Limnologica 41 (2011) 10–19

Contents lists available at ScienceDirect

Limnologica

journal homepage: www.elsevier.de/limno

Bank filtration in the sandy littoral zone of Lake Tegel (Berlin): Structure and dynamics of the biological active filter zone and clogging processes

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ARTICLE INFO

Article history:
Received 18 November 2008
Received in revised form
17 July 2009
Accepted 9 December 2009

Keywords:
Bank filtration
Biofilms
Clogging
Extracellular polymeric substances (EPS)
Particle retention

ABSTRACT

This study focused on clogging processes and on the benthic microalgal and meiofaunal assemblage in the sandy littoral zone of Lake Tegel, which are significantly involved in bank filtration, in a long-term. Our approach combined field studies and "in situ" experiments to highlight the structure of the biological active filter zone as well as the mechanisms and effects of clogging in the interstices that influence the infiltration process.

Campaigns to measure "in situ" infiltration rates and hydraulic potential were conducted monthly from March 2004 to April 2005. Meiofaunal abundances and fine particulate organic matter (FPOM) were determined every 6 weeks in freeze cores down to depths of 50 cm. In parallel, concentrations of carbon, nitrogen and chlorophyll *a* were measured in samples of unfrozen sediment cores, that were divided in 1-cm steps down to depths of ≥ 10 cm. Similar sediment profiles were generated for analysis of colloidal carbohydrates, extracellular polymeric substances (EPS) and proteins between December 2005 and June 2006. Electron microscopy was used to visualize biofilm structure. Long-term experiments with natural FPOM and melamine resin particles as fluorescent tracers were performed to study "in situ" particle retention and transport, respectively. Additionally seston input was quantified during a 1-week period in April 2005.

Infiltration rates showed a high temporal and spatial variability, but were not correlated with hydraulic conductivities as hydraulic gradients changed a lot. Likewise a correlation between infiltration rates and hydraulic potentials was not observed, indicating clogging processes. These are triggered to a high extend by biological compounds. In addition, seston input and intermittent gas intrusion are considered to reduce the hydraulic conductivity considerably. No significant "in situ" transport of inert natural fluorescent tracers was observed. However, a complete and permanent clogging of the sandy sediment does not occur, and daily infiltration rates of 0.7–27 L m^{-2} h^{-1} (mean 9 L m^{-2} h^{-1}) guarantee a sufficient water supply by bank filtration for decades.

Introduction

Induced bank filtration is the favoured strategy for drinking water abstraction as it can be operated with high cost-efficiency and low energy requirements. However little is known about the seasonal dynamics of biological functioning or the high complexity of fine to middle coarse sandy interstices in standing waters or low land rivers under infiltrating conditions (Gunkel and Hoffmann, 2009). Biological functioning is based on carbon input, transfer and turnover as well as on the modulation of clogging processes by the inhabiting microflora and meiofauna (DVGW, 2004).

Clogging, the decrease of hydraulic conductivity in a porous medium, influences sediment permeability and cohesiveness thus leading to limited infiltration capacities in the upper zone of the littoral interstices, an ecotone where infiltration, biomass and bioactivity as well as the turnover of biological–chemical compounds are of major importance (Gunkel et al., 2009; Hoffmann and Gunkel, 2010). Clogging is a well-known phenomenon, which occurs commonly in a wide range of systems like lake shores, river banks and beds (Baveye et al., 1998; Schälchli, 1992; Brunke, 1999). However, in contrast to river bank and bed sediments, periodic de-colmation due to floods does not occur in low land lakes and flow-regulated low land rivers (Gunkel and Hoffmann, 2009). Clogging mechanisms are usually classified into physical, chemical and biological factors or a combination thereof (Baveye et al., 1998). In detail, factors comprise the accumulation of suspended solids (Okubo and Matsumoto, 1983; Schälchli, 1992; Langergraber et al., 2003), precipitates, the formation of gas bubbles (Soares et al., 1989; Seki et al., 1998) and sediment compaction (Pérez-Paricio and Carrera, 2001) as well as biological clogging due to microorganisms and the excretion of extracellular polymeric substances (EPS, Vandevivere and Baveye, 1992 a,b; Le

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doi:10.1016/j.limno.2009.12.003

Bihan and Lessard, 2000). So far clogging mechanisms like biological processes have been studied mostly in laboratory experiments (Mauclaire et al., 2004) and hydraulic conductivities were made for confined systems such as ponds (Siegrist et al., 1991) or slow sand filters (Mauclaire et al., 2006).

The benthic boundary layer functions as an important retentive structure for particles, besides chemical gradients are most obvious and microbial activities are maximal in this layer supporting biofilm growth and the formation of dense microbial mats (Lawrence et al., 1998, 2002; Paterson, 2001; Gunkel and Hoffmann, 2009). Biofilms and the associated algae are of special importance as they absorb toxic metal ions and organic compounds, while the enzyme activities of the bacterial microconsortia lead to elevated mineralization efficiencies (Flemming, 1991; Decho, 2000). Other well-known properties of biofilms are the high water binding capacity, stabilization of the surrounding sediments (Yallop et al., 2000) and low diffusive velocities inside the biofilms (Flemming et al., 1999). Structure determination of extracellular polymeric substances (EPS) forming biofilms has shown substantial progress during the last decades (Characklis and Marshall, 1990; Wingender et al., 1999; Flemming and Wingender, 2001). The focus of recent investigations has concerned the capacity of the bank filtration to retain pharmaceuticals and cyanotoxins (Heberer et al., 2007; Grützmacher et al., 2007).

This study approach combined field observations and "in-situ" experiments to identify the effective clogging mechanisms and their effects on hydraulic conductivity on a long time-scale in context with biocoenotic dynamics concerning benthic microalgae and meiofauna. Amongst other methods, self-designed plexiglass chambers for the measurement of infiltration rates and fluorescently labelled FPOM as a novel tool for studying particle retention, respectively, transport (Gunkel et al., 2009) were used "in-situ" to map approximate real conditions. Results shall clarify the long-term structure and function of the biological active filter zone. The study is part of a bank filtration research program (Beulker and Gunkel, 1996; Gunkel and Hoffmann, 2006, 2009; Hoffmann and Gunkel, 2006; Gunkel et al., 2009) as well as the NASRI project (Natural and Artificial Systems for Recharge and Infiltration) which studied among other topic the hydrogeology (Greskowiak et al., 2006), dissolved organic carbon (Grünheid et al., 2005) and cyanotoxins (Grützmacher et al., 2006).

