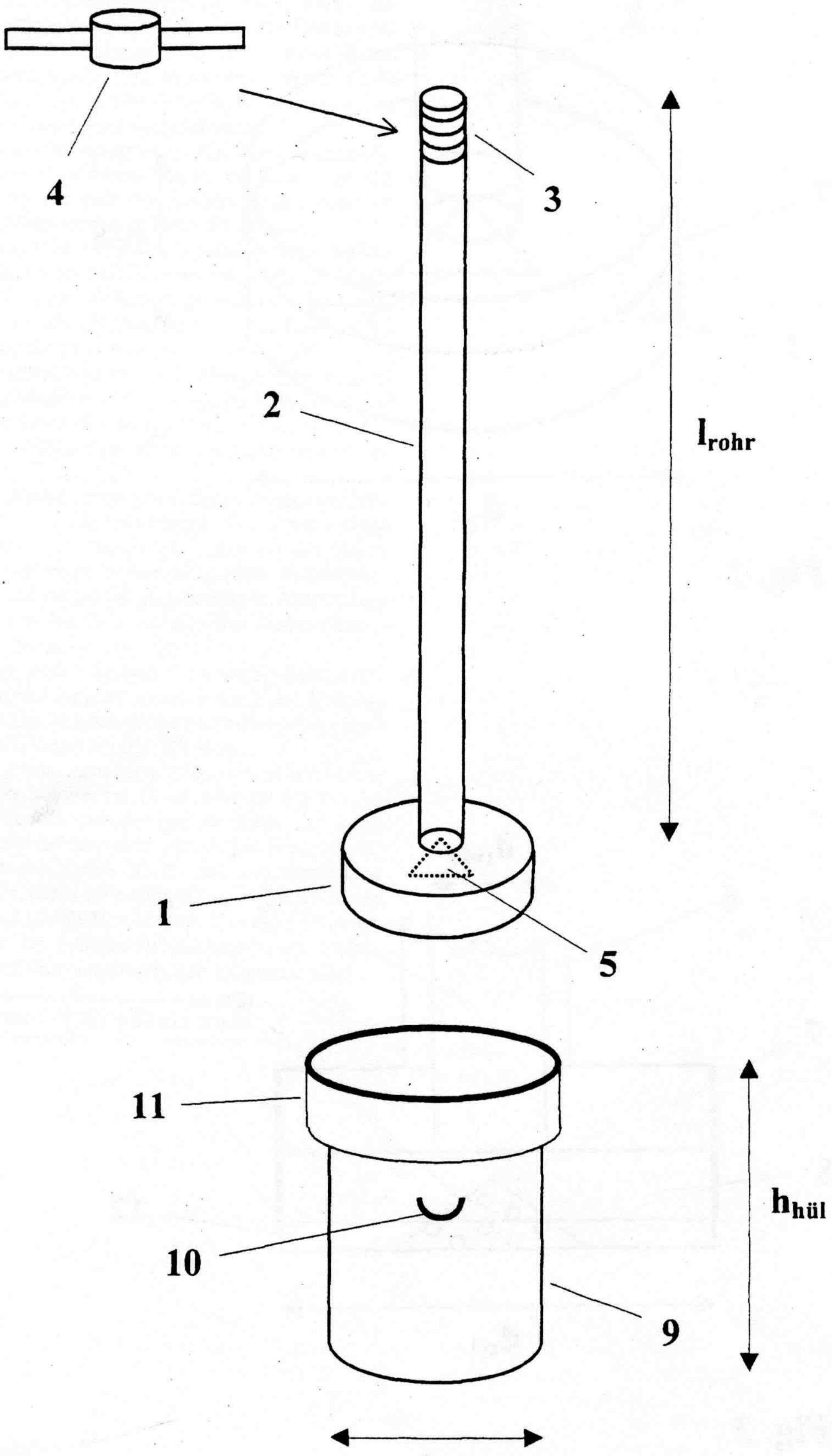


Fig. 1

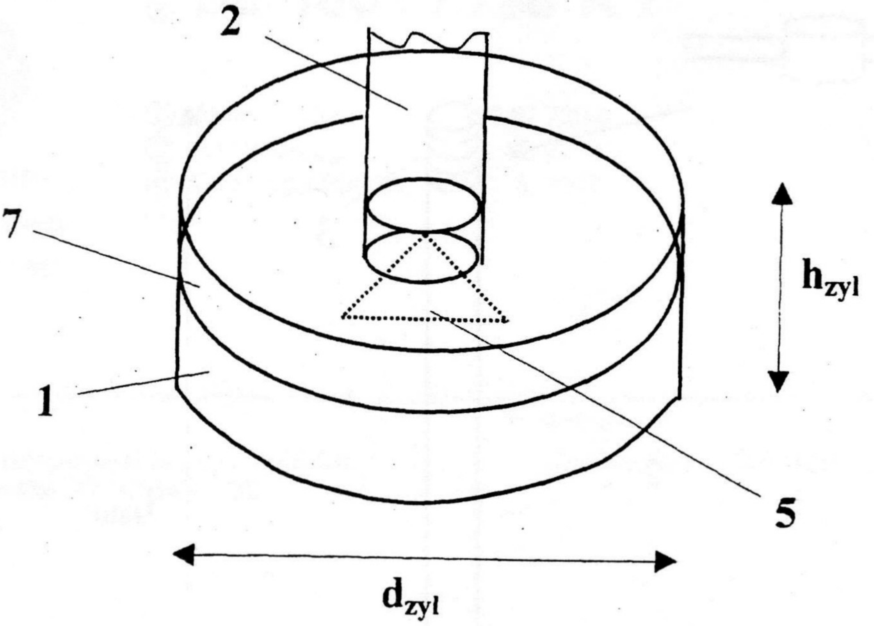


Fig. 2

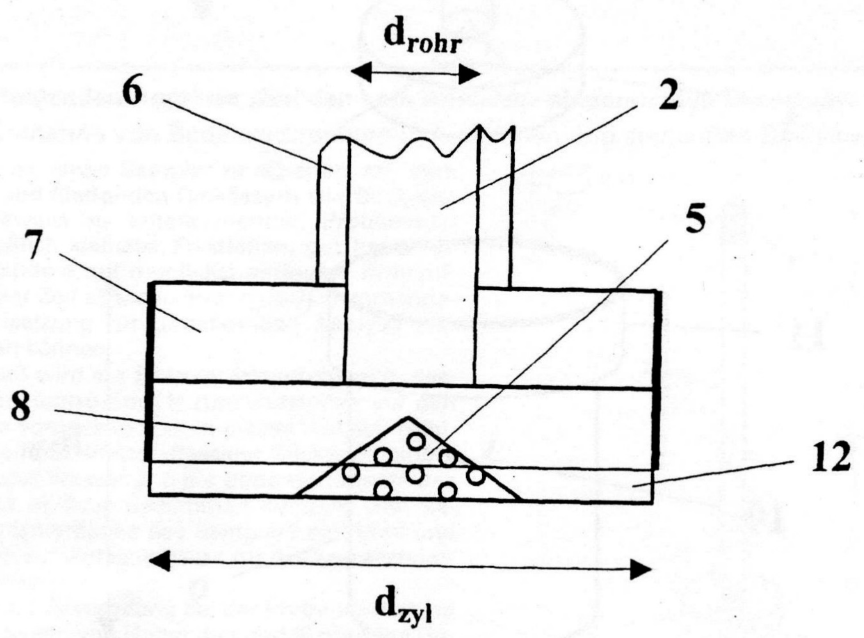


Fig. 3

LEBENSLAUF

Persönliche Angaben

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Schulausbildung

1977-1987	Polytechnische Oberschule „Friedrich Schiller“, Zeulenroda
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1987-1989	VEB Binnenfischerei Knau, Ausbildung zum Binnenfischer

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1989	VEB Binnenfischerei Knau
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Studium

1993-1998	„Friedrich Schiller Universität“ Jena, Studium der Biologie Hauptfach: Ökologie, Nebenfächer: Zoologie, Botanik, Mikrobiologie; Thema der Diplomarbeit: „Aufenthalt und Flugverhalten von Plecopteren-Imagines (Insecta) in der Bach-Aue am Beispiel der Leutra (Thüringen).“

Wissenschaftliche Arbeit:

1997-1998	Mitarbeit im Monitoring-Programm zur Auswirkung des Stauseebaus Leibis-Lichte im Schwarzatal – Makrozoobenthos-Untersuchung
1998	Gutachten zur Gewässergüte der Leutra im Leutratal (Thüringen) für den NABU
1998-1999	Gewässerökologische Untersuchungen der Quellabflüsse an der Leutra im Leutratal für UHL Jena

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2000-2002	Mitarbeit im Monitoring-Programm zur Auswirkung des Stauseebaus Leibis-Lichte im Schwarzatal – Fisch-Bestands-Erfassungen
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Lehre

1999	Leitung des Forschungspraktikums Ökologie „Einfluss von Makrozoobenthos auf die Sedimentation von POM“
1999-2002	Geländepraktikum Ökologie „Bedeutung des Makrozoobenthos als Indikator für die Gewässergüte“
1999-2002	Vorlesung „Ökologie der Erde“ faunistischerTeil
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Publikationen

Publikationen in begutachteten internationalen Zeitschriften:

Wagner, F. (im Druck): Flight behaviour of merolimnic insects from Leutra River (Thuringia, Germany). Aquatic Insects

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Symposiumsbeiträge:

Poster „Verteilung fliegender merolimnischer Insekten im Nahbereich eines kleinen Fließgewässers, Leutra (Thüringen)“, Tagung der Deutschen Gesellschaft für Limnologie 1999 in Rostock

Vortrag „A new method for sampling sediment in rivers and shallow lakes”, 28. Kongress der SIL 2001 in Melbourne (Australien)

Vortrag „Bottom-Sampler oder Hess-Sampler – Verfahren zur Sedimentbeprobung im Vergleich”, Tagung der Deutschen Gesellschaft für Limnologie 2001 in Kiel

Poster „Impact of weirs and canalisation on the retention of particulate organic matter (POM) in a temperate second order stream“, 4th International Ecohydraulics Symposium 2002 in Kapstadt (Südafrika)

Vortrag „Auswirkungen struktureller Degradation von Fließgewässern auf die Retention partikulärer organischer Substanz“, Tagung der Deutschen Gesellschaft für Limnologie 2002 in Braunschweig

Patent:

Deutsches Patent für einen „Sampler zur Entnahme von Bodensedimenten in fließenden und stehenden Gewässern“, Patent: DE 100 57 738 A1

Curriculum Vitae

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Education

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1990-1992	Kreisvolkshochschule Zeulenroda (Abitur), (high school, evening classes)
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Wagner F., Arle, J., Rothe., J. (submitted 2003): Chemical and isotopic composition of detritus as markers of organic matter processing elucidating impacts of river channel alterations on benthic organic matter (BOM). Freshwater Biology

International Conferences

Oral Presentation „A new method for sampling sediment in rivers and shallow lakes", 28. Kongresses der SIL, 2001, Melbourne (Australia)

Poster „Impact of weirs and canalisation on the retention of particulate organic matter (POM) in a temperate second order stream", 4th International Ecohydraulics Symposium, 2002, Capetown (South Africa)

Patent

German Patent „Sampler zur Entnahme von Bodensedimenten in fließenden und stehenden Gewässern" (Technique for sampling bed sediments in streams and shallow lakes), Patent No.: DE 100 57 738 A1

Selbständigkeitserklärung

Ich versichere an Eides statt, dass mir die geltende Promotionsordnung bekannt ist. Ich habe die vorgelegte Dissertation selbst angefertigt, sowie alle benutzten Hilfsmittel, persönlichen Mitteilungen und Quellen vollständig angegeben.

Es wurde nicht die Hilfe eines Promotionsberaters in Anspruch genommen. Es haben keine Dritten geldwerte Leistungen unmittelbar oder mittelbar für Arbeiten erhalten, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen. Es wurde weder diese noch eine andere Dissertation bei einer anderen Fakultät der FSU oder anderen Hochschule zur Prüfung vorgelegt.

Jena, den 28.04.2003

Falko Wagner