WATER RESEARCH 42 (2008) 3930–3940

Available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/watres

Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study

K. Bratieres*, T.D. Fletcher, A. Deletic, Y. Zinger

Department of Civil Engineering, Monash University, Victoria, 3800, Australia

ARTICLE INFO

Article history:
Received 27 February 2008
Received in revised form
2 June 2008
Accepted 3 June 2008
Available online 24 June 2008

Keywords:
Biofilter
Bioretention
Stormwater treatment efficiency
Sediment
Nitrogen
Phosphorus

ABSTRACT

A large-scale column study was conducted in Melbourne, Australia, to test the performance of stormwater biofilters for the removal of sediment, nitrogen and phosphorus. The aim of the study was to provide guidance on the optimal design for reliable treatment performance. A variety of factors were tested, using 125 large columns: plant species, filter media, filter depth, filter area and pollutant inflow concentration. The results demonstrate that vegetation selection is critical to performance for nitrogen removal (e.g. *Carex appressa* and *Melaleuca ericifolia* performed significantly better than other tested species). Whilst phosphorus removal was consistently very high (typically around 85%), biofilter soil media with added organic matter reduced the phosphorus treatment effectiveness. Biofilters built according to observed 'optimal specifications' can reliably remove both nutrients (up to 70% for nitrogen and 85% for phosphorus) and suspended solids (consistently over 95%). The optimally designed biofilter is at least 2% of its catchment area and possesses a sandy loam filter media, planted with *C. appressa* or *M. ericifolia*. Further trials will be required to test a wider range of vegetation, and to examine performance over the longer term. Future work will also examine biofilter effectiveness for treatment of heavy metals and pathogens.

1. Introduction

The rapid rate of the urban development experienced in recent decades has lead to significant changes in both volume and quality of stormwater runoff (Line and White, 2007; Walsh et al., 2004). In particular, increased nutrient inflows can stimulate excessive and unbalanced growth of plants and algae, leading to oxygen depletion and eventual eutrophication of the water body. In response to this, improved stormwater management aims to intercept, attenuate and retain stormwater flows, improving their quality, and restoring the flow regime closer to the pre-developed level. Such techniques are often referred to as low impact development (LID) systems in the USA (Department of Environmental Resources, 1999), water sensitive urban design (WSUD) in Australia (Lloyd, 2001) and sustainable urban drainage systems (SUDS) in the UK (CIRIA, 2000). Of the range of WSUD treatment technologies available, biofiltration (bioretention) is becoming increasingly widely used, due to its flexibility in terms of size, location, configuration and appearance. For example, biofilters might be used as vegetated strips along roadsides, or as 'rain-gardens' within private gardens or public open space, or even be incorporated as street-trees within the landscape. Biofilters operate by filtering runoff through planted filtration media (typically a soil medium) and provide treatment through fine filtration, extended detention and biological uptake (Melbourne Water, 2005). Despite the popularity and active implementation of biofilters in many parts of the world

* Corresponding author. Tel.: +61 (3) 9905 4957; fax +61 (3) 9905 5033.
E-mail addresses: katia.bratieres@eng.monash.edu.au (K. Bratieres), tim.fletcher@eng.monash.edu.au (T.D. Fletcher), ana.deletic@eng.monash.edu.au (A. Deletic), yaron.zinger@eng.monash.edu.au (Y. Zinger).
0043-1354/$ – see front matter
doi:10.1016/j.watres.2008.06.009

(e.g. USA, Dietz and Clausen, 2006; Hunt et al., 2006; Australia, Lloyd et al., 2002; parts of Europe, Muthanna et al., 2007), only limited data are available on their performance in pollutant removal.

Most studies of biofilter performance have reported quite good removal for total Kjeldahl nitrogen (TKN) and ammonia (NH_3) (Davis et al., 2001, 2006; Henderson et al., 2007a; Hsieh and Davis, 2005a,b). However, in almost all studies (both laboratory and field), nitrate (NO_3^-) has been shown to leach out of bioretention systems, thus often resulting in poor total nitrogen (TN) removal. Total phosphorus (TP) removal has generally been moderate to good (Davis et al., 2001, 2006; Hsieh and Davis, 2005a,b; Hsieh et al., 2007). Finally, measured removal efficiencies for total suspended solids (TSS) were found to be consistently high (>90%) in all of the reviewed studies (e.g. Hatt et al., 2006, 2007; Hsieh and Davis, 2005a,b).