Material and methods

Study site

Lake Tegel, a low land lake as a glacial enlargement of the River Havel, in Berlin, Germany, has an area of 396 ha and a mean depth of 6.6 m. Water balance and water quality is determined by the inflow of two rivulets (Tegeler Fließ and Nordgraben) and by water exchange with the River Havel. After a severe eutrophication period, a phosphate elimination plant was built and nowadays lake water quality is mesotrophic, but organic rich anoxic sediments are still typical and periodically cyanobacteria blooms occur (Heinzmann and Chorus, 1994; Schauser et al., 2006).

Near the shore of Lake Tegel, bank filtration for Berlin's water supply is achieved through several galleries with 116 wells, 30–60 m deep, and distance to the lake is about 100 m. The pumping rate for each well ranges from 50 to 150 $m^3\ h^{-1}$, leading to a capacity of up to 260,000 $m^3\ d^{-1}$ used for the drinking water supply for 700,000 inhabitants.

Lake Tegel has a sedgy littoral zone with forest stands, sporadically interrupted by beach sections caused by erosion, with sparse macrophyte growth. Experiments were conducted at a water depth of 30–50 cm, about three meters away from the splash water zone, and different micro habitats were studied (sandy erosion shore and *Nuphar* stand) at the eastern shore of Lake Tegel (N52°34'13.81" E13°15'25.52" to N52°34'10.65" E13°15'24.42").

Interstitial characteristics of Lake Tegel shore

Grain size distribution of sediment was assessed by wet sieving. Permeability of the sediment was estimated with Hazen's method (k_f=permeability in $m\ s^{-1}$; Beyer, 1964) considering particle size distribution and water temperature.

The littoral sediments at Lake Tegel contain fine to middle sized sands, which are poorly sorted. The sediment permeability (k_f values) calculated from sediment grain size distribution after Beyer (1964) lie between 5×10^{-5} and $1 \times 10^{-4}\ m\ s^{-1}$ and are smallest in the upper sediment layer due to a higher proportion of fine sands (Table 1).

Infiltration rates

In situ infiltration rates at the study site were determined by the use of self-designed plexiglass chambers (19 cm inner diameter, 20 cm height), which were pressed 2 cm deep into the sediment and connected pressureless via tube fittings to plastic bags (Hollister Inc.), filled with a weighed amount of lake water (about 1.5 L in each bag). After 24 h the bags were retrieved and reweighed. Daily infiltration rates during a study period of 4 days were assessed monthly from March 2004 to April 2005 at several sampling sites. Simultaneously, the hydraulic potential (n=3 per chamber) was measured and k_f values were calculated according to Darcy's Law. Pore water velocity ($m\ h^{-1}$) was calculated from infiltration rate (median) and mean porosity.

Sampling techniques

Sediment samples were usually taken with acrylic glass tubes (30 cm length, 6.2 cm inner diameter). Sediment cores were

Table 1
Sediment characteristics.

Sediment depth (cm)	0–5	5–10	10–15	15–20	20–25	25–28
Water content (%)	20.3	20.2	11.5	14.5	17.6	16.8
Mean grain diameter (mm)	0.13	0.14	0.27	0.25	0.22	0.23
d_{10} (mm)	0.07	0.07	0.09	0.11	0.09	0.10
Sorting coefficient (So)	1.48	1.47	1.61	1.46	1.44	1.41
Ununiformity U	2.15	2.46	3.22	2.36	2.56	2.35
Skewness (Sk)	0.97	0.85	1.02	1.12	1.09	1.13
Porosity	0.40	0.40	0.26	0.31	0.36	0.35
k_f according to Beyer [$m\ s^{-1}$]	5×10^{-5}	5×10^{-5}	7×10^{-5}	1×10^{-4}	8×10^{-5}	1×10^{-4}

immediately divided into profiles of 1 cm between 0–10 cm, 14–15 cm and 19–20 cm and frozen (−18 °C) until analysis of chlorophyll *a*, C, N, carbohydrates, EPS and proteins.

Freeze cores of 50 cm length were taken to quantify meiofaunal abundances and FPOM.

Analysis of C/N and chlorophyll a

C and N analyses were carried out using a Vario EL III Elementar C–N Analyser, and chlorophyll *a* was performed according to DEV (1986); the organic carbon of algae can be calculated by chlorophyll *a* multiplied by a factor of 30 up to 100 (literature data analysis by Margaleff, 1983). C, N and chlorophyll *a* measurements were performed every 6 weeks during May 2004 and March 2005. For C/N analysis, aliquots (20–30 mg) of lyophilized and grounded sediment samples were used as well as ashed samples (4 h, 550 °C).

For the determination of algal chlorophyll *a*, sediment extraction was carried out (14 and 3 h, respectively) with absolute ethanol twice at room temperature after ultrasonication (1 min, Bandelin Sonorex Super RK 106, 35 kHz). Chlorophyll *a* analyses were carried out according to DEV (1986).

Carbohydrates, EPS, proteins

For the analysis of carbohydrates and extracellular polymeric substances (EPS) samples were taken monthly between December 2005 and June 2006. The extraction of colloidal carbohydrates was carried out using 0.1 n Na_2-EDTA according to Underwood et al. (1995). 0.5–1 mL of the sample were used for carbohydrate measurement using the phenol–sulphuric acid procedure (Dubois et al., 1956). Calibration was done with glucose as a standard. The percentage of EPS in the colloidal-EDTA fraction was measured after precipitation with 70% ethanol (Decho, 1990) followed by the phenol–sulphuric acid procedure. Relations between extraction protocols for activated sludge EPS and EPS complexation properties according to Comte et al. (2006) were not considered here.

Proteins were measured with Bradford reagent following the standard micro assay protocol (Sigma). 1 mL of the supernatant was used in the assay after extraction with 0.1 n Na_2-EDTA as described above. Protein concentrations were determined in January, April and June 2006.

Seston and leaves input as particulate organic matter (POM)

For the determination of seston input, daily water samples were taken during one week in April 2005, sieved (100 μm) and filtered through glassfiber filters (Whatman). Autumn leaf fall was measured in November 2005 using leaf traps 3–7 m away from the shore.

Leaves traps ($29.5 \times 24.5 \times 10\ cm^3$) with a mesh size of 1 cm were exposed on the sediment surface with distances of 3, 5 and 7 m to the shore line (three parallels each) in November, 15th 2005; after 3, 6, 9, 15, 22 and 28 days the coarse organic matter was sampled. Results were corrected to leaf decay measured in parallel using small net cages ($20 \times 20 \times 5\ cm^3$, 1 cm mesh size, the bottom covered with 5 mm gaze), filled with air-dried alder leaves (*Alnus glutinosa*, 4.04 ± 0.05 g d.w. each one). Three parallel leaf packs were retrieved after 3, 14, 28, 42, 63 and 154 days, oven-dried to constant weight (60 °C), mass-loss (in %) was described by the equation $y = 100e^{-0.04x}$.

Area-related POC inputs were converted into % POC per sediment d.w. using the equation:

$$POC[\%] = POC[g\ dm^{-2}]/(1-\Phi)\rho_s$$

with Φ = porosity of the upper sediment layer (0.4), ρ_S = density of dried sediment (2.67 g cm^{-3}).

Meiofauna and fine particulate organic matter (FPOM)

Freeze-core samples were taken every 6 weeks between April 2004 and February 2005. The frozen cores (approximate 50 cm length) were transported to the laboratory immediately after sampling and divided into sections of 5 cm. Organic compounds were separated from sand through washing over a sieve cascade that resulted in the different size fractions of $<1->0.5$, $<0.5->0.3$, $<0.3->0.1$ and $<0.1->0.045$ mm. Samples were fixed with formaldehyde solution (4%) and stained with 0.02% Rose Bengal solution. The meiofauna was sorted on a high taxonomic level and enumerated using a binocular (Stemi SR, Fa. Zeiss). Afterwards FPOM in the samples was dried to constant weight (60 °C), weighted and organic carbon was determined as LOI (4 h, 550 °C); for wet weight/ volume calculation, a water content of 80% was assumed.

Scanning electron microscopy with energy dispersive spectroscopy (SEM–EDS)

For scanning electron microscopy with energy dispersive spectroscopy (SEM–EDS) analyses stainless steel tubes (1 cm height, 0.7 cm Ø) were pressed into the sediment layers to different depths. These mini cores were either air dried or fixed with 2% glutaraldehyde and then dehydrated using water–alcohol exchange, followed by similar alcohol-acetone exchange (Westall and Rincé, 1994). The cores were then critical point dried. All samples were sputtered with gold, the mini sediment cores were inserted completely into the vacuum chamber of the SEM. A SEM–EDS Hitachi S 2700 electron microscope was used with an acceleration voltage of 20 kV and IDFix hard and SAMx software for EDS analysis.

Fluorescence labelled tracers

Melamine resin particles of 2.44 ± 0.04 μm diameter (mean ± SD) labelled with 7-amino-4-methylcoumarin (AMC) were used (microParticles, GmbH). The blue fluorescing MF-AMC particles (λ_{ex} 360 nm/λ_{em} 429 nm) had a density of 1.5 g cm^{-3} and a hydrophilic surface either charged positively by amino groups or negatively by carboxyl-groups. In relation to sediment surface area, the particle concentration inside the sediment core was $1.7 \times 10^6\ cm^{-2}$ in experiments with positively and negatively charged particles (April and July 2005) and $2.2 \times 10^6\ cm^{-2}$ in experiment with negatively charged particles (August 2005).

Air-dried FPOM from alder leaves (*Alnus glutinosa*) was labelled with fluorescein-5-isothiocyanate (FITC, λ_{ex} 506 nm/λ_{em} 529 nm; microParticles GmbH). The number of particles used in the experiments was 7.8×10^5 (sd = $\pm 1.4 \times 10^5$) according to a particle area of $1.2 \times 10^4\ mm^2$ and a dry weight of 0.1 g. The corresponding particle density in the in-situ sediment cores was $2.6 \times 10^4\ cm^{-2}$ (sd = $\pm 4.6 \times 10^3$) at the start of the experiments. The stock suspension was of high stability and showed a strong fluorescence signal even after 18 months (for details see Gunkel et al., 2009).

In-situ sediment core technique for fluorescent tracer studies

The uptake and transport of AMC-labelled melamine resin particles and FITC-labelled FPOM were studied in in-situ sediment cores that consisted of acrylic glass tubes with an inner diameter

of 6.2 cm and a length of 25 cm, pressed into the sediment down to 15 cm. The selected sediment core depth had to be at least 5 cm deeper than the transport depth of the fluorescence marker to avoid any environmental contamination. Each core was topped with a PVC cap in which an open tube fitting was integrated for tracer suspension injection. In situ experiments with AMC-labelled melamine resin particles were carried out in April 2005 (positively charged particles) and July 2005 (negatively charged particles). Three parallel samples were recovered after exposure times of 3, 7 and 14 days. In August 2005 another trial using negatively charged particles was carried out over a study period of 3 days; inside the core the top sediment layer of either 1, 2, 4 or 6 cm was removed before tracer injection to study particle retention below the biologically active zone.

A long-term experiment with FITC-labelled FPOM started in December 2005. Samples were retrieved after 14, 28 and 126 days (one core at each time period, 3 subsamples in each). Transport of FITC-labelled FPOM during short-time intervals up to 14 days is detailed in Gunkel et al. (2009).

In the laboratory, the sediment cores were divided into layers of 1 cm each. The overlying water was filtered through 0.2 μm Nucleopore filters, and the filters were used for direct particle counts. A defined well-mixed aliquot of sediment (9.4 cm^3) was suspended in deionized water for microscopic analysis, wet-sieved, homogenated and for MF-AMC particles ultrasonicated. Analysis-Software (Soft Imaging System GmbH) was used for the measurement of FPOM areas.

Laboratory sediment core experiments for the assessment of recovery rates were performed in the same manner with sediment cores from the shore of Lake Tegel. Laboratory studies showed a recovery rate for spiked sediment samples of 64 ± 9 up to $88 \pm 13\%$ (MF-AMC particles) and of $90 \pm 16\%$ (FITC-labelled FPOM), respectively. The recovery rate is less than 100% because when using microscopic counting, some particles were covered by sediment particles and thus rendered invisible.

All microscopic studies were performed using a light microscope (Zeiss Axioskop) equipped with a UV lamp (Osram HBO 50) and Neofluar objectives of different magnification. A Zeiss filter set 09 (BP 450-490, FT 510, LP 515) was used in the FITC studies, and filter set 02 (BP 365, FT 395, LP 420) was used in the AMC fluorescence studies.

An *H*-test for three independent parameters was used to test for significant alterations in the particle number of inert AMC-labelled particles with time: three sets of samples (n_i=9) from corresponding sediment depths at three different times of exposure (3, 7 and 14 d) were tested for significant differences in particle number.

Results

Infiltration characteristics

Considering all locations and sampling dates infiltration rates vary between 0.7 and 27.0 L m^{-2} h^{-1} the median being 9.0 L m^{-2} h^{-1}. This corresponded to pore water velocities of 0.02 m h^{-1}. At one location and during short time intervals the observed variation in infiltration rates was high. In contrast to the high k_f values calculated according to Beyer of 10^{-4}–10^{-5} (Table 1), k_f values based on in situ infiltration rates and hydraulic potential, measured in the upper 2 cm, were from 4×10^{-7} to 6×10^{-5} m s^{-1} indicating severe clogging processes in the interstices (Table 2). In particular during the winter period, hydraulic conductivities decreased about 10^{-2} compared with the Beyer values. The differences in hydraulic conductivities and infiltration rates were not correlated due to unsteady hydraulic gradients, which were generated by an alternating pumping regime and the influence of k_f values. The increase in dynamic viscosity with falling water temperatures only partially explained the decline in k_f values; a decrease of water temperatures from 20 to 5 °C only accounted to a change in hydraulic conductivity from 4.8×10^{-4} to 3.1×10^{-4} m s^{-1} (= −34%). Atmospheric air intrusion and POM entry by leaf fall in autumn must be considered as other parameters that reduced hydraulic conductivities.

Table 2
Hydraulic conductivities in 2 cm depth at different locations in summer (April 04–September 04) and winter (October 04–April 05).

Location	Mean summer k_f-value [m s^{-1}]	Mean winter k_f-value [m s^{-1}]
Pallisade passage	6×10^{-6}	8×10^{-7}
Erosion area	6×10^{-5}	n. d.
Water lillies	2×10^{-5}	2×10^{-6}
In front of reeds 1	7×10^{-6}	4×10^{-7}
In front of reeds 2	2×10^{-6}	1×10^{-6}
In front of reeds 3	8×10^{-6}	7×10^{-7}
In front of reeds 4	3×10^{-5}	n. d.

Atmospheric air intrusion

Enhanced groundwater abstractions by the bank filtration wells during summer led to a drop of the groundwater table near the lake of about 2 m and the formation of a large unsaturated sandy littoral soil horizon, filled with atmospheric air. This gas bubble stretched down under the lake to water depths of 1 m and led to a decrease in hydraulic conductivities due to enhanced hydraulic gradients in late summer/autumn period (Hoffmann and Gunkel, 2010). The real extent and dynamic of this unsaturated soil horizon is not yet quantified; similar conditions are known from infiltration ponds and rivers during excessive water abstraction (Denecke, 1997; Greskowiak et al., 2006; Hiscock and Grischek, 2002).

Interstitial particulate organic material (POM)

Biological compounds from epipsammic algae, biofilms and detritus, as well as rhizomes of macrophytes, built up the standing stock of particulate organic matter (POM), which significantly reduced the free pore space. In the upper sediment (0–10 cm), the potential pore volume (as sum of free water, bound water, POM and carbonate) amounted 42–45% of the total sediment volume (Fig. 1), and nearly half of the volume was filled with POM and POM water (17–21% of the sediment volume, that is 37–48% of the pore volume). Even at depths below 10 cm this fraction constituted 7% of sediment volume (23% of the pore volume). In comparison, the inorganic carbonates contributed only up to 3% of the sediment volume (Fig. 1).

The seston concentration in the overlying water column during April and May 2005 was 7–32 mg L^{-1} and the organic proportion was 3–8 mg L^{-1}. With regard to the median infiltration rate a monthly input of sestonic particles of 45.4–207.4 g m^{-2} with 20.1–49.8 g m^{-2} as the organic fraction can be expected. The latter values corresponded to 13–31% of the POC.

Temporary leaf fall (7–3 m distance to shore line) led to external inputs of approximately 5.0–29.0 g C m^{-2} per month during autumn, contributing 3 – 18% to POC.

The annual mean POC pool in the upper 0 – 1 cm amounted to approximately 159.2 g m^{-2}. The depth distribution of different sized fractions of FPOM is shown in Fig. 2. The FPOM decreased with sediment depth from 1.5% of sediment dry mass at 0–5 cm to

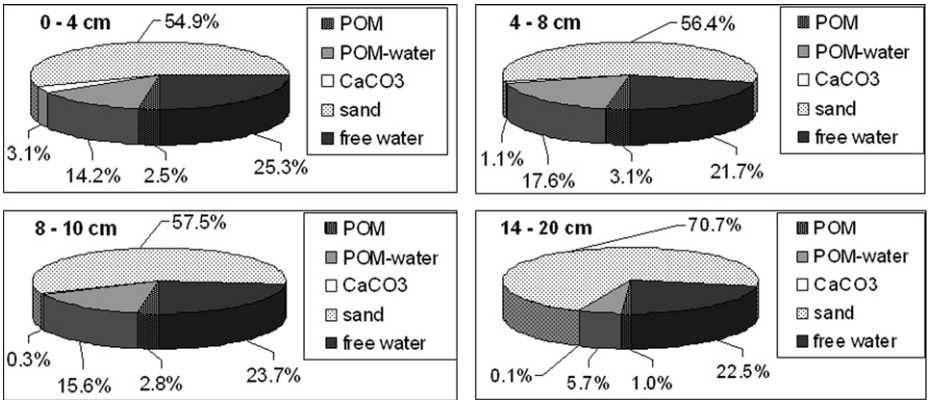

Fig. 1. Sediment and interstices compounds as vol-% (mean 2004–2005) calculated from C/N analyses, assuming 80% water content of POM.

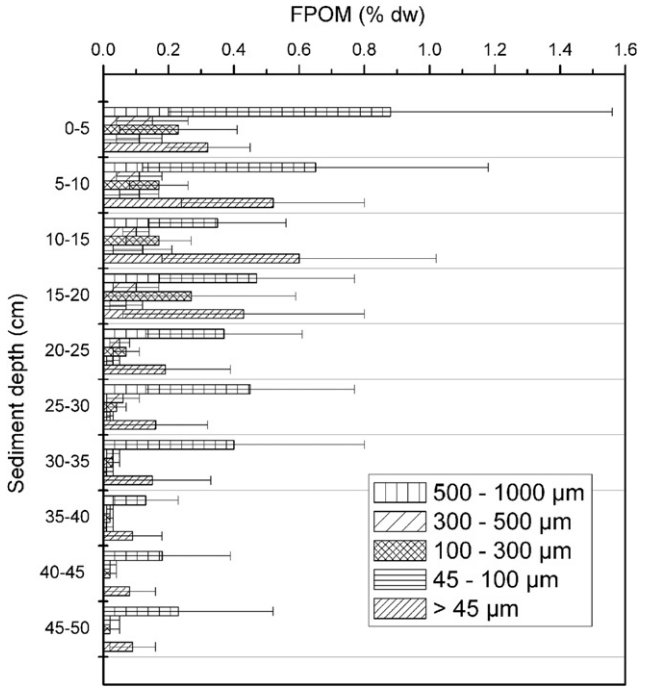

Fig. 2. Depth distribution of different FPOM size classes between March 2004 and February 2005; data presented are means ± standard deviation.

0.5% at a sediment depth of 35 cm. The size class >1 mm usually contributes most to POM-biomass followed by FPOM <100 µm and >0.45 µm. The relative and absolute proportions of FPOM gained importance from the surface to the middle depths of the sediment, resulting in the highest percentages of the fine fraction at 15 cm. These results indicated that coarse material is fragmented to smaller size classes near the sediment surface and is then transported to deeper layers. The distribution of the finest FPOM fraction was well in accordance with the abundance of the detrivorous meiofauna (Gunkel et al., 2009).

Meiofaunal abundances

Meiofaunal abundances varied a lot during the course of the year (March 2004–February 2005, Table 4). Peak abundances reached 17.000 Ind. dm^{-3} in November and approximately 12.000 Ind. dm^{-3} in April, lowest abundances were observed in March 04, August 04 and February 05 with $720-1.350$ Ind. dm^{-3}. Nematodes and Harpacticoida dominated the meiofaunal assemblage with of 90–98%. In contrast to the high abundance the meiofaunal biomass only constituted 30 g d.w. per dm^{-3} sediment as annual mean, this was adequate to 0.2% of the POC in 0–1 cm depth (conversions according to Hakenkamp et al., 2002). Abundances of organisms continuously decreased significantly with sediment depth. In the surficial sediment layer of 0–5 cm abundances usually were 2–7-fold higher than in the 5–10 cm layer. In 10–15 cm depth ≤ 100 individuals dm^{-2} and in 15–20 cm ≤ 20 Ind. dm^{-2} were found.

Table 3
Organic carbon of algae as percentage of total organic carbon (%) in different sediment depths (Min–Max according to Margaleff, 1983)

Sediment depth (cm)	Summer min–max	Winter min–max
0–1	8.2–27.3	7.8–26.0
1–2	10.8–35.9	6.9–23.1
2–3	8.1–26.9	4.9–16.2
3–4	8.7–29.0	4.3–14.5
4–5	4.4–14.5	1.5–5.0
5–6	1.3–4.5	0.3–1.0
6–7	0.2–0.6	0.1 – 0.2

Microalgal biomass

In the surficial sediment layer up to a depth of 4 cm, colmation is triggered to a large extent by the production of autochthonous biomass including biofilm formation. Here, epipsammic algae (predominantly diatoms) are highly abundant reaching numbers between 3×10^6 cells mL^{-1} and 1.5×10^7 cells mL^{-1} (Hoffmann and Gunkel, 2010), corresponding to maximum chlorophyll *a* values of 24 µg m L^{-1} in April/May. The proportion of planktonic algae in the sediments constituted only about 2%. Thus the abundance of epipsammic algae exceeded those of phytoplankton in lake water by 100–500-fold, and chlorophyll *a* was 2400-fold higher in the sediment than in a similar volume of lake water. Table 3 shows the percentages of epipsammic algal carbon in relation to total organic carbon, which varied around 8% at 0–4 cm (summer) and 0–2 cm (winter), respectively, and reached up to 36% of the total carbon at 2 cm (Table 4).

Biofilm structure

The biofilm covers large particle areas thereby filling out the pore space (Fig. 3A and B). In air-dried samples open pores

occurred and allowed water to flow through (Fig. 3B). In some parts, the structure appears really compact (Fig. 3A and B), in other parts the biofilm formed a more fibrillous net (Fig. 3C) with associated microorganisms (bacteria, diatoms and protozoa). Epipsammic diatoms (Fig. 3D) were often embedded in the thick biofilm matrix while bacteria were found only on more loose structures.

Extracellular polymeric substances (EPS) are formed by carbohydrates and proteins, which build up a three-dimensional structure with fibrillous and more compact areas.

EDTA-extractable carbohydrates, most of them colloidal, showed the highest concentrations at a sediment depth of 0–1 cm, the corresponding values being 413–817 $\mu g\, g^{-1}$ sediment (d.w.) which was in good agreement with maximal algal biomass. Carbohydrates continuously decreased with sediment depth down to concentrations of $< 100\ \mu g\, g^{-1}$ d.w. at a depth of 19–20 cm (Fig. 4). No significant seasonal changes were observed. The percentage of the high molecular weight fraction of EPS varied between 16–54% at a depth of 0–1 cm and was > 50% in deeper sediment layers most of the time.

Proteins are made up only a tenth of the colloidal carbohydrates. They also showed a significant decrease according to sediment depth, with mean values of $50.6 \pm 10.8\ \mu g\, g^{-1}$ d.w. ($\pm$ s. d.) sediment at a depth of 0–1 cm to $18.5 \pm 6.0\ \mu g\, g^{-1}$ d.w. sediment at a depth of 19–20 cm. The percentage of proteins related to organic carbon was only 0.5%.

Table 4
Seasonal changes of meiofaunal abundances in 0–10 cm sediment depth [N dm^{-3}] between March 2004 and February 2005, including animal seizes < 1 mm and > 100 μm.

Taxon	Mar 04	Apr 04	May 04	Jul 04	Aug 04	Oct 04	Nov 04	Feb 05
Nematoda	679	9990	8081	6803	753	4069	4417	305
Harpacticoida	11	780	233	233	251	2197	6993	880
Phyllopoda	0	30	0	253	24	188	1352	7
Copepoda	0	0	0	0	0	0	223	0
Ostracoda	8	460	320	86	112	416	292	69
Oligochaeta	14	470	480	122	9	30	0	7
Chironomidae	4	100	10	8	65	102	275	21
Rotifera	7	300	55	60	0	238	759	0
Tardigrada	0	90	0	7	15	203	1813	0
Bivalvia	0	0	20	0	3	0	0	20
Gastropoda	0	30	0	0	0	9	434	17
Gammaridae	0	0	0	0	0	0	25	7
Ephemeroptera	0	0	0	128	9	0	90	14
All taxa	723	12,250	9199	7700	1241	7452	16,673	1347

Clogging effects

Experiments with inert MF-AMC particles added to in-situ sediment cores resulted in an effective particle retention which was highest in the uppermost sediment layer of 1 cm regardless of whether particles were positively or negatively charged whether exposure time was 3 days or more (Figs. 5 and 6). 80–90% of recovered particles were consistently found at a sediment depth of 0–1 cm and 10–20% at 1–2 cm. Statistical analysis of particle distribution could not detect significant differences ($p < 0.05$) within the upper 2 cm of the sediment with time, however, the vertical decrease in particle number from 0–1 to 1–2 cm was significant.

If overlying sediment layers were removed within the in-situ sediment core before particle exposure (Fig. 7), the pattern of particle retention was almost comparable to the undisturbed sediment cores and 80% of recovered particles were retrieved from the remaining uppermost centimetre, indicating effective particle retention structures (as EPS structures) in the interstices down to a depth of 6 cm. However, the recovery rate decreased from 83% (no removal of sediment) to 73% after removal of the uppermost centimetre and to 46–53% after the removal of 4–6 cm of sediment.

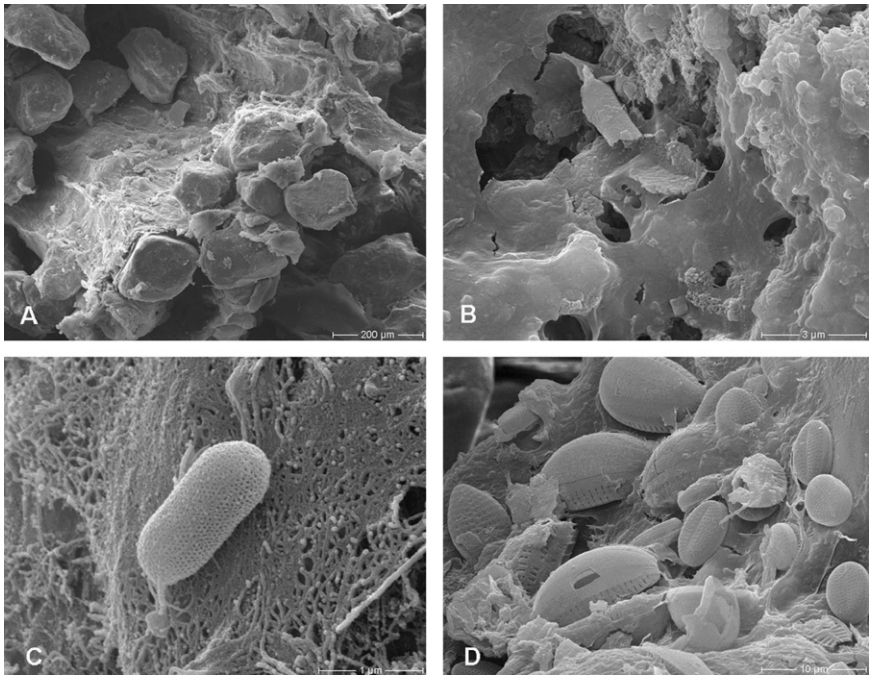

Fig. 3. (A) Biofilm, bank side, 17.05.04, 1–2 cm depth, after critical point drying. (B) Porous biofilm, between reeds, 05.02.04, 7–8 cm depth, after air-drying. (C) Biofilm with microconsortia, bank side, 17.05.04, 3–4 cm depth, after critical point drying. (D) Diatoms embedded in thick biofilm matrix, bank side, 13.12.04, 3–4 cm depth, after critical point drying.

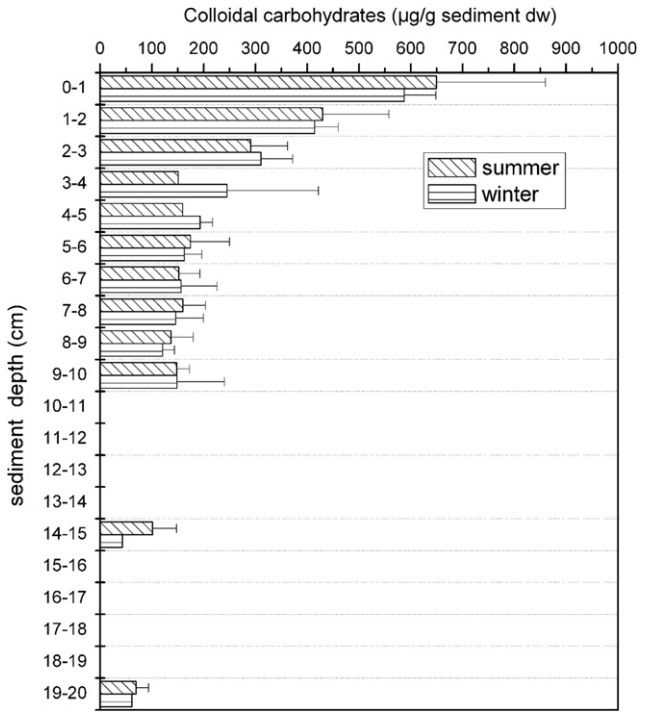

Fig. 4. Vertical distribution of EDTA-extractable (colloidal) carbohydrates; data presented are means ± standard deviation during winter period (December 2005–March 2006) and summer period (April–June 2006), respectively, n=4.

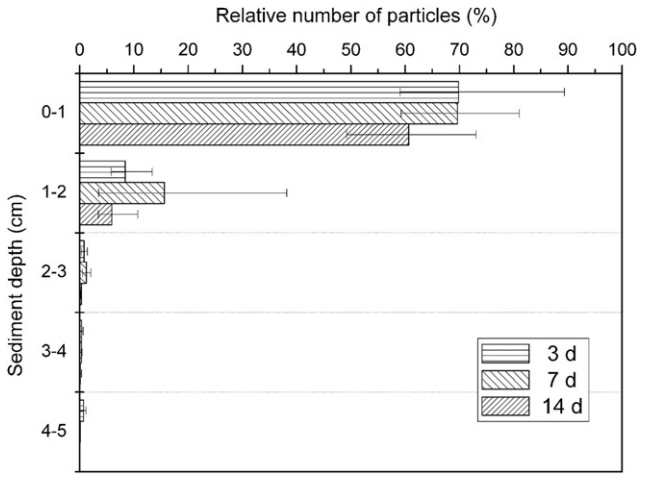

Fig. 5. Depth distribution of positively charged MF-AMC particles as percentage of exposed particles in in-situ sediment cores, April 2005; mean ± minimum and maximum; n=3.

In-situ sediment core experiments with FITC-labelled FPOM showed no significant particle transport below a sediment depth of 1 cm sediment either during 14 days (Gunkel et al., 2009) or over a study period of 126 days (Fig. 8). Within 14 days of exposure particle numbers decreased from 7.6×10^5 at the beginning of the experiment to 1.5×10^5 which corresponded to 19% of the exposed particles. After 28 and 126 days the number of recovered particles at a depth of 0–1 cm was 7% of the original number. In deeper sediment (1–5 cm) less than 0.1% of the FITC-labelled FPOM was found after 14 days, and only 0.4% after 126 days. Below 5 cm only amorphous fluorescing structures (e.g. faeces) were observed sporadically.

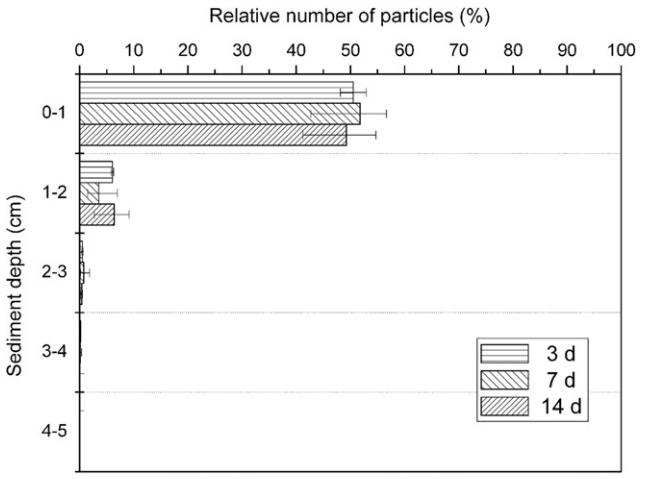

Fig. 6. Depth distribution of negatively charged MF-AMC particles as percentage of exposed particles in in-situ sediment cores, June 2005. Data presented are means ± minimum and maximum values; n=3.

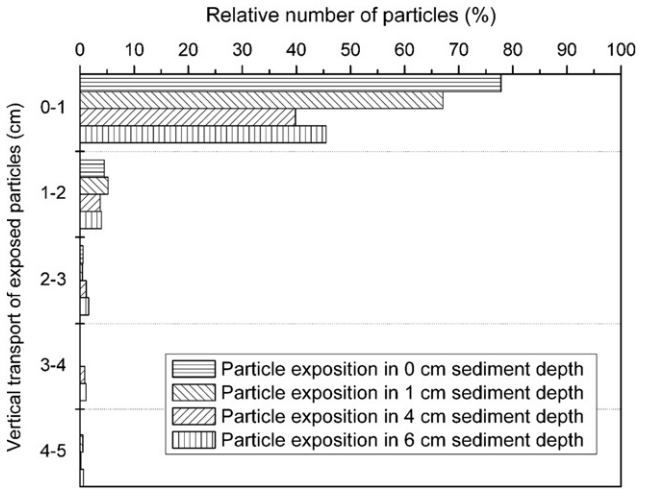

Fig. 7. Depth distribution of negatively charged MF-AMC particles as percentage of exposed particles in in-situ sediment cores after removal of the superficial sediment layer, 3 days of exposure, August 2005. Before the start of the experiment sediment layers of different thickness were removed.

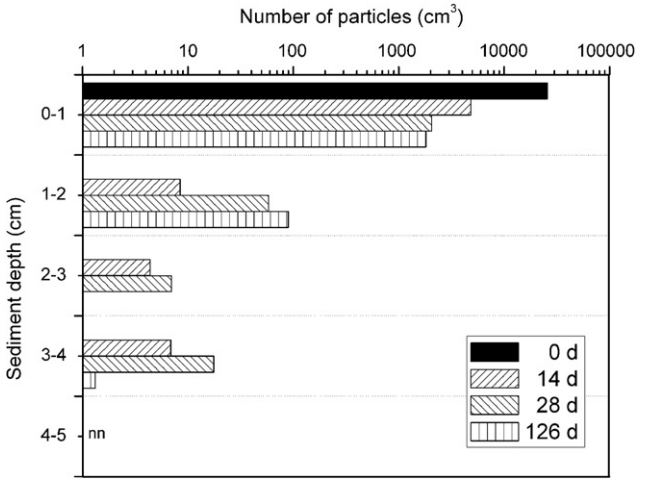

Fig. 8. Distribution of FITC-labelled FPOM recovered from different sediment depths after 14, 28 and 126 days, respectively; in-situ sediment core experiments (November 2005–March 2006).

Discussion

Clogging processes

The clogging of the interstices under natural, but infiltrating conditions in Lake Tegel, is caused to a large extent by POM, which is composed of living biomass such as epipsammic diatoms, biofilms, macrophyte rhizomes and detritus. This biological clogging reached down to a sediment depth of least 10 cm. Complete clogging did not occur due to high carbon turnover (Hoffmann and Gunkel, 2010) and feeding activity by the abundant detritivorous meiofauna (Gunkel et al., 2009), probably combined with reopening of the interstices by wave action. This type of clogging is different to the compact, surficial clogging layer regularly observed during slow sand filtration (Rinck-Pfeiffer et al., 2000; Langergraber et al., 2003). In Lake Tegel, up to 48% of the interstitial pore volume was filled with POM, mainly FPOM $< 100\,\mu m$ and > 1 mm, respectively. Epipsammic algae contributed at least 8% to organic carbon and produced EPS, both being important components of the finest FPOM-fraction in the upper sediment layer. No significant seasonal changes were observed in FPOM and EPS components. Anyhow, hydraulic conductivities decreased in late autumn about 10^{-2} compared with the Beyer values.

The intrusion of sestonic matter is often considered to be the most important clogging factor (Rice, 1974; Hiscock and Grischek, 2002; Langergraber et al., 2003). According to Okubo and Matsumoto (1983), the concentration of suspended solids should not exceed 2 mg L^{-1} and that of DOC should not exceed 10 mg L^{-1} in order to sustain a high infiltration capacity over longer periods during artificial groundwater recharge. The results from this study indicate that the deposition of sestonic particles can contribute up to one third of the organic matter found in the upper sediment layer and to 0.3–1% of sediment dry weight. Leaf fall temporarily accounted for similar inputs as organic seston. However, the clogging process is also strongly determined by photoautotrophic and heterotrophic production, conversion and decomposition of organic matter in the interstices. Additionally atmospheric air intrusion from the bank side in late summer surely is an important clogging factor with a dimension not quantified yet (Gunkel and Hoffmann, 2009).

EPS components

Polysaccharides are known to build up EPS and to decrease hydraulic conductivities (Ragusa et al., 1994; Vandevivere and Baveye, 1992a; Le Bihan and Lessard, 2000). Comparable concentrations of water-extractable carbohydrates in the sediments of an oligotrophic lake were reported by Hirst et al. (2003). De Zoysa and Ragusa (1995) found a strong positive correlation between chlorophyll *a* and polysaccharides in the sediments of an irrigation channel which complied with our results. In the sandy littoral interstices of Lake Tegel, highly abundant viable diatoms, always imbedded in a thick biofilm matrix, are important producers of colloidal carbohydrates (Hoagland et al., 1993; Underwood et al., 1995; Underwood and Smith, 1998) in addition to bacteria, which also can reach high cell numbers of approximately $2 \times 10^9\,g^{-1}$ sediment wet weight (Beulker and Gunkel, 1996). Colloidal carbohydrates showed the same decrease with sediment depth as that of chlorophyll *a*, while the high molecular weight (polymeric) fraction did not show obvious changes with depth. A strong correlation between water-extractable carbohydrates and chlorophyll *a*, in contrast to EPS and chlorophyll *a* was also found by De Brouwer et al. (2000) and Stal (2003). Yallop et al. (2000) demonstrated that EPS were not a constant fraction of colloidal extracts and that the relative proportions can vary between 16% and 58%, which is in accordance with our findings.

In relation to organic carbon at 0–1 cm (annual mean = 1%) and using a factor of 0.44 for the conversion of polysaccharides to organic carbon, the percentage of colloidal carbohydrates was about 4% of the POC, while the percentage of EPS was 1% of the interstitial POC. If we consider that EPS make up only 1% of biofilms while up to 99% consists of water (Costerton et al., 1986; Taylor and Jaffé, 1990; Flemming, 1995; Neu and Lawrence, 1999), the resulting percentage of the biofilm volume at a depth of 0–1 cm is 3% of the sediment volume or, in relation to POM volume (with 80% water content) up to 20%.

Compared to polysaccharides the concentrations of proteins related to bacteria and their exoenzymes in the interstices of Lake Tegel were significantly lower.

Interstitial biofilms in the littoral zone of Lake Tegel were of high morphological variability, sometimes showing a dense formation, sometimes forming loose aggregates of fibrillous structure. This high variability in morphological structure is in accordance with the findings of other authors (e.g. Westall and Rincé, 1994) and can be caused by the variable chemical nature of EPS (Wingender et al., 1999) and to external effects that result in swelling, condensing and reorganization of the biofilm matrix (Decho, 2000). In the case of air-dried samples possible artefacts could not be excluded. Taylor and Jaffé (1990) described an "open pore" model: a decrease in permeabilities due to biofilm formation led to an increase in fluid shear stresses that limited the biofilm development and kept the pore space open. The authors further assumed a balance between biofilm growth and decay as well as between biofilm detachment (due to shear forces) and re-attachment (due to infiltration).

Infiltration and particle transport

In-situ sediment core experiments indicate a significant retention of inert particles regardless of whether positively or negatively charged particles were used or whether the time of exposure was 3 or 14 days. The particles had a diameter of 2.44 μm and were therefore a similar size to that of small algal cells. Compared with the effective mean pore water velocity of 0.5 m d^{-1}, particle transport should have been in a similar range, however, it should be pointed out that the exposed fine resin particles were completely hindered in vertical transport and accumulated at a sediment depth of 0–2 cm. In Lake Tegel the interstices built an effective filter system for particle retention. Severe clogging mainly induced by biological processes combined with inhomogeneties of the pore space, especially the three-dimensional EPS structures and adsorptive processes on EPS causes this phenomenon. This is in accordance with the findings of other studies (Miettinen et al., 1996; Schulte-Ebbert, 2004), where 80–90% of the microorganisms were withheld during bank filtration. According to Schubert (2000) suspended solids and microorganisms were retained even at the surficial layer of the motile bottom (sandy to gravel) during bank filtration at the riverine Rhine. In experiments by Huettel and Rusch (2000) the penetration depth of the green alga *Dunaliella* was 1.8 and 1.2 cm, respectively, in fine sands and increased linearly with the logarithm of permeability. Hofmann et al. (1998) found that particle transport in groundwater only concerned colloidal particles ($< 1\,\mu m$) with a mean size between 100 and 200 nm.

The use of natural FPOM (< 1 mm) as a fluorescing tracer showed effective retention of in situ organic matter in the uppermost centimetre. Only low vertical transport efficient down to 2 cm occurred during 126 days of exposure. A particle shift beyond a depth of 5 cm was not observed (Gunkel et al., 2009).

These results confirm that the superficial sandy layer functions as a biological filter and has a thickness of a few centimetres and a complex three-dimensional structure composed of algae, bacteria and other microorganisms embedded in an EPS matrix, illustrated by the SEM microphotographs. In addition, investigations recently carried out indicate that cyanobacterial cells, protozoans (*Cryptosporidium, Giardia*) and respiratory viruses were not transported by the infiltrating water into deeper sediment layers (Medema et al., 2003; Hijnen et al., 2004; Grützmacher et al., 2007; Gunkel and Hoffmann, 2009). Our results support the idea of the biological filter function and clearly point out the high significance of biological processes.

After 14 days 80% of the exposed particles were degraded, but no significant particle transport by infiltration water below 1 cm depth was observed; we assumed, that easily degradable organic matter was lost due to decomposition and grazing by the heterotrophic biocoenosis (macrozoobenthos, meiofauna, fungi and bacteria). The uptake of fluorescing FPOM by several meiofaunal organisms was proved in previous experiments (Gunkel et al., 2009). Furthermore peak meiofaunal abundances in November 2004 and April 2005 were isochronic to leaf fall and primary production maximum (Hoffmann and Gunkel, 2010). Regarding the observed depth distribution of different seize classes of natural FPOM >100 μm, some mechanisms such as horizontal input (macrophyte rhizomes) or extraordinary storm events leading to sediment rearrangement were conceivable. The distribution of the size class >0.45 and <100 μm (i.e. composed of benthic algae, EPS, organic seston and excretion products) is supposed to be the result of internal production, FPOM transport within the food chain as well as depth infiltration of ultrafine and colloidal particles. This study emphasizes the functional role of the meiofauna and other detritivores to counteract clogging processes.

Conclusion

Ground water recharge as well as bank filtration in sandy littoral zones are strictly limited by the littoral boundary sediment layer which is a highly active biological zone of about 10 cm depth, built up by interstices algae, bacteria, produced EPS and meiofauna. The upper part of the boundary layer serves as a filter with a high retention capacity for fine particles with sizes down to 2.44 μm as well as for POM and hereby reduces the infiltration rate significantly. External inputs of seston particles and POM (temporary leaf fall), atmospheric air intrusion from the bank side as well as the internal POM (e.g. macrophyte rhizomes, microalgae, biofilms) are important clogging factors in the limnic–lenitic environment controlling the infiltration characteristics. The infiltration rates showed a high temporal and spatial variability during the 2 years investigation period that is also related to sediment inhomogenities and an alternating pumping regime during raw water abstraction. Experimental results emphasize the long-term physical stability of the uppermost layer. We assume that the high turnover of FPOM by consuming meiofauna and other microorganisms as well as physical factors (e.g. wind waves) prohibits complete clogging thus making it a reversible and highly dynamic process. The balance between internal production and external inputs on the one hand and turnover by detritivores on the other hand is the pre-condition to guarantee a long-term stability of infiltration capacities playing a crucial role in bank filtration.

Acknowledgements

We thank the German Scientific Society (DFG) for financing this project (Gu 307/11-1/2). The investigations were supported by Dipl. Ing. Ulrich Gernert, ZELMI, TU Berlin (SEM-EDS) and the Lab. of Soil Science, TU Berlin (C/N analyses).

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