Biofilter treatment of stormwater: temperature influence on the removal of nutrients

Traitement des eaux de ruissellement par biofiltration: influence de la température sur l’absorption des nutriments

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RÉSUMÉ

Les nutriments peuvent causer l’eutrophisation des masses d’eau naturelles. Il est donc essentiel de traiter les ruissellements d’orage pour réduire les charges en nutriments. Les biofiltres qui font appel à des médias, des biofilms et des végétaux représentent une bonne option de traitement des nutriments. Cet article présente les résultats d’une étude sur colonne biofiltre à basses températures (+2°C, +8°C, contrôle à +20°C) qui peuvent induire des problèmes spécifiques de performances des biofiltres. Il a été démontré que les polluants liés aux particules (STS et une fraction élevée de phosphore), ont été notablement réduits sans être négativement influencé par des basses températures. Toutefois, il n’y a pas eu de réduction d’azote ; il faut noter que le NO_x a été produit dans des colonnes ce qui peut s’expliquer par une dénitrification insuffisante et une forte lixiviation au niveau des colonnes.

ABSTRACT

Nutrients can cause eutrophication of natural water bodies. Thus, urban stormwater which is an important nutrient source has to be treated in order to reduce its nutrient loads. Biofilters which use media, biofilms and plants, are a good treatment option regarding nutrients. This paper presents the results of a biofilter column study in cold temperatures (+2°C, +8°C, control at +20°C) which may cause special problems regarding the biofilter performance. It was shown that particle bound pollutants as TSS and a high fraction of phosphorus were reduced well without being negatively influenced by cold temperatures. Nitrogen, however, was not reduced; especially NO_x was produced in the columns which can be explained with both insufficient denitrification and high leaching from the columns.

KEYWORDS

Biofilter, cold climate, nutrients, stormwater treatment.

1 INTRODUCTION

Nutrients can cause eutrophication in receiving water bodies (Browman et al., 1979; Hunho et al., 2003; Pitt et al., 1999). Stormwater runoff is an important source of nutrients in urbanised areas (Graves et al., 2004; Hampson, 1986; Larm, 2000; Taylor et al., 2005), and it should therefore be treated.

Stormwater biofiltration which is also known as bioretention is a novel option that might be able to treat nutrients in stormwater in order to prevent eutrophication. A biofilter consists of filter media placed in a trench or basin that is planted on the top. It has a detention storage on the top (by placement in a depression) and a drainage pipe at the bottom to collect the treated water. Stormwater is treated by mechanical, biological and chemical processes in the filter media, but also by the plants and biofilms, that develops in the media and on the plant roots (Hsieh et al., 2005; Prince George's County, 2002).

Several studies conducted so far, showed a significant removal of phosphorus, phosphate and ammonium whereas only lower reduction or even production of nitrate was observed (Davis et al., 2001; Henderson et al., 2006; Lloyd et al., 2001). However, biofilters are a relatively new technology and hence, only limited data of the performance of these systems are available. Particular problems could arise when implementing biofilters in regions with constant or temporary cold temperatures, due to less bioactivity, shorter growing seasons and a smaller number of adapted plant species. However, these systems may still perform well in these instances, since adequate nutrient removal has been achieved in constructed wetlands in cold subalpine climate (Heyvaert et al., 2006). The biofilter performance in cold temperatures is the deciding factor to their successful implementation in regions with rainfall on non-frozen ground during cold periods (autumn, winter and spring in temperate climate; autumn, later spring and summer in cold climate).

This paper presents preliminary results of a study of the performance of biofilters in relation to temperature. The aim was to determine the nutrient removal performance of stormwater biofilters in low temperatures in order to enable an analysis whether there is a correlation between temperature and treatment rate.

2 MATERIAL AND METHODS

2.1 Experimental set-up

Laboratory tests were conducted on 20 columns made of PVC stormwater pipe (inner diameter: 377 mm, area: 0.11 m^2, height: 1300 mm). A transparent top (height: 400 mm) allowed water to pond without affecting the plant light availability. The inside wall has been sandblasted to prevent preferential flow along the wall. A drainage pipe (diameter: 58 mm) at the bottom lead to a sampling outlet.

