Optimisation of the nitrogen retention capacity of stormwater biofiltration systems

Optimisation de la capacité de rétention de l'azote par les systèmes de biofiltration des eaux pluviales

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RESUME

L'excès d'azote dans les eaux de ruissellement pluvial est une des causes de l'eutrophisation des milieux aquatiques. Il a été montré que l'utilisation de biofitres végétalises permet de réduire les concentrations en azote à leur exutoire. Cependant, il semble possible d'améliorer leur rendement épuratoire. Cet article a pour but l'étude des mécanismes de transformation de l'azote dans les biofiltres et l'optimisation de leur design afin d'augmenter leur rendement épuratoire. 18 colonnes ont été construites afin de tester l'influence de la profondeur de la zone anaérobie sur la dénitrification. L'ajout d'une source de carbone qui agit comme un donneur d'électron a aussi été testé. Les colonnes ayant une source de carbone ont un rendement épuratoire moyen supérieure à 90% alors que les systèmes sans source de carbone ont un rendement épuratoire moyen de 50%. L'analyse des profils en fonction de la profondeur montre que la minéralisation est le facteur limitant pour le traitement de l'azote. Ces résultats permettront d'améliorer les normes pour le design des biofiltres.

ABSTRACT

Excess nitrogen in stormwater is a principal cause for eutrophication of many water bodies in the world. Biofilters, which used a vegetated soil media, have been shown to reduce nitrogen concentrations in stormwater, although there is substantial scope to improve their current nitrogen removal performance. This paper explores the nitrogen transformations in biofilters and optimised theirs design to maximise removal. To achieve this, 20 columns were constructed to test a range of submerged anoxic zone (SAZ) depths, to maximise denitrification. The effect of adding a carbon source to act as an electron donor supplement in the filter media was also tested. Nitrate removal of up to 99% was achieved, with removal by columns with added carbon significantly greater, with a mean removal of greater than 90%, whilst the non-carbon columns showed an average 50% nitrate removal. Depth profiles revealed that mineralization is the limiting step of nitrogen removal in the biofilter columns. The results will contribute to guidelines for optimal biofilter design.

KEYWORDS

Biofilters, carbon\electron donor, eutrophication, stormwater, submerged anoxic zone.

INTRODUCTION

An excess of nutrients in stormwater (urban runoff) has become one of the main causes of eutrophication in Australian waters, as well as in water bodies of many other countries. Stormwater contains high concentrations of dissolved organic and inorganic nitrogen from a wide range of sources. Total Nitrogen (TN) composition may contain up to 91% of dissolved nitrogen, dominated by nitrate (up to 47%) during wet and dry weather [*Taylor, et al.*, 2005]. The traditional approach to stormwater management is to convey water as fast as possible from where it falls to downstream waterways via the urban drainage system. However, this approach has recently been modified towards more 'at-source' solutions, due to some extent to the emergence of Water Sensitive Urban Design (WSUD). One of the key elements of WSUD is the management of urban stormwater, both as a resource and for the protection of water ecosystems. WSUD has multiple environmental benefits, including reducing pollutant export, retarding storm flows and improving the urban landscape.

Biofilters (also called bioretention systems or biofiltration systems) are a potentially promising solution for reducing nutrient stormwater discharge to receiving waters [*Lloyd, et al.*, 2001; *Wong*, 2006]. In biofilters, nitrogen compounds can be transformed (by coupled nitrification and denitrification) into nitrogen gas which is released back to the atmosphere.

Biofilters have been traditionally constructed as vegetated buffers on top of a soil, sand or gravel filtration medium in shallow trenches (figure 1), basins or landscaped areas [*Melbourne Water*, 2004]. Stormwater flows over the vegetation, and may be subject to temporary ponding, during which time the stormwater slowly seeps through the filter material towards the effluent. During infiltration, the stormwater undergoes several treatment processes, such as sedimentation, adsorption, ion exchange, decomposition, and bioremediation. At the bottom of the biofilter a perforated pipe collects the treated water for conveyance to downstream waterways.

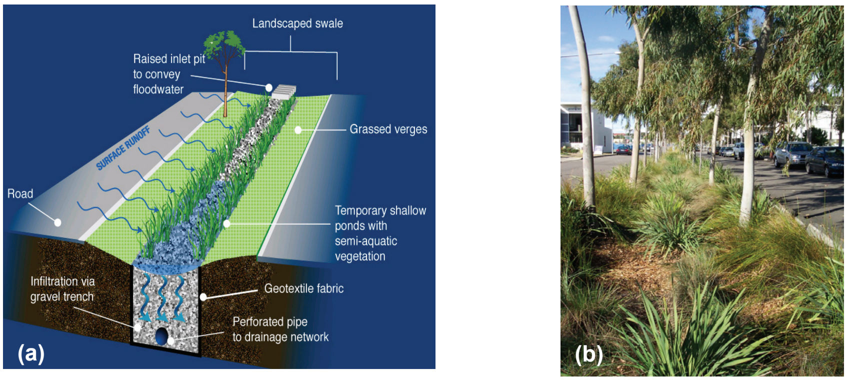

Figure 1(a) Schematic biofilter trench. (b) A biofilter trench at Vic-park, Sydney.

Biofilter systems are used to remove a range of pollutants from stormwater runoff, such as suspended solids, nutrients, metals, organic compounds and pathogens. However, given the importance of managing the TN discharge into receiving waters, there is a need to understand the role of biofilters in reducing TN concentrations and loads. If we understand the governing processes involved, we will be able to optimise biofilters for nitrogen removal.

A review of past studies suggests that there is a need to enhance anaerobic processes (i.e. denitrification) in order to improve nitrate removal [*Davis, et al.*, 2001; *Gerardi*, 2003; *Hunho, et al.*, 2003]. Hunho, et al's (2003) study suggests that creation of an anoxic zone within the filters and/or a carbon source should enhance the denitrification bacteria activity. It further suggests that a cellulose-based organic carbon source, such as woodchips, should be used (woodchips have been shown to promote a high nitrate removal of up to 95%). They have shown no evidence of leaching out of the system, with low turbidity at the outflow (of only 2.4±1.7 NTU). This all means that woodchips will provide a stable substrate in the filter media.

Other researchers suggest that the role of plants in nitrogen removal is crucial. Henderson et al's [2005] study of vegetated biofiltration mesocosms demonstrated 67 and 52% higher TN removal by the vegetated mesocosms in sand and loam, respectively.

However, there is a need to enhance the nitrogen removal by biofilters, to maximise protection of receiving waters. Currently Biofiltration systems are considered somewhat as a “black box” in terms of nitrogen species transformation. Only input/output observations have been conducted, and generally on TN removal rather than individual species of nitrogen. If developed further, biofilters may become a valuable technology for protecting receiving waters from eutrophication.

The aims of this research are to understand the nitrogen transformation processes, and the factors that affect them, in order to optimise biofilters for nitrogen removal, specifically, this paper deals with the following design questions:

1. How can nitrogen removal be maximized in biofilters? What are the limiting factors in this process?
2. Is there a need for submerged anoxic zone (SAZ) in biofilter systems? If so, what would be its optimal level(s)?
3. Is there a need for carbon/electron donor source in biofilter systems?

Outcomes of this study have shown a nitrate removal of up to 100%, and TN removal consistently in excess of 70%, using a SAZ with organic carbon added.

Materials and methods

In order to understand and optimize the nitrogen processes involved in biofilters during rainfall, 20 (two prototypes) biofilter PVC columns were built (Figure 2a) and placed in a covered greenhouse (Figure 2b). The rationale for the design was to build a biofilter test rig with the ability to sample the treated water-front along the biofilter depth profile in order to elucidate the nitrogen transformations involved. The biofilter column diameter (375mm) is wide enough to accommodate plants and to minimise wall flow, or "edge" effects. In addition, the biofilter is equipped with the ability to control the water table, allowing manipulation of the submerged anoxic zone (SAZ) and testing of its effects on the nitrogen profile.

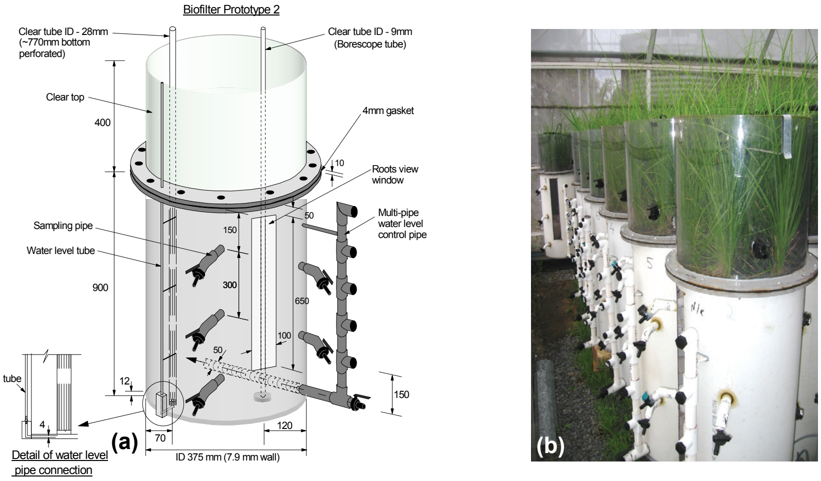

Figure 2: (a) biofilter column assembly (b) biofilter columns in the greenhouse

Filter media configuration

The main consideration in the selection of media was to use cost-effective local materials (i.e. carbon substrate for dentrifiers) that have sufficient stability to withstand wash-off into the treated water. The filter-media configuration consists of four main layers:

1. A 400 mm layer of sandy loam at the top planted with tall sedge; *Carex appressa*.
2. A 400 mm layer of fine sand mixed with woodchips for dentrifiers in the SAZ. Two sources of shredded woodchips (3 mm) were chosen: 1) incorporated pea straw, and; 2) red-gum. The total mass of carbon/electron donor that is required for denitrification was calculated on the basis of 3.5 mg/L influent TN concentration, 653 mm/year (Melbourne) annual rainfall for a period of 15 years.
3. A 30 mm transition layer of river sand, to prevent wash-out from the column.
4. A 70 mm drainage layer of small gravel at the bottom of the column to convey the treated water to the slotted drainage pipe (placed in this layer).

Preparation of semi-synthetic storm water

Since real stormwater can not be stored without significant changes to its quality, a compromise was made in the form of semi-synthetic stormwater for all experiments. Semi-synthetic stormwater was created to mimic fresh stormwater, by mixing in-situ sediments from a stormwater pond (<300 µm fraction) with tap water, and adding any necessary missing or deficient elements according to their typical concentrations in Melbourne stormwater (Table 1).

Experimental set-up

After a three month plant establishment phase (with watering by tap water), the columns underwent a pre-treatment period. The pre-treatment consisted of one week of repeated cycles (n=3) of flushing and overnight choking using pond water. A volume of 25 L of pond water was used in every cycle while the SAZ water level was set at 450 mm. This served the purpose of inoculation to promote biofilm growth as well as flushing any residues of tap water in the filter media. The pre-treatment was followed by a pilot phase of 2 weeks, during which time 25L of stormwater was introduced twice weekly; similar to the average annual rainfall frequency in

Melbourne (every 2.5 days) [*Bureau of Meteorology*, 2005]. In addition, the outflow was sampled at every second dosing to establish initial and quasi-steady-state nitrogen removal.

Pollutant	Concentration (mg/l)	Chemicals additives source
Total Suspended Soiled	150	Sediments slurry
Total Nitrogen	2.13	From N additives
NH3	0.29	Ammonium chloride (NH_4Cl)
NO_X	0.74	Potassium nitrate (KNO_3)
Organic N (ON)	1.10	Sediments slurry and DON
Dissolved ON	0.60	Nicotinic acid ($C_6H_5O_2N$)
Total Phosphorus	0.35	Sediments and FRP
PO_4^- (Phosphate ortho=FRP)	0.12	Potassium phosphate (KH_2PO_4)
Copper	0.05	Copper sulphate ($CuSO_4$)
Lead	0.14	Lead nitrate ($PbNO_3$)
Zinc	0.25	Zinc chloride (ZnCl)
Cadmium	0.0045	Cadmium nitrate ($Cd(NO_3)_2$)

Table 1: Typical Melbourne stormwater pollutant concentrations [based on concentrations reported by [*Duncan*, 2003; *Taylor, et al.*, 2005]

Phase 1: Optimization of anaerobic zone

The 18 bioreactor columns were tested for a range of submerged anoxic zone levels. The SAZ range tested was 0 mm, 150 mm, 450 mm, 600 mm (n=3 replicates for each), and 6 columns were used as a control group, without a carbon/electron donor substrate. The non-carbon columns were tested for 0 mm and 450 mm of SAZ.

Phase 2: Nitrogen species depth profile within the biofilter

Five samples were collected from each column to measure the depth profile of nitrogen compounds depth, including one sample for influent and two for effluent, and three points sampled the water-front at different depths (150, 300 and 600mm). One of the effluent samples represented the first flush (A) coming out of the bottom pipe, while the late flush sample (B) represented the treated water front.

Dosing and sampling

The columns were dosed with 25L of semi-synthetic stormwater twice a week for a period of 8 weeks, while sampling occurred twice; at week 6 and 8 (further sampling is ongoing). Every sample was analyzed for TN, NOx, NH_3, Total Dissolved Nitrogen (TDN) and for Total Organic Carbon. In addition, Organic Nitrogen (ON) and its dissolved form (DON) were calculated by the constituents of nitrogen: DON=TDN–NO_X–NH_X and ON=TN–NO_X–NH_X [*Taylor, et al.*, 2005].

Results and Discussion

To date, two events have been sampled, and the removal patterns of the two sampling events have shown very similar behaviour, apart from the fact that the inlet concentration at the first sampling event had a lower ON content. Given the consistency of behaviour, the presented results focus primarily on the most recent event sampled (at week 8). The results are presented in two sections; Nitrogen species removal and depth profile. The removal percentage and concentration were calculated as the average of three replicate columns, unless otherwise stated.

Phase 1: Optimization of anaerobic zone

The columns demonstrated exceptionally high removal of NOx, ammonia, organic nitrogen and TN. The columns that included carbon substrate in their SAZ demonstrated a NOx removal of up to 99% (B sample; figure 3) and 100% removal at sample A (data is not shown), compared with less than 50% in the non-carbon control columns (Figure 3; t-test P=0.004). Clearly, addition of organic carbon as an electron donor in the anaerobic zone is beneficial to the rate of denitrification.

Average removal of ammonia was up to 96% at 150 mm of SAZ, decreasing down to 83% when SAZ level was raised to 600 mm. However, the non-carbon columns showed a steady removal of 96-97% throughout all SAZ levels. One possible explanation for the relatively high effluent ammonia concentration in the carbon columns compared to the non-carbon columns is ammonification in the SAZ, probably due to low carbon/nitrogen ratio of the pea straw. In addition, ammonia may also be produced via the process of dissimilatory nitrate reduction (DNR). The DNR process has been observed to be favoured in highly anoxic conditions when carbon availability is high, relative to nitrate availability [*Tiedje, et al.*, 1982]. It is possible that this accounted for the source of ammonia in the effluent. Organic nitrogen average removal depleted from 62% to 51% when the SAZ level was raised from 0mm to 600mm. This is mainly due to anoxic conditions being imposed by the SAZ, while mineralization of ON is an oxygen dependent process.

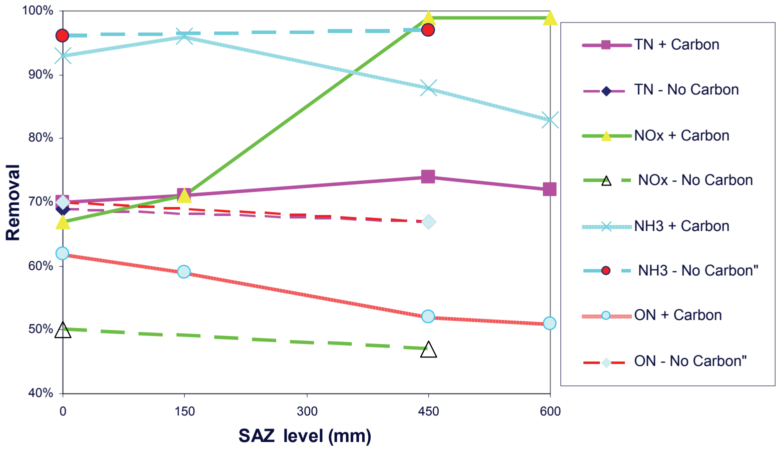

Figure 3: Nitrogen species removal under a range of SAZ level

Average removal of TN in a presence of carbon in B sample (the treated waterfront) increased by 4%, from 70% at 0 mm SAZ level to 74% at 450 mm SAZ level. Carbon dependency behaviour in B sample showed an increase in TN removal, however this difference was not statistically significant ($P_{port\ B}$=0.229). This was probably due to competition between mineralization bacteria and other bacteria community in the filter media, such as dentrifiers that dominated the SAZ. Since TN removal is primarily in the dissolved form (79%-92% of TN), and the Total Kjeldahl Nitrogen (TKN; NHx and NOx) is well removed, the dissolved ON that is controlled by slow mineralization process and dependent on oxygen, retards the overall TN removal.

The main consideration in optimizing the anaerobic zone was to maximise TN removal. This was achieved by the presence of carbon in the filter media and at SAZ level of 450 mm, demonstrating steady 99-100% of NOx removal at the carbon columns.

Phase 2: Nitrogen species depth profile within the biofilter

The depth concentration profile (Figure 4) was analyzed for the highest average TN removal value (74%) achieved in optimized SAZ (the carbon columns at 450 mm SAZ level). The NOx profile showed significant reduction from -150 mm and further deep down, indicating where anaerobic conditions become dominant. NOx reduction along the biofilter depth profile was exceptionally high. An outflow concentration of 0.005 mg/l nitrate as N was observed in the first flush while the late flush (B) showed 0.011mg/L nitrate as N. These values meet the *ANZECC (2000) nutrient trigger guidelines for south-east Australia estuaries of 0.015 mg/L.

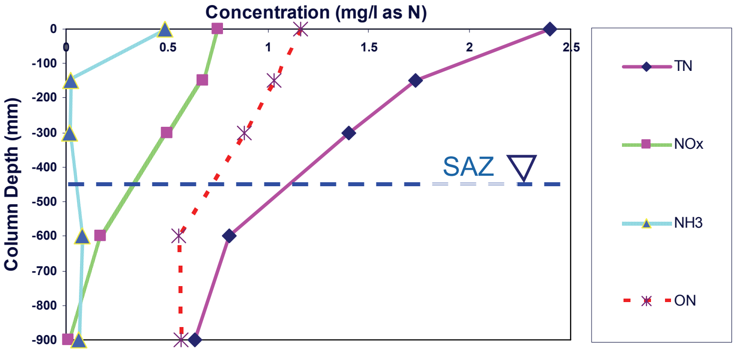

Figure 4: Nitrogen species depth profile (SAZ: 450mm & carbon columns)

As expected, the ammonia concentration profile decreased rapidly from the surface to -150 mm, but then increases somewhat. However, there was no evidence an accumulation of NH_3 in the anaerobic zone. This suggests that the coupled nitrification denitrification reaction rate in that system was very effective. However, ON concentrations profile showed a steady reduction behaviour from the biofilter surface down to -600 mm and remained consistent through to the outlet (-900 mm). Since mineralization of organic proceeds slower in anaerobic *versus* aerobic conditions due to the reduced efficiency of heterotrophic decomposition in anaerobic environments, this behaviour may reflect the highly anoxic/reducing conditions created by SAZ at 450 mm water level. In addition, the lower root density at this depth decreases the bacteria population, lowering mineralization capacity. This may explain the observations at effluent, where the ON concentration (0.57 mg/L as N) reflected almost all the TN (89%) in the treated water at the outlet (0.64mg/L).

A large reduction in TN from 2.4 mg/L to 0.64 mg/L (0.53 mg/L at the 1st sampling) was demonstrated at the effluent. The TN concentration profile showed higher reduction at the upper layer (-150 mm), where ammonia reduction was dominant in terms of TN composition and demonstrated a steady moderate reduction in the mid filter media layer (-600mm) when NOx and ON removal dominated TN. At the bottom of the anaerobic layer the TN reduction slowed down since mineralization of ON was inhibited by higher anoxic and reduction conditions, leaving 90% of TN as organic nitrogen.

In addition, there was no significant reduction in ammonia and organic nitrogen below the depth of 600 mm. However, NOx continued to decrease from 0.17 mg/L to 0.011 mg/L at the outlet. These observations indicate that at low concentrations of nitrate influent a filter media depth of 600 mm should be used, whilst a greater depth may be required if there are very high influence NOx concentrations.

Conclusions

The most important observation in this study was the combination of carbon and SAZ for the efficient removal of nitrate from stormwater. The best outcome was achieved by SAZ levels of 450 mm, effectively removing up to 100% of nitrate and achieving the over 70% removal of TN from stormwater. This is well above some other commonly used systems such as wetlands and swales [*Wong*, 2006]. The use of carbon/electron donor was the critical limiting factor for denitrification. Additionally, it was found that the limiting factor in TN removal was the mineralization process which carried out by aerobic bacteria. Further studies are needed to explore the optimisation of aerobic processes in biofilters.

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