

The effects of drying and wetting on pollutant removal by stormwater filters

Les effets du séchage et du mouillage sur la rétention des polluants par des filtres

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RESUME

Les biofiltres sont soumis à de hauts niveaux de variabilité dans leur fréquence et durée de mise en eau et dans les périodes de temps sec entre ces mises en eau. Les effets des périodes de mouillage et de séchage sur la performance de cinq filtres non végétalisés ont été testés en laboratoire où ils ont été soumis à différentes fréquences d'inondation et de temps sec. Il est montré que la capacité de traitement des sédiments, métaux lourds et phosphore n'est pas influencée par les périodes de séchages et de mouillage. Cependant elles ont une influence sur la concentration en azote avec des concentrations en sortie plus forte après de longues périodes de temps sec. Ces résultats influencent les méthodes de dimensionnement car ces pics de concentration en azote peuvent avoir des effets désastreux sur les milieux aquatiques présents à l'exutoire de ces systèmes.

ABSTRACT

Biofiltration systems experience high levels of variability in the frequency and period of inundation and intervening dry period. The effect of alternate wetting and drying on the treatment performance of five different non-vegetated, soil-based filters was tested in the laboratory, where they were exposed to varying periods of inundation and drying. The wetting and drying regime did not influence the treatment of sediment, heavy metals and phosphorus. However, it did have a marked influence on nitrogen, with significantly higher outflow concentrations observed upon re-wetting following extended dry periods compared with wet periods. This result has implications for current design practices, since these nitrogen pulses could have detrimental ecological consequences for downstream receiving waters.

KEYWORDS

Biofilters, drying, re-wetting, stormwater, treatment

INTRODUCTION

Urbanization results in a higher proportion of impervious surfaces, which decreases the potential for infiltration of rainfall. This leads to higher and more frequent runoff volumes from urban areas, a higher intensity of flooding and increased stream bank erosion. Elevated levels of pollutants in urban runoff are detrimental to the ecological health of urban waterways and receiving waters. In cities with separate drainage and sewerage systems, stormwater is the primary degrader of streams (Walsh, 2000).

Biofiltration systems (also known as biofilters and bioretention systems) are an effective structural stormwater management technique (Fletcher *et al.*, 2005). They are typically configured as vegetated filtration trenches or basins with an underlying collection pipe. Biofiltration systems aim to replicate the physical, chemical and biological processes that occur within the natural environment, that is settling of particulates as vegetation decreases flow velocities, mechanical straining of particulates and sorption of dissolved pollutants as water infiltrates through the filter media, and transformation and uptake of pollutants by microorganisms and plants (if the system is vegetated).

Like all stormwater treatment devices, biofiltration systems experience high levels of variability in the frequency and period of inundation and intervening dry period. However, evaluation of their performance has to date focused on treatment of actual events, with little consideration given to their inter-event (dry weather) behaviour. As a result, the effect of alternate wetting and drying on underlying pollutant removal processes is largely unknown. Recent observations of elevated nitrogen concentrations during inter-event periods within urban catchments (Taylor *et al.*, 2006) and large nutrient pulses from ephemeral riverine and lake sediments upon rewetting (Baldwin and Mitchell, 2000; Scholz *et al.*, 2002) suggest that extended dry periods may result in an initial flush of stormwater pollutants from biofilters upon inundation. Such a flush could have significant ecological consequences, particularly for small streams with limited buffering capacity.

Information regarding the influence of wetting and drying regimes on the pollutant removal performance of biofiltration systems will increase understanding of their operation, and ultimately assist in improving their design.

This laboratory experiment is the first step in a multi-stage research project. In this experiment, the filter media was tested in isolation (separate from any effects of vegetation). The performance of these media in combination with vegetation will be tested in subsequent experiments.

2. METHODS

Non-vegetated filter columns were constructed from 10 cm diameter polyvinyl chloride (PVC) pipe to test the behaviour of six different filter media (Table 1). The depth of the filter was 100 cm (80 cm filter media + 20 cm drainage layers), plus 50 cm of extended detention (ponding) depth. PVC half-pipes (2 cm diameter) were installed at 20 cm intervals in the filter media for collection of samples for water quality analysis (Figure 1). Selection of filter media was based on a review of potential media types, taking into consideration issues such as cost, durability, clogging risk, and sustainability. Sand filters have long been used in water treatment, providing a baseline to compare the relatively new use of soil media against. The idea was to evaluate the sandy loam currently recommended by design guidelines for biofilters (e.g. Melbourne Water, 2005), as well as several, sandy loam-based variations that were selected to target specific removal processes. In total, 18 filter columns were built, with three replicates of each type of filter media. The vertical dimensions of the filter columns are reflective of field conditions, however the areal dimensions are

necessarily small to provide a more flexible system for experimental variation and which requires less input water than real systems.

Semi-synthetic stormwater was applied to the filter columns according to a regime based on a typical Melbourne, Australia climate. The rationale for using semi-synthetic stormwater, as well as the preparation method, have previously been described (Hatt *et al.*, 2006); target pollutant concentrations are presented in Table 2. Despite constant mixing, there was considerable variation in pollutant concentrations in the semi-synthetic stormwater. This was not entirely unexpected, given that the sediment was collected from a natural source. This variation introduces extra complexity to the data analysis, particularly with respect to relative changes in pollutant concentrations through the filter columns. However, pollutant concentrations in stormwater are naturally variable, and the range of concentrations observed here are within the typical reported range of pollutant concentrations (Duncan, 1999), and so this variation in effect allows for performance testing across a range of concentrations.

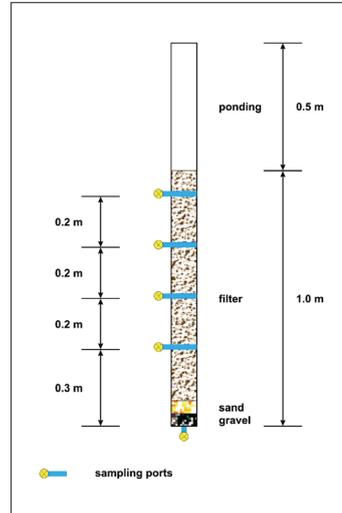


Figure 1. Diagram of the filter columns

Abbreviation	Filter Media	Depth (cm)	Rationale
S	Sand	80	Baseline design
SL	Sandy loam	80	Currently recommended
SLH	4:1 sandy loam: Hydrocell	80	Increase retention time
SLVP	8:1:1 sandy loam: vermiculite: perlite	80	Target heavy metals
SLCM	8:1:1 sandy loam: compost: light mulch	80	Enhance biological activity
SLCMCH	3:1:1 sandy loam: compost: light mulch	60	Enhance biological activity
	Charcoal	20	Sorb dissolved organics

Table 1. Filter media types

The application frequency was varied to simulate natural climate variability. During “wet periods”, the filters were flooded three times weekly (because on average it rains every 2.5 days in Melbourne, Bureau of Meteorology, 2006) with 1.8 L of semi-synthetic stormwater (equivalent to a one month average recurrence interval storm for a filter sized at 0.2% of the catchment area). While these relatively large storm volumes are an exaggeration of real conditions, they were necessary to allow for sample collection, and so they provide an assessment of performance under “near worst-case” conditions. The filter columns were not inundated at all during “dry periods”. The alternating wet and dry periods were as follows: weeks 1 – 12, 17 – 20, 26 – 27, 30 – 33, 38 – 42 = wet, weeks 13 – 16, 21 – 25, 28 – 29, 34 – 37 = dry.

Water samples were collected from the lateral sampling ports, as well as inflow and outflow, on a weekly basis for the first three weeks, and then less frequently as the experiment progressed. Standard methods (Hosomi and Sudo, 1986; APHA/AWWA/WPCF, 1998) were used to analyse for total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), filterable reactive phosphorus (FRP),

Pollutant	Concentration (mg/l)
Total Suspended Solids	150
Total Nitrogen	2.1
Total Phosphorus	0.35
Copper	0.05
Lead	0.14
Zinc	0.25

Table 2. Typical Melbourne stormwater pollutant concentrations (Duncan, 1999)

ammonia (NH₃), nitrate/nitrite (NO_x), and heavy metals (copper – Cu, lead – Pb, and zinc – Zn).

The influence of wetting and drying was assessed by plotting outflow pollutant concentrations against both time and the antecedent dry weather period (ADWP). Samples were classified as being taken in either wet or dry periods. Outflow pollutant concentrations were compared between wet and dry periods using independent sample t-tests with significance accepted at $p \leq 0.05$.

3. RESULTS

Trends in pollutant concentrations were effectively identical for each soil-based media type, hence only results for sandy loam are reported, for brevity. Where differences were observed, they are noted.

3.1 Sediment

Inflow concentrations of suspended solids ranged from 44 – 204 mg/l (Figure 2), however all media types consistently and effectively removed sediment (Table 3). Some variation in sediment removal was evident, as shown in Table 3. This variation is most likely attributable to “conditioning” of the filters, that is, the higher outflow sediment concentrations were typically observed during the early stages of the experiment and are the result of fines washing out of the filter columns (Figure 2). Outflow concentrations decreased with time as this supply of fines was exhausted.

Sediment removal remained consistently high, regardless of the length of the antecedent dry weather period. There were no significant differences in outflow concentrations of sediment during wet and dry periods (Table 3. **Mean percentage removal of sediment and heavy metals by each media type**

3.2 Metals

Trends in concentrations of heavy metals closely followed that of suspended solids, that is, high removal rates of metals were consistently observed, despite variation in inflow concentrations (range Cu: 0.13 – 0.41 mg/l, Pb: 0.21 – 1.5 mg/l, Zn: 0.30 – 1.8 mg/l). Removal of copper, lead and zinc was consistently high for the entire experimental period; mean removals were in excess of 92%, with little variation between replicates (Table 3). Again, wetting and drying did not influence outflow concentrations of heavy metals (Table 3. **Mean percentage removal of sediment and heavy metals by each media type**

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3.3 Phosphorus

Effluent phosphorus concentrations from the soil-based filters were always higher than inflow (Figure 3), indicating that phosphorus is being leached from the filter media. It can also be seen that this phosphorus is almost entirely dissolved (>86%).

Elevated levels of phosphorus were relatively constant for the duration of the experiment, and were not influenced by wetting and drying.

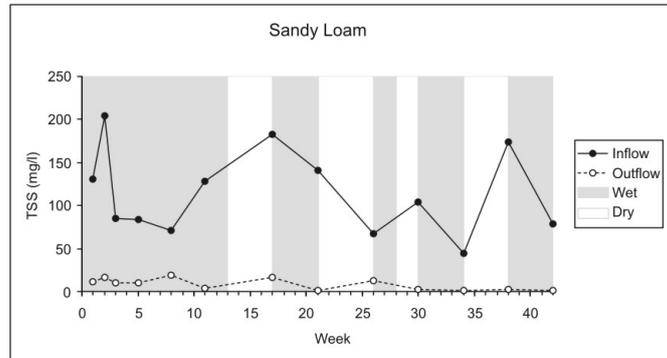


Figure 2. Mean inflow and outflow sediment concentrations from the sandy loam filter columns

Media	Mean % Removal \pm 1 Standard Deviation			
	TSS	Cu	Pb	Zn
S	98 \pm 3	95 \pm 5	99 \pm 3	98 \pm 3
SL	91 \pm 8	97 \pm 1	99 \pm 2	98 \pm 1
SLH	91 \pm 7	96 \pm 2	98 \pm 3	98 \pm 1
SLVP	88 \pm 7	95 \pm 2	96 \pm 6	99 \pm 1
SLCM	90 \pm 9	93 \pm 3	96 \pm 7	96 \pm 2
SLCMCH	95 \pm 2	92 \pm 4	95 \pm 6	96 \pm 2

Table 3. Mean percentage removal of sediment and heavy metals by each media type

Pollutant	Mean (mg/l)		t	p
	Wet	Dry		
TSS	8.24	8.58	-0.1	0.94
TP	0.52	0.54	-0.4	0.70
TN	1.87	5.18	-14.8	0.00
TDN	1.67	4.92	-12.7	0.00
NH ₃	0.013	0.026	-2.2	0.05
FRP	0.46	0.47	-0.4	0.73
NO _x	1.31	4.00	-12.4	0.00
Cu	0.0055	0.0078	-2.0	0.08
Pb	0.0049	0.0023	0.9	0.36
Zn	0.011	0.012	-0.2	0.82

Table 4. Comparison of wet and dry outflow concentrations from the sandy loam filter columns using independent t-tests (degrees of freedom = 11, significance when $p < 0.05$ denoted by bold)

3.4 Nitrogen

Like phosphorus, effluent nitrogen concentrations from the soil-based filters were always higher than inflow, and again, were almost entirely dissolved (>92%, most of which was NO_x) (Figure 4). Unlike the pollutants discussed above, the ADWP clearly influenced effluent nitrogen concentrations (Figure 5), with significantly higher concentrations of nitrogen in the outflow immediately following an extended dry period (Table 3. **Mean percentage removal of sediment and heavy metals by each media type**

). There is a strong linear relationship between antecedent dry days and effluent nitrogen concentrations, despite the variation in outflow concentrations after two

antecedent dry days. Correlation coefficients between ADWP and outflow concentrations (r^2) were always greater than 0.82 for TN and NO_x , although they were more variable for NH_3 (ranging from 0.37 for SL to 0.90 for SLCMCH).

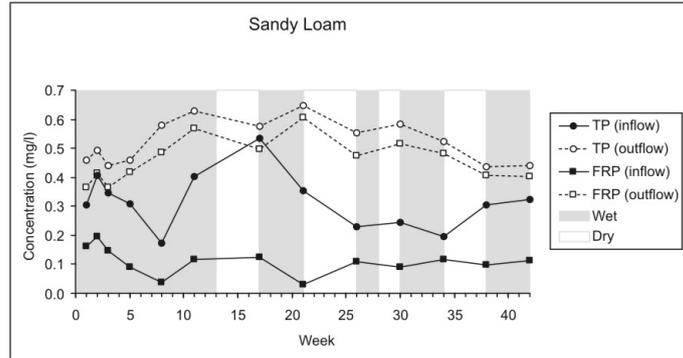


Figure 3. Mean inflow and outflow concentrations of phosphorus from the sandy loam filter columns

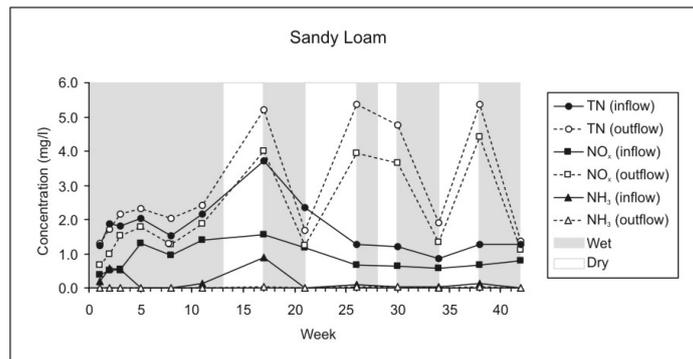


Figure 4. Mean inflow and outflow concentrations of nitrogen from the sandy loam filter columns

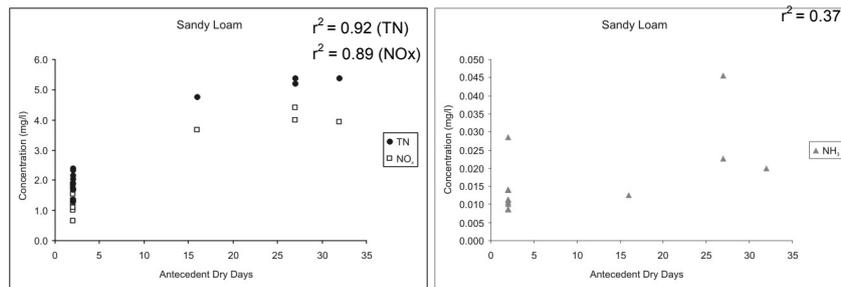


Figure 5. Mean outflow nitrogen concentrations from the sandy loam filter columns vs. ADWP

4. DISCUSSION

Given that the primary removal mechanism for sediment is mechanical straining, it is not surprising that sediment removal not affected by wetting and drying. It is also not entirely unexpected that heavy metals were also not affected by wetting and drying, since they are largely particulate-bound (Muthukumaran *et al.*, 2002).

Like metals, phosphorus tends to be particulate associated (Taylor, 2006), and so can be removed to a certain extent by physical processes. This physical removal of incoming particulate phosphorus is likely to be occurring in the soil-based filters, however the breakdown and subsequent leaching of native organic matter not only negates this removal, but causes these filters to be a source of, rather than a sink for, phosphorus.

Studies of ephemeral riverine sediments suggest that phosphorus removal by soil-based stormwater filters might improve following a short dry period, since increasing oxygen levels leads to the formation of amorphous ferric oxyhydroxides, which have a high binding capacity for phosphorus (Baldwin and Mitchell, 2000). However, as the length of the dry period increases, effluent phosphorus concentrations are likely to increase upon re-wetting, due to aging of the oxyhydroxides (and thus a reduced affinity for phosphorus) as well as release of cell-bound phosphorus from bacteria as they are killed during drying (Scholz *et al.*, 2002). These processes that have been observed in riverine sediments are likely to also be occurring in soil-based stormwater filters, however their influence here is overwhelmed by the leaching of native phosphorus from the filter media.

Particulate organic nitrogen (PON) accounts for roughly 20-25% of TN in Melbourne stormwater (Taylor, 2006). Stormwater filters are able to remove this fraction of TN by physical processes, however, under aerobic conditions, PON will be mineralised to NH_3 and NO_x . These species are highly soluble, therefore promoting biological processes is critical for removal of nitrogen. Coupling nitrification and denitrification promotes a net removal of nitrogen, since N_2 can escape from the filter in gaseous form. However, there must be both aerobic and anaerobic conditions in close proximity for this to occur. Such conditions may be found within the highly biologically active thin layer of soil adhering to plant roots. Biological processes in these filter columns are limited by the lack of vegetation; conditions conducive to denitrification are absent, cutting short the mineralisation-nitrification-denitrification process, leaving a large proportion of "partly processed" nitrogen available for leaching.

The marked influence of dry and wetting on effluent nitrogen concentrations is somewhat surprising. McComb and Qiu (1997) suggest that drying enhances aerobic microbial mineralisation of organic matter, resulting in a build-up of NH_3 in the soil media. Cell-bound nitrogen (NH_3) is also released from bacteria as they are killed during drying (Scholz *et al.*, 2002). Upon re-wetting, this accumulated NH_3 is released into the water phase, where aerobic conditions favour transformation to NO_x .

The Melbourne climate is temperate, with an average rainfall of 661 mm and no distinct dry season (Bureau of Meteorology, 2006). Based on ten years of rainfall data for this region, the mean ADWP is five days, which does not result in significantly elevated levels of nitrogen in the effluent of soil-based filters. However, the 90th percentile ADWP is 11 days, long enough to produce significantly elevated effluent nitrogen concentrations upon re-wetting. In other words, if there are 50 rainfall events in one year, five of these will result in an export of high levels of nitrogen from non-vegetated, soil-based filters to downstream receiving waters. Large nutrient pulses have the potential to trigger algal blooms in receiving waters. On the other hand, drying and re-wetting is an integral part of freshwater aquatic ecosystems because the resulting nutrient pulse stimulates system productivity, and so the impact of these nutrient pulses will depend on the nature of the receiving waters.

The results of this study suggest several design implications. Current design recommendations for biofilters provide adequate removal of sediment and heavy metals, and it is anticipated that this will remain consistent for the lifespan of the filter. Since the completion of this experiment, further laboratory experiments have commenced, which are testing soil-based filter media with limited organic matter, and

these are showing promising results in terms of phosphorus removal. Therefore, current design recommendations should also ensure adequate phosphorus removal, as long as organic matter is limited. The challenge lies in managing the nitrogen pulses that occur upon re-wetting. Laboratory experiments are currently being carried out where a permanent saturated (anaerobic) zone is maintained at the bottom of vegetated filter columns to promote denitrification, thus catching nitrogen pulses before they are leached from the system. Preliminary results indicate that coupled nitrification-denitrification is occurring, thus enhancing nitrogen removal.

5. CONCLUSION

The effect of extended dry periods and subsequent re-wetting on outflow pollutant concentrations from non-vegetated, soil-based filters was tested in the laboratory. The results demonstrated that the treatment performance of biofilters is not influenced by wetting and drying, with respect to sediment, heavy metals and phosphorus removal. Removal of sediment and heavy metals remained consistently high, regardless of the length of the ADWP. The wetting and drying regime had a marked influence on outflow concentrations of nitrogen, with significantly higher outflow concentrations observed upon re-wetting after extended dry periods compared with wet periods. This result has implications for current design practices, since these nitrogen pulses could have significant ecological consequences for downstream receiving waters. Further work is currently being undertaken, where the treatment performance of vegetated filter columns incorporating anaerobic sumps to catch these nitrogen pulses is being tested.

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