The filter media in the columns included four layers:
/1/ top layer, 400 mm, medium to coarse sand with 20% topsoil in the upper 100 mm,
/2/ bottom layer, 400 mm, fine to medium sand,
/3/ transition layer, 30 mm, coarse sand and
/4/ drainage layer, 70 mm, fine gravel.

The columns were planted with *Carex rostrata* Stokes (Bottle sedge) which is widespread in the northern hemisphere (Anderberg et al., 2006). The plant density in the columns was 8 plants per column, which corresponds to a density of approximately 64 plants/m^2. Before they were planted in the columns, the plants were grown for 5 weeks outside to develop a substantial root system. After the planting, the plants were grown in the columns for two month and irrigated with tap water.

In order to investigate the temperature effect on the biofilter performance, the tests were carried out in three thermostat controlled climate rooms at constant temperatures of +2°C (+35.6°F), +8°C (+40.4°F) and +20°C (+68°F). 5 columns each were placed in +2°C and +8°C climate room, and 10 columns at +20°C. The air temperature in the climate rooms was logged at a 15 minute interval using one EBI 20-T and two EBI 2T-112 temperature loggers (ebro Electronic, Ingolstadt, Germany). All columns were illuminated with high pressure sodium greenhouse lamps (G-Power Agro, 400 W, 55 000 lm) 12 hours daily.

Figure 1: Biofilter columns in climate room

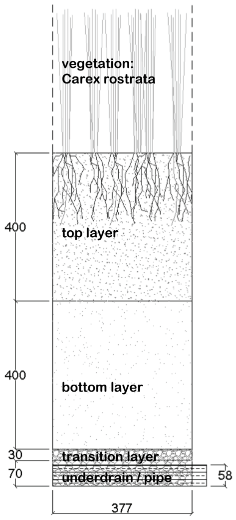

Figure 2: Biofilter column configuration

2.2 Stormwater application

Since natural stormwater neither was available in the required quantity with constant water quality over the time of the experiment, nor could be stored without significant changes to its quality, semi-synthetic stormwater was used. It was made by mixing tap water and gully pot sediment with certain pollutants to achieve the targeted concentrations, as outlined in Table 1. The original tap water - gully pot sediment mixture contained 110000 mg/L TSS, 23 mg/L total nitrogen and 59 mg/L total phosphorus. A new mixture was made for every stormwater application. The tap water used for dilution was stored at the respective temperature (for at least 24 hours). Additionally to the stormwater treatment tests, 5 columns kept at +20°C were used as controls and watered with distilled water only (Blanks).

Pollutant	Targeted concentration	Source
pH	6.9	H_2SO_4
Total suspended solids (TSS)	140 mg/L	tap water - stormwater gully pot sediment (sieved through a 400µm sieve, at the gully pot: ca. 6500 vehicles/day)
Total phosphorus	0.3 mg/L	KH_2PO_4 (potassium dihydrogen phosphate)
Total Nitrogen	1.4 mg/L	0.32 mg/L nitrate: KNO_3 (potassium nitrate) 0.24 mg/L ammonium: NH_4Cl (ammonium chloride) organic nitrate: $C_6H_4NO_2$ (nicotinic acid)

Table 1: Semi-synthetic stormwater pollutants and their sources

In Luleå (Sweden) it rains approximately two times per week in September and October (the month with the most rain events in cold temperatures) and the total precipitation is around 110 mm during that period (Swedish Meteorological and Hydrological Institute SMHI, 2005). This corresponds to an average of 5.4 L/m^2 stormwater runoff per rain event from a catchment with 85 % impervious surfaces and assuming that the biofilter area represents 4% of the catchment area (Wong et al., 2006). Therefore every column was watered by 15 L of stormwater twice weekly.

2.3 Sampling and analytical methods

From the semi-synthetic stormwater a mean sample was taken in 3 replicates before every stormwater application. All outflow water was collected in PE-tanks until the next irrigation event., it was stored at +2°C, a composite sample was taken from each PE-tank, i.e. 20 samples per each application. Up to the present, experiments and analyses have been carried out for 8 events, i.e. 4 weeks.