Unfortunately, only a few studies have gone further and reported on factors influencing treatment performance. For example, Henderson et al. (2007a) and Hatt et al. (2007) found that without plants, soil-based filter media may act as a source, rather than a sink, of some pollutants, particularly nitrogen. The former study (Henderson et al., 2007a) also revealed that fine sand or sandy loam is effective filter media for biofiltration, because they provide adequate support for plant growth, and display minimal leaching. Further concerning filter media, Hsieh and Davis (2005a,b) stress that care should be taken when using organic matter in areas where nutrient discharge is of particular concern, because while it can be beneficial for removing certain pollutants like metals (Davis et al., 2001; Sun and Davis, 2007), its decomposition may result in a net leaching of phosphorus from the media. Finally, some reports have showed that with increasing depth, biofilters perform better for TP removal (Davis et al., 2001, 2006), whereas NO_3^- leaching may increase (Davis et al., 2006; Hatt et al., 2007).

Despite the usefulness of many of these studies in providing proof-of-concept for biofilters, all have been relatively small-scale and limited in scope, where only a small number of factors were investigated. Given the increasing adoption of biofilters, it is critical that advice on their optimum design be based on a rigorous study, which tests all key design characteristics to identify significant factors and their possible interactions.

In response to this need for better guidance on optimisation of biofilter design, the Facility for Advancing Water Biofiltration (FAWB), based at Monash University in Melbourne, Australia, conducted a large-scale laboratory study of 125 biofiltration columns. The aim of the study was to analyse the effect of the following factors on nutrient and sediment removal: presence and type of vegetation, depth and type of filter media, biofilter area (relative to its catchment size) and pollutant inflow concentration.

Based on this study, we make recommendations relating to the optimum design elements of a biofilter which is capable of effectively removing both nutrients and sediment. We discuss the need for biofilters to utilise a sandy loam filter media, be planted with species which maximise nutrient removal (e.g. *Carex appressa* or *Melaleuca ericifolia*), and be sized to at least 2% of the catchment area.

2. Materials and methods

2.1. Experimental set-up

A total of 125 biofilter columns were tested in a specially constructed greenhouse with a clear impermeable roof, which allowed full natural sunlight, but prevented rainfall into the columns (to allow us to control the quantity and quality of water entering the columns). The columns were constructed from 375 mm diameter PVC pipes, with a transparent Perspex top section allowing for plant growth and ponding of water. The inner wall of the columns was sand blasted in order to minimise preferential flow effects. The soil media were placed above transition and drainage layers (sand and gravel, respectively), which prevented wash-out of the filter media and clogging of the slotted collection drainage pipe (Fig. 1). A detailed soil analysis, undertaken prior to any watering activity, is available in the supplementary information (Table 4).

In order to determine the influence of design parameters and operating conditions on the pollutant removal performance of biofilters, a range of factors was tested (Table 1). Plant selection was based on criteria described in Read et al. (2008) and included plants of different characteristics (e.g. tree, shrub, sedge). Five replicates were tested for each configuration, based on a compromise between likely variability, which was estimated using a power-test conducted on a pilot study, and available resources. The 'reference' columns were planted with *C. appressa* (a commonly used sedge species, had a 700 mm deep sandy loam filter media), were sized to 2% of the catchment area and received stormwater of 'typical' concentration (refer to Section 2.2). The selected sizing and media specifications were based on typical current practice and guidelines (Melbourne Water, 2005).

The biofilters were planted in January 2006 (with 7 plants per column) and watered (with tap water) as required for 6 months to allow establishment.

2.2. Experimental procedure

The twice-weekly dosing regime of 25 L per column was based on typical Mediterranean climatic patterns (in this case, for Melbourne, with average annual rainfall of 653 mm) and on a biofilter sized to 2% of its catchment area. Target concentrations (Table 2) were matched to 'typical' worldwide and Melbourne urban stormwater quality characteristics, reported by Duncan (1999) and Taylor et al. (2005), respectