Clogging processes in a bank filtration system in the littoral zone of Lake Tegel (Germany)

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Abstract

Several physical, chemical and biological mechanisms play a role in the clogging of sediment interstices regularly observed in sand filter and infiltration basin systems. Whereas the hyporheic zone has been the focus of many investigations, little is known about the lenitic limnic zone, which is typical in lowland areas with lakes and low flow rivers. One must assume that clogging is regulated by both the build-up and the input of particulate organic matter (POM).

In the present study, we collected samples from the littoral zone of Lake Tegel, Berlin, Germany, to analyze relevant carbon turnover processes. High concentrations of POM were detected in the upper sediment layer, with 3.4% ds down to 20 centimeters depth. A very high biomass of interstitial algae was found in the first 5 cm of sediment (25 µg Chl a per cm^{-3}); this was 1000 times higher than in the lake water. The pore system of the sediment was filled to about 50% with POM, and the algae volume comprised about 25 % of POM. Only low amounts of POM were transported from the lake water downwards into the interstices, and the transport of FPOM (a few centimeters per day) was much lower than the water flow (32 – 260 cm d^{-1}). The DOC concentrations in lake water (~ 8 mg L^{-1}) and interstitial water (~ 6 mg L^{-1}) were determined by the in situ bioactivity of interstitial organisms in addition to DOC input from lake water.

Keywords

Bank filtration, clogging, hyporheic zone, interstices, littoral, meiofauna.

INTRODUCTION

The hyporheic zone is a dynamic ecotone between the aquatic and the groundwater ecosystems. Consequently, the physical, chemical and biological parameters used in limnology and hydrogeology to characterize the two ecosystems tend to display high gradients. The significance of the ecotone is given by the natural and artificial groundwater recharge and the need for adequate groundwater protection.

The hyporheic zone has been the subject of many investigations, most of which have focused on marine sandy beaches, but also on mountain areas with running water containing sandy and stony substrates. This lotic-limnic hyporheic zone must be distinguished from lenitic hyporheic interstices, which are typically found in lowland areas with lakes and low flowing rivers. Compared to lotic systems, fine sand and silt are the dominant substrates in lowland rivers, and infiltration processes are strictly reduced.

Although we have a good understanding of the marine hyporheic interstice (Higgins and Thiel 1988) and of the limnic-lotic hyporheic zone (Pennak 1988, Brunke and Gonser 1997), little is known about the ecological processes that maintain the limnic-lenitic ecotone (Pennak 1988, Hakenkamp et al. 2002). The main mechanisms are the infiltration of water, the mechanical retention of suspended particles, and the mineralization of particulate organic matter (POM) and of dissolved organic carbon (DOC). However, the hyporheic interstice is also a zone of primary production by microalgae, which, like meiofauna, are part of the interstitial food web (Wasmund 1986, Beulker and Gunkel 1996). Thus, biological processes like primary production of biomass, fragmentation of crude POM

(CPOM) to fine POM (FPOM) by consumer organisms, the uptake of DOC by heterotrophic organisms and the excretion of DOC by all interstitial organisms are some factors to be considered. Our investigations at Lake Tegel in Berlin, Germany demonstrated the significance of the bio-coenosis on interstitial clogging. As the numbers of different species (diversity) and organisms (abundance) were remarkably high, we assume that the meioflora and meiofauna play a significant role in the water purification processes related to bank filtration (Beulker and Gunkel 1996).

A better understanding of colmation, the process by which the clogging of sediment interstices occurs, is required since it can severely obstruct the artificial vertical sand filters for groundwater recharge (Rinck-Pfeiffer 2000). The permeability of the hyporheic interstices depends on the hydraulic conductivity of the sediments layers, which is influenced by mechanical, chemical and biological processes related to clogging. Well-known mechanical factors causing clogging are the input of fine sand particles (silt) and the occurrence of gas bubbles (oxygen or methane), while chemical processes are mainly the precipitation of carbonates, iron hydroxides, and sulphur or sulphides. The main biological sources include the excretion of extracellular polymeric substances (EPS), in most cases polysaccharides or polypeptides (Flemming et al. 1998). Meiofauna presumably influence or regulate the clogging intensity by engaging in activities such as burrowing. However, data on these dynamic interactions, the build-up of EPS and structural destruction by interstitial fauna are scarce. Most of the available information has to do with artificial ground water recharge systems, the inflow conditions of which are significantly different from those of littoral zones.

METHODS

Our investigations were carried in the sandy littoral zone of Lake Tegel, a lake-like extension of the River Havel, in Berlin. Lake Tegel has an area of 2.82 km^2 and a mean depth of 5.5 m; it can be characterized as moderately eutrophic. Along the shoreline of Lake Tegel, 130 wells for water extraction are located close to the surface (30 m) and below the marl (< 62 m). The lake is therefore subject to exfiltration. Sampling equipment was inserted in the littoral zone of the lake (water depth of about 50 cm). Sampling was conducted regularly (infiltration rate and water chemistry every 3 weeks, meioflora and fauna every 6 weeks) for a period of one year.

The infiltration rate was measured in pressureless enclosures 25 cm in diameter; inflow into the enclosures was determined using water-filled bags. DOC was determined using a TOC analyzer (*LiquiTOC*). Sediment cores were extracted by pressing plastic tubes (Ø 5 cm) into the sediment; freeze cores were also obtained following the method of Bretschko and Klemens (1986). The abundance and diversity of interstitial flora and fauna in the samples was assessed after separation by water cascade analysis. The taxonomic determination was reduced to about 90% of the species and biomass, and the species were generally determined to the level of the genus (Beulker and Gunkel 1996). Chlorophyll was assessed by sand extraction after DEV (1996). Carbon and nitrogen levels were determined using a CN analyzer (Carlo Erba Inst.). The structure of the biofilm and the occurrence of EPS was studied by REM-EDX analysis using small sediment cores of 10 x 10 mm, which were spluttered with gold and exposed directly in the REM. POM was measured gravimetriccally as ash-free dry mass after cascade floating separation from sand, silt and meiofauna. Proteins and polysaccharides were identified by light microscopy after staining the sediment samples with Coomassie Brilliant Blue G-250 for proteins and Alcian Blue for polysaccharides.

RESULTS AND DISCUSSION

The Lake Tegel test site is a sandy area (fine sand: 10–30%, medium sand: 55–60%, coarse sand: 5–30%) with some reed stands (*Phragmites australis*) and water lilies (*Nuphar lutea*). Both stands are remnants of an ancient reed zone, which today is protected by a palisade, but is still impacted by swimmers and lake eutrophication. Characteristic parameters of the littoral zone at Lake Tegel are given in Table 1. The infiltration rate was determined to be 3–27 L m^{-2} h^{-1}.

Table 1. Characteristics of the eastern littoral zone of Lake Tegel (near the island of Reiswerder)

	Depth (cm)				
	0 – 5	*5 – 10*	*10 – 15*	*15 – 20*	*20 – 25*
Sediment water content (%)	20.3	20.2	11,5	14.5	17.6
Mean particle diameter (mm)	0.2	0.3	0.5	0.5	0.4
Sorting coefficient (Müller)	1.8	1.7	1.9	1.6	1.5
Nonuniformity	3.8	4.0	3.8	2.4	2.4
Pore volume coefficient	0.40	0.40	0.26	0.31	0.36
Kf (Hazen, 10 °C, m s^{-1})	7 x 10^{-5}	7 x 10^{-5}	3 x 10^{-4}	5 x 10^{-4}	4 x 10^{-4}

The littoral sediment is enriched with particulate organic matter (POM), which must be divided in two groups, CPOM (crude POM), a food source for shredder organisms, and FPOM (fine POM), a food source for sediment feeders and filterers. POM can be transported with the water flow into the sediment and is retained in the pore system; this may be one reason for clogging phenomena. The POM concentrations are high (about 1% ds) in the upper layer (down to 20 cm) and decrease to 0.25% at 50 cm sediment depth (Fig. 1). Investigations carried out with monodisperse polymeric resin microparticles and with fluorescein (FITC)-labeled fine organic particles (algae, leaves) indicate that POM is not transported downwards, and that FPOM transport is restricted to the topmost 2 to 3 cm of sediment (Beulker et al. 2005). Water flux, as determined in infiltration chamber measurements (3–27 L m^{-2} h^{-1}), leads to an infiltration velocity of 32–260 cm day^{-1} in the pore system, while the particle transport amounts to a few cm per day. Therefore, water infiltration does not lead to any remarkable extent of passive particle transport. However, significant quantities of CPOM are fragmented to FPOM in the interstitial biocoenosis.

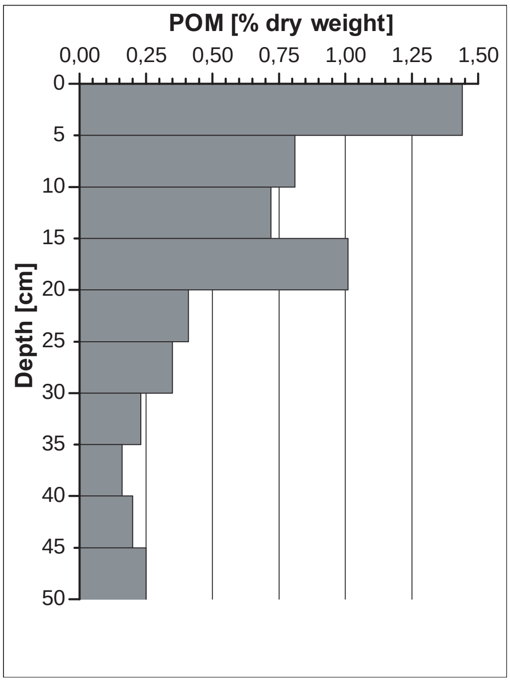

Figure 1. Vertical particulate organic matter (POM) distribution (> 100 µm) in the bank filtration system within the upper littoral sediment layer of Lake Tegel

Besides POM input, primary production is also assumed to be another source of organic carbon in the interstices; this theory was confirmed by our microscopic analyses. The sediment particles were densely colonized with algae (mainly diatoms), which are known sources of extracellular polymeric substances (EPS; Fig. 2) and detrital POM. This interstitial flora is a biocoenosis especially adapted to the sediment pore system. That at Lake Tegel was colonized mainly by epipsammic organisms (aufwuchs) attached to sediment grains (abundance: 60–90%). Diatoms were the dominant species; diatoms are able to move within the sediment and can even migrate to micro zones under optimal conditions. The most prevalent diatom species were Amphora pediculus, Cocconeis spp.,Achnanthes clevei, A. minutissima and A. lanceolata. Some interstitial algae like nanoflagellates (Trachelomonas, Euglena) were also found. Pelagic species from the lake water are also transported into the interstices to a small extent (abundance: 0–25%; Beulker and Gunkel 1996).