All samples were analysed for total N (N_{total}), ammonium (NH_4^+), nitrate/nitrite (NO_x), TSS, pH and temperature. Before analysing P and N, the samples were digested with peroxisulphate (according to the Swedish standard method SS 028127) and oxidised with peroxisulphate (SS 028131), resp. The dissolved samples were filtered using Whatman ME25 membrane 0.45µm pore size filters. The analyses were conducted with a continuous micro flow analyser (QuAAtro, Bran+Luebbe, Hamburg, Germany) according to the device-specific methods no. Q-031-04 for P and PH4-, no. Q-003-04 for N_{total} and NO_x and no. Q-001-04 for NH_4^-.

TSS was determined by filtration through Whatman GF/A 1.6 µm pore size glass microfibre filters (SS-EN 872) in one replicate. Water temperature and pH were measured with a field pH-meter (pH330, WTW GmbH, Weilheim, Germany). The electric conductivity was measured with a hand-held conductivity meter (check mate 90, Mettler-Toledo Ltd., Essex, England).

3 RESULTS AND DISCUSSION

The mean inflow and outflow concentrations for all the tests are shown in Table 2, while the mean treatment efficiencies are presented in Table 2. The results show a rather similar pattern over the run-time.

	Stormwater treatment				Blanks	
	inflow $^{(2)}$	Outflow $^{(3)}$			inflow	outflow $^{(3)}$
	all temp.	2°C	8°C	20°C	20°C	20°C
pH	6.9	7.32	7.4.	7.44	5.2	7.4
TSS (mg/L)	142	3.7	5.1	4.6	<2	13
P_{total} (mg/L)	0.292	0.054	0.058	0.056	<0.002	**0.142**
$P_{diss.}$ (mg/L) $^{(1)}$	0.046	0.009	0.012	0.014		
N_{total} (mg/L)	1.38	1.38	1.54	4.23	<0.01	3.14
$N_{dissolved}$ (mg/L)	1.10	0.72	0.89	3.79		
NO_x (mg/L) $^{(1)}$	0.24	0.72	0.89	3.78	<0.005	2.66
NH_4 (mg/L) $^{(1)}$	0.32	0.11	0.14	0.15	0.11	0.11

Table 2: Mean in- and outflow pollutant concentrations at the different temperatures of the 8 measured events. $^{(1)}$ only the first 4 events have been analysed, $^{(2)}$ three replicates analysed, $^{(3)}$ mean value of five replicate columns

Permeability: Before starting the stormwater application, the outflow curves of one irrigation event (15 L/column) was measured in two minute intervals. The peak of the outflow curve occurred most often after 10 to 16 minutes, for 4 columns after 20 minutes and for two columns after only 34 minutes. Two hours after irrigation, between 10 and 12 litres, and when sampling occurred, 95 to 99% of the inflow had run through the columns.

pH: The average pH-value of the stormwater and distilled inflow water was 6.9 and 5.0, respectively. The pH increased in the columns and the outflow pH of both the stormwater columns at all temperatures and the blank tests was around 7.4.

	Temperature		
	2°C	8°C	20°C
TSS	97%	96%	97%
P_{total}	80%	79%	80%
$P_{diss.}$ [2]	81%	74%	71%
N_{total}	±0%	-12%[1]	-208%[1]
$N_{dissolved}$	35	21%[1]	-240%[1]
NO_x [2]	-198%[1]	-265%[1]	-1460%[1]
NH_4 [2]	64%	56%	51%

[1] negative reduction means production,

[2] only the first 4 events have been analysed

Table 3: Mean pollutant reduction in inflow and outflow at the different temperatures of the 8 measured events. The reduction was calculated as: 100%-(in/out*100%). In and out is the mean concentration of five replicate columns at each temperature.

TSS: Reduction in TSS was 96-97%, with no temperature effect on this rate. This is not surprising since the TSS removal is mainly a matter of mechanical filtration which is not influenced by temperature (unless the soil media soil freezes forming channels). The blank tests (with distilled water inflow) showed even higher concentrations of TSS in the outflow as columns watered by stormwater, suggesting that the solids in the outflow are not the stormwater solids but mobilised particles from the soil media. Because of the high TSS removal a high (temperature independent) removal of particle bound pollutants could be expected.

Phosphorus: In the stormwater inflow 85 % of the total phosphorus was particle bound. The fraction was slightly different in the outflow at the different temperatures (2°C: 88% particle bound, 8°C: 85% particle bound and 20°C: 82%particle bound).

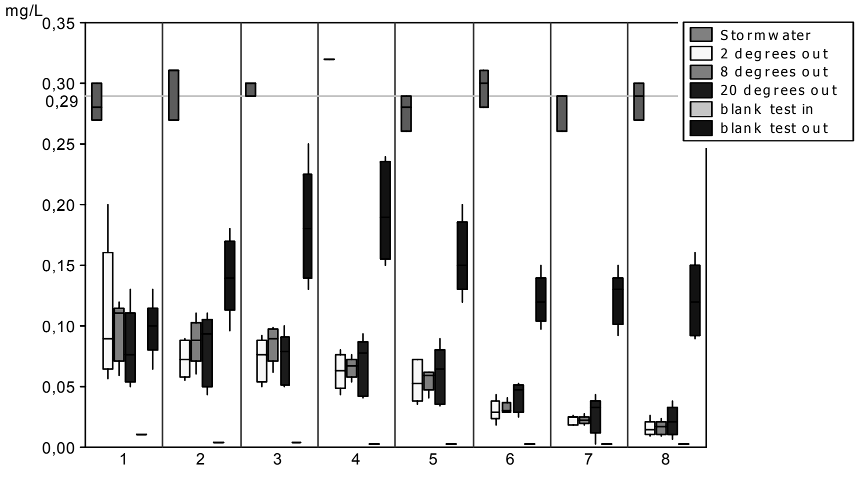

Figure 3: Box plots of in- and outflow total phosphorus concentrations of the 8 measured events.

A temperature independent removal of 80% was detected for total phosphorus. There is a decrease in the outflow concentrations over time (Figure 3). The dissolved phosphorus was retained well too, with some temperature dependence; its reduction rate was higher at cold temperatures. The results make sense, if we assume that physical filtration is the main mechanism for P removal, while biological activity within the soil may case leaching of P from media (the higher biological activity occurs at higher temperatures). This leaching is getting smaller with time as the source is depleted, which explains the decreasing outflow concentrations with time in Figure 3. Anyway, the mechanical removal of phosphorus is the most important factor and therefore overall P removal is high. However the high outflow concentration contained in the blanks (over 2.5 higher than in 20°C stormwater columns) are yet to be explained.

Nitrogen: While the biofilters in +2°C and +8°C showed little or no production of total nitrogen, a high production (on average -208% removal) was observed at +20°C (Figure 4). The blank tests at +20°C showed also high production of nitrogen. Applied to the 20°C stormwater column outflow concentration this means that at the warm temperature leaching from the columns might cause nearly 75% of the total outflow concentration. If this assumption were right, it would mean that the inflow nitrogen concentration (1.38mg/L) was reduced by around 20% and the whole production was caused by leaching.

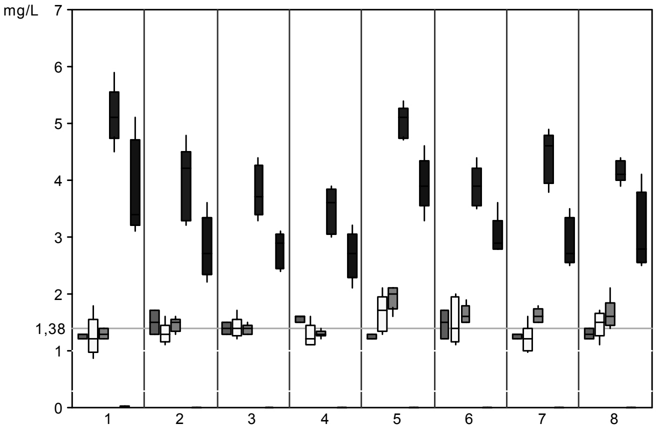

Figure 4: Box plots of inflow and outflow total nitrogen concentrations of the eight measured events. For legend see figure 3

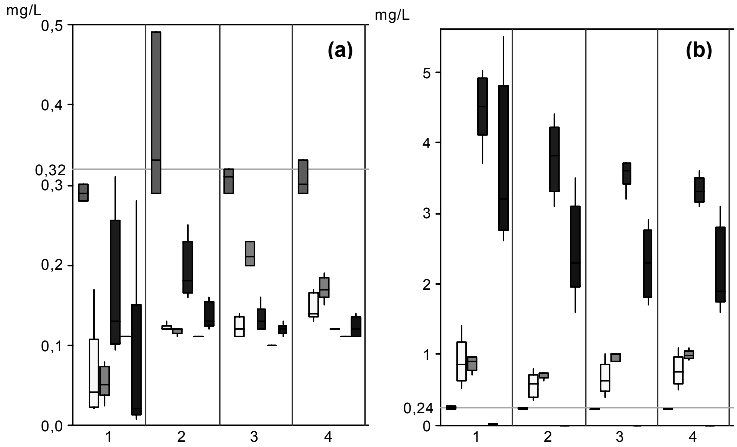

Figure 5: Box plots of the inflow and outflow dissolved NH_4 (a) and dissolved NO_x (b) concentrations of the eight measured events. For legend see figure 3.

The total nitrogen in the synthetic stormwater was 82% dissolved while in the treated outflow water, 98 % was dissolved. The proportion of the nitrogen compounds changed during the treatment in the biofilter. While NH4- was reduced at all temperatures, NOx was produced. This means that a nitrification in the unsaturated zone of the biofilter was happening and therefore NH4- levels decreased and NOx levels increased. Since no denitrification was taking place due to the lack of an anoxic zone and/or a carbon source, levels of NOx at the outflow were highly elevated (Hunho et al., 2003; Zinger et al., 2007).

However a strong temperature effect was demonstrated: the higher the temperature the higher the NO_3 production due to increasing nitrification with increasing temperatures. More importantly, more nitrogen from the soil leached to the outflow water at higher temperatures.

Unfortunately, it is not clear whether the leaching will stop over time as plants mature, as it was in similar biofilter studies (Zinger et al., 2007). The plants had only 2-3 months of establishment, while in Zinger at al experiments they had 5 months to establish. It is known that plants (and in particular their roots) play a major role in N removal since unvegetated filters do always leach (Hatt et al., 2006; Lee et al., 2006).

4 CONCLUSION

The good reduction of particle bound pollutants (TSS, particle bound phosphorus) due to mechanical filtration indicates that biofilter treatment of stormwater might even work in cold temperatures, removing at least the particle bound pollutants. This verifies the findings of other cold climate studies (Bäckström, 2002)

However, the results showed no good overall removal of nitrogen from the stormwater. Contrariwise, a very high production of NO_x was shown which was probably caused by nitrification. A production to such extent was not expected as other studies could show a reduction or only little production of nitrogen even in biofilters without an anoxic zone (Hunho et al., 2003; Scholz, 2004; Zinger et al., 2007). However, it is possible that short establishment time of the plants in the presented experiments is the main cause of this.

The biofilters showed the best results regarding nitrogen (i.e. the lowest production) at cold temperatures. It should be studied if, introducing an anoxic zone and/or a carbon source for improved denitrification, this result could be confirmed or if it would run contrary to it, i.e. that a lower microbiological activity in cold temperatures would hinder the denitrification as well as resulting in a higher overall nitrogen reduction at warm temperatures due to combined nitrification and denitrification and a continuous balance of inflow and outflow concentration due to only little chemical reactions in the filter.

Further research should be conducted to investigate if the removal of N will happen over time. Furthermore, blank tests should be conducted in the cold temperatures too to be able to distinguish both, the stormwater and the leaching caused outflow concentrations.

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