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Optimising nitrogen removal in existing stormwater biofilters: Benefits and tradeoffs of a retrofitted saturated zone

Yaron Zinger[a,*], Godecke-Tobias Blecken[b], Tim D. Fletcher[c], Maria Viklander[b], Ana Deletić[a]

[a] Centre for Water Sensitive Cities, Department of Civil Engineering, Monash University, Victoria 3800, Australia
[b] Department of Civil, Mining and Environmental Engineering, Luleå University of Technology, 971 87 Luleå, Sweden
[c] Department of Geography & Resource management, Melbourne University, 500 Yarra Boulevarde, Burnley, Vic, 3121, Australia

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ABSTRACT

Nitrogen excess is a key trigger for eutrophication of water bodies. Stormwater can be an important N source in urban environments and thus requires effective treatment. Stormwater biofilters can remove a wide range of pollutants. However, removal of N is often insufficient due to a lack of denitrification in freely drained biofilters. We tested whether existing stormwater biofilters with poor N removal could be enhanced if a saturated zone is retrofitted to create anaerobic conditions for effective denitrification. We evaluated this by measuring removal of nitrogen, phosphorus and metals in retrofitted biofilters using laboratory mesocosms. For over 18 months five replicates of typical biofiltration configurations, that include freely draining 690 mm deep loamy sand media above a 140 mm deep transition layer and a 70 mm gravel layer planted with popular plant species (*Dianella revoluta*, *Microlaena stipoides* and *Carex appressa*), were tested for typical operational conditions. The biofilter columns planted with *D. revoluta* and *M. stipoides* showed poor N removal, while biofilters planted with *C. appressa* were performing well. All columns were then retrofitted with a 450 mm deep saturated zone, and testing continued using the same operational conditions. After retrofitting the saturated zone, NO_x removal was significantly increased (mean increase: 370% for *Dianella* and 180% for *Microlaena*) which enhanced overall N removal. TP removal was less efficient after retrofitting the saturated zone due to presence of organic matter in the filter media within the saturated zone. The removal of metals was not affected in practical terms, despite some statistically significant effects. The results of this study suggest that retrofitting a saturated zone in existing standard biofilters should be recommended if the existing filter has inadequate N removal and if N discharges pose a potential threat to the receiving environment.

1. Introduction

To develop a more sustainable urban environment, stormwater treatment technologies have been implemented. Amongst these, stormwater biofilters, also known as bioretention systems or rain gardens, are becoming an increasingly popular technique, in part due to their effectiveness and adaptability. Implementing biofilters mitigates the negative effects urbanisation has on the hydrological cycle by aiming to re-introduce pre-development processes into the urban environment. Depending on the stormwater and recipient characteristics, target pollutants in stormwater are (inter alia) TSS, heavy metals (mainly Cd, Cu, Pb and Zn) and nutrients (Eriksson et al., 2007), all of which have been demonstrated to be able to be treated, to variable extents, by biofilters (Dietz, 2007; Davis et al., 2009; Hatt et al., 2007).

To improve water quality, stormwater biofilters use vegetated filter media (Davis et al., 2001), with the vegetation playing a critical role. On top of the filter a depression provides temporary storage and detention of stormwater. The treated water can either be infiltrated to the in situ soils, or be discharged towards a receiving water body, or be collected for stormwater harvesting measure.

Water quality treatment in stormwater biofilters has generally been found to be effective and reliable. For example, TSS, heavy metal and (commonly) phosphorus removal is very efficient and the removal rates both in laboratory experiments and field tests often exceed 80 or 90% (Davis et al., 2001). However, nitrogen removal has commonly been more variable and less efficient (Henderson et al., 2007; Collins et al., 2010), and a net leaching of nitrogen has been quite commonly shown (Blecken et al., 2010; Hunt et al., 2006), which obviously has major impacts for

* Corresponding author. Tel.: +972 524642444; fax: +972 3 6597994.
E-mail address: yaron.zinger@monash.edu (Y. Zinger).

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receiving waters. While aerobic nitrification occurs in the usually well-drained filter media, anaerobic denitrification is often lacking. This has been identified as the main reason for insufficient N removal or leaching (Dietz and Clausen, 2006; Kim et al., 2003). Thus, to enhance anaerobic denitrification in the filter media, the introduction of saturated zone (which we refer to as SAZ) in the filter, combined with a carbon source (acting as an electron donor to facilitate denitrification), has been suggested and successfully tested (Dietz and Clausen, 2006; Kim et al., 2003; Zinger et al., 2007; Zhang et al., 2011). Furthermore, it has been shown that the choice of plant species may be important for N removal, particularly where the biofilter media contain significant amounts of in situ nitrogen (Read et al., 2008).

However, since the SAZ has been developed only relatively recently, its implementation, design and function is not yet included in many design guidelines (e.g. Prince George's County, 1993; U.S. EPA, 2004; Melbourne Water, 2005; Prince George's County, 2007 do not include SAZ as a common design element). Hence, the vast majority of existing stormwater biofilters lack a SAZ and thus may have relatively poor nitrogen removal capability (particularly if the choice of plants used has not focussed on those capable of nitrogen retention), despite being effective for other pollutants. If nitrogen removal is of concern, one strategy to overcome this environmental threat is to retrofit a SAZ to existing biofilter systems, simply by elevating their outlet, thus maintaining a permanent water level in the base of the biofilter. However, if a biofilter is initially designed with a SAZ, usually an additional carbon source is included in the SAZ as an electron donor to facilitate denitrification (Kim et al., 2003; Zinger et al., 2007; Yang et al., 2010; Zhang et al., 2011). Adding such a carbon source, however, is not possible when retrofitting a SAZ (since it would entail the replacement of the whole filter material); this omission might compromise effective denitrification.

Thus, the principal aim of this study was to evaluate the influence of a retrofitted saturated zone (RSAZ) without an additional carbon source, on nitrogen removal by stormwater biofilters, focusing on the potential to enhance the N removal of poorly performing biofilters.

When retrofitting a SAZ to enhance nitrogen removal, it is important that the effective treatment of other pollutants is not compromised. The potential impacts on TP removal are of particular concern, as P adsorbed to sediments within the retrofitted saturated zone could potentially be released under sub-oxic conditions (Correll, 1999). Metal removal is unlikely to be impacted by the SAZ; rather, it has been shown that the SAZ has advantages for Cu removal and when extended drying is expected (Blecken et al., 2009a,b). However, there is still a lack of studies investigating the effect of a SAZ on these pollutants (Collins et al., 2010). Hence, to evaluate the impact of a RSAZ comprehensively, metal, phosphorus and TSS removal were also included in this study.

2. Methods

2.1. Experimental set-up

Fifteen biofilter columns (Fig. 1) were constructed, which had an inner diameter of 375 mm, and a total height of 1300 mm, made up of 900 mm PVC stormwater pipe and 400 mm transparent Perspex (facilitating temporary storage of stormwater without shading the plants). The 690 mm deep filter layer consisted of sandy loam (with a d_{50} of approximately 0.25 mm). Below it, a 140 mm deep sand transition layer (70 mm medium sand, diameter 0.25–0.50 mm; 70 mm coarse sand, diameter 0.50–1.00 mm). The bottom drainage layer consisted of 70 mm deep fine gravel, diameter 3–5 mm) with an embedded drain pipe which was connected to the sampling outlet.

The 15 biofilter columns were divided into three groups of five replicates, based on their vegetation type. The filters were planted with either *Dianella revoluta* (Blueberry lily), *Microlaena stipoides* (Weeping Grass), or *Carex appressa* (Tall sedge). Those groups are herein labelled as *D*, *M* and *C* according to the plant species. *Dianella* and *Microlaena* were chosen due to their poor nitrogen removal (partly significant leaching) in standard biofilter configuration (Read et al., 2008). It was hypostatised that such filters would require retrofitting of a saturated zone if N removal is to be enhanced. Filters planted with *Carex* were selected as 'controls', since they were shown to be highly efficient for nitrogen removal even without a saturated zone (removal rate of around 50–70% was reported by Read et al., 2008).

The columns were placed in a greenhouse located in Melbourne (Australia) with open mesh on the sides, maintaining exposure of the columns to the local climatic conditions, but with a transparent roof ensuring that the filters did not receive inflow from actual precipitation. This assured that the amount of water and pollutants received by each column was experimentally controlled.

2.2. Experimental procedure and sampling

After construction and planting, the biofilter columns were allowed 6 months establishing time (settling of filter media, plant

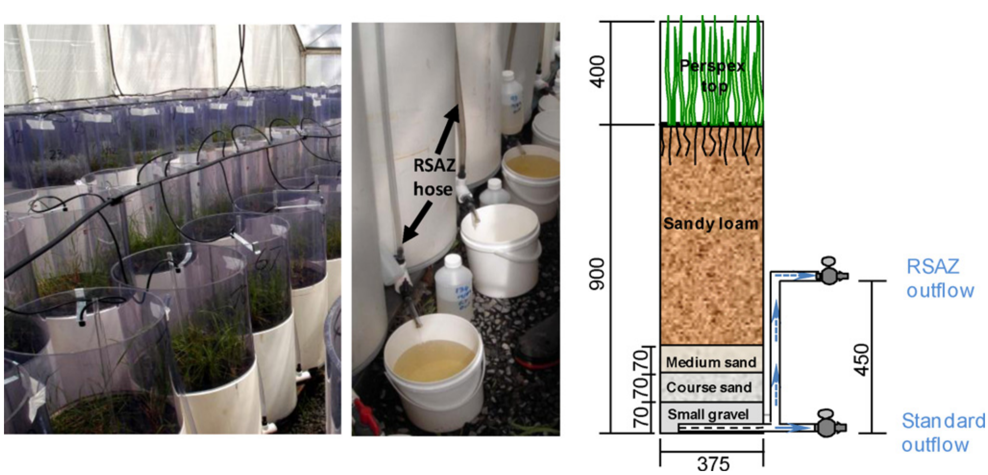

Fig. 1. Left: Biofilter columns (mesocosms) in the greenhouse. Middle: pre RSAZ sampling event. Right: standard column design with outflow at the bottom and after retrofitting saturated zone (RSAZ) with outflow 450 mm from the bottom. All measures in mm.