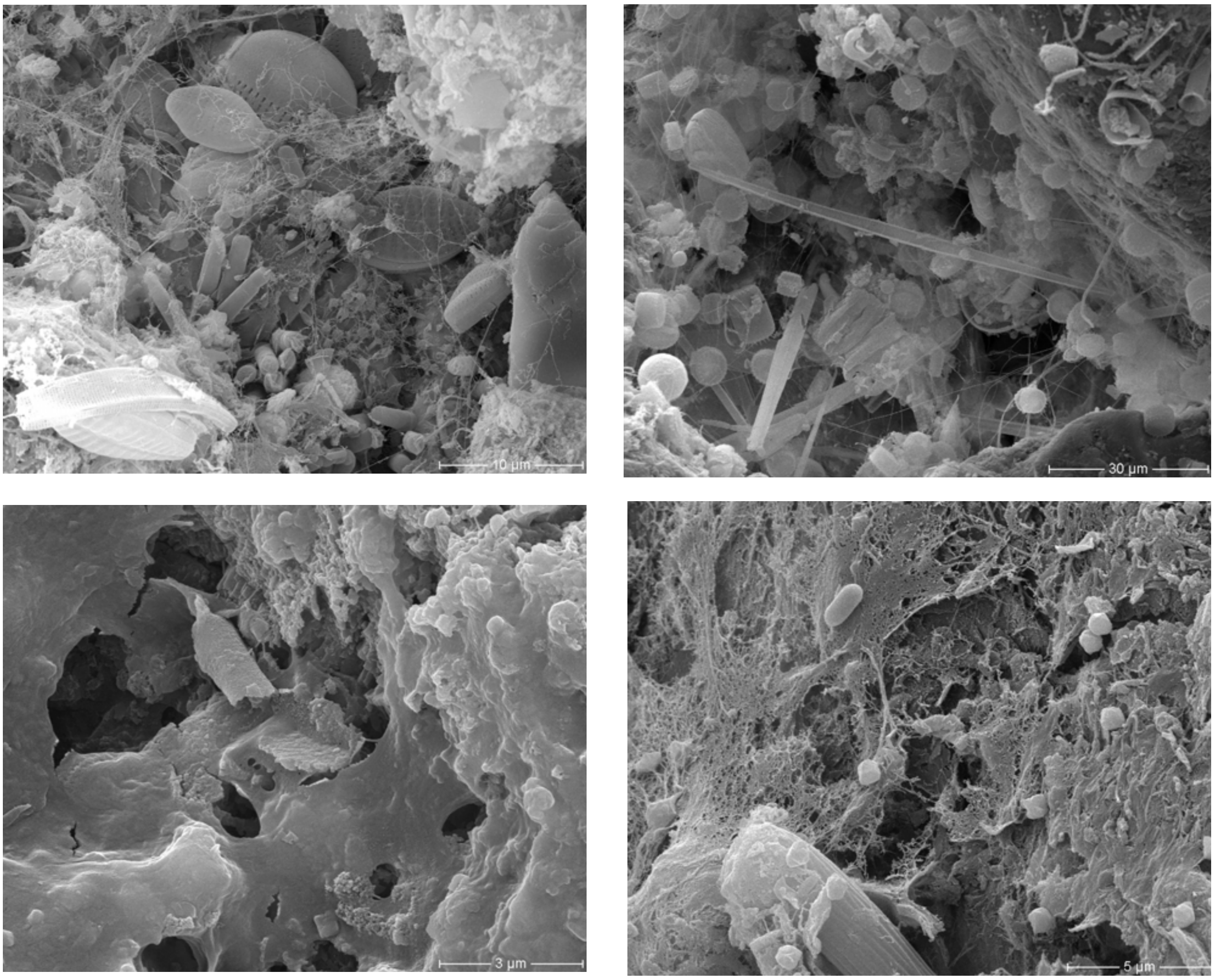

*Figure 2. Interstices of the littoral sandy zone of Lake Tegel,
a) 3–4 cm depth, diatoms with fibrillary EPS, 24.8.04; b) 0–1 cm depth, diatoms with EPS 25.02.04;
c) 7–8 cm, flat EPS, 05.02.04; d) 3–4 cm depth, dense EPS web with bacteria and diatom, 17.05.04*

The vertical distribution of chlorophyll a (Chl a) confirmed our assumption that algae significantly influence the composition of the upper sand layer (Fig. 3). The Chl a concentration was very high (21 to 28 µg cm^{-1}) in the upper 5 centimeters of sediment and decreased with depth, with only traces of Chl a detected at 9 centimeters depth. A Chl a concentration of about 25 µg cm^3 is extremely high compared with the lake water, which even under eutrophic conditions contained only about 20 µg L^{-1}. The algae biomass in the interstices was about 1,000 times higher than in the overlying water body, and the algae biomass in the upper 5 cm of sediment interstices corresponded to the algae biomass of a 50 m water column. The calculated algae biomass (Margaleff 1983) was about 40 g C m^{-2}; this is certainly high, but similar to figures reported for epipsammic algae in small creeks (Cummins et al. 1966, Ruhrmann 1990).

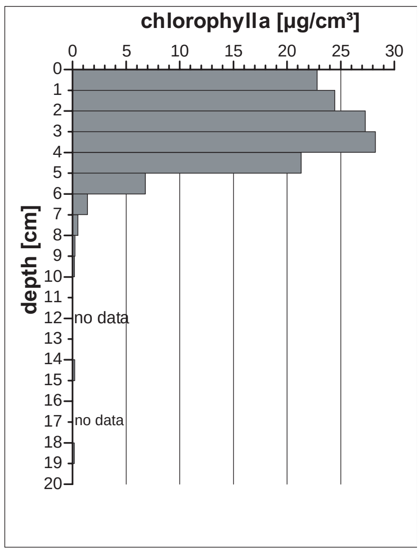

Figure 3. Vertical chlorophyll a concentrations within the upper littoral sediment layer of a bank filtration site at Lake Tegel (mean values from March to August 2004)

The great significance of the interstitial flora was confirmed by the parallel development of a comparably large number of interstitial fauna: a total of 77 taxa were identified, whereby nematodes and annelids (worms) plus crustaceans and copepods (water flies) were the dominant species. With an average 7,000 individuals per dm^{-2} in the upper sediment layer, i.e., at depths of 0 to 10 cm (minimum individuals /dm^{-2}: 430; maximum: 9,700; Beulker and Gunkel 1996), this abundance of the interstitial fauna is very high. Comparable abundance and diversity levels can also be found in marine sandy beaches (Higgins and Thiel 1988)

The composition of the sediment in the upper interstitial zone is shown as weight percentages in Fig. 4a and as volume amounts in Fig. 4b, which point out the significance of the POM within the interstices. The average POM volume in the upper sediment zone (0–5 cm) was found to be 19.4%, while the sediment pore volume was calculated to be about 40 %. Thus, the sediment pore system is half filled by organic material; 20% of the POM is dry substance and 80% is cell water or bound water.

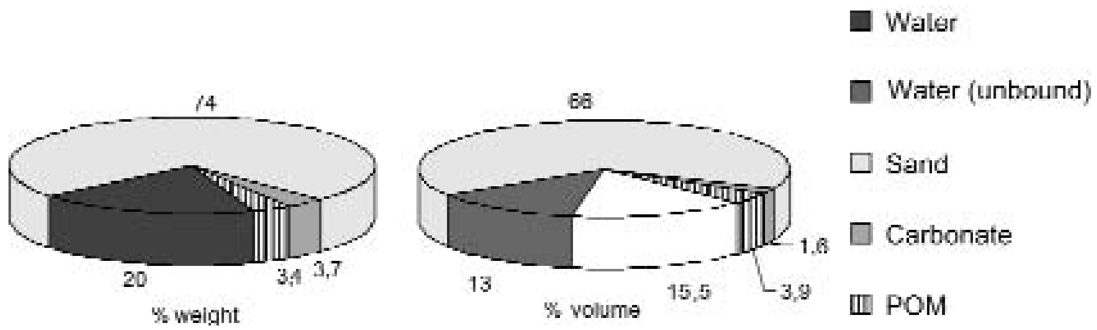

Figure 4. Composition of the upper littoral sand zone (0–5 cm) of Lake Tegel relative to a) weight (water and dry weight of sand, POM and carbonate) and b) volume. POM was calculated based on the organic carbon (C org) content under consideration of a biomass of 20% and a water content of 80% of the algae; leaves are wood debris were excluded

The composition of the POM volume can be specified by correlating chlorophyll a (Chl a) to organic carbon (C org): C org = Chl a x (30 to 100); (Margaleff 1983). Accordingly, the C org concentration of the algae was calculated as 0.8 to 2.5 g/l, while the observed Corg (algae and POM) was 10 g L^{-1}. Living algae therefore comprise about 8 to 25% of the POM volume. This is supported by our findings obtained by correlating Chl a to algae dry substance based on Chl a = 0.5–3% of the dry substance (Margaleff 1983), the analogous algae biomass is 3 to 25 g L^{-1}, corresponding to 7 to 50% of the POM. Considering the wide scattering of the relation between Chl a to carbon content and to biomass, it is notable that about 25% of the POM consisted of living algae.

CONCLUSIONS

Our structural analysis and study of carbon turnover processes at Lake Tegel suggest that interstitial algae play an important role in interstitial clogging. Based on our findings, we must assume that the permeability of the sediment is determined by biological processes. Algae, consumer organisms (shredders, filterers and predators) and bacteria are part of the interstitial food web. Bacteria are maintained in the system by DOC uptake (microbial loop) and POM mineralization. This biocoenosis responsible for clogging of sediment interstices makes up about 50 % of the pore system. The biomass of the interstitial algae was used to estimate carbon activity levels (Table 2), assuming a daily reproduction rate of 20 %, which is low for limnic systems. These data indicate that the DOC of pore water is mainly determined by algae production, and DOC input from the lake is low. The interstitial biocoenosis is responsible for purification processes of infiltrated water and we must assume that the efficiency is regulated by the stability of the biocoenosis.

Table 2. Parameters of C turnover in littoral sediment interstices of Lake Tegel (means for 2004), (= calculated data)*

Parameter	*Turnover in the interstices*
C org total (POC)	5,000 mg C dm^{-2}
C org interstitial flora (algae, 0 – 5 cm depth)	350 – 1,750 mg C dm^{-2}
Primary production of algae (~ 20% d^{-1}) *	70 – 350 mg C dm^{-2} d^{-1}
Infiltration rate to groundwater	0.5 – 6 L dm^{-2}
DOC input by lake water infiltration	3.5 – 42 mg C dm^{-2} d^{-1}
DOC input by interstices algae *	~ 14 – 70 mg C dm^{-2} d^{-1}
DOC output to groundwater	2.5 – 30 mg C dm^{-2} d^{-1}
Δ DOC (input – output)	1 – 12 mg C dm^{-2} d^{-1}
DOC mineralization *	~ 15 – 82 mg C dm^{-2} d^{-1}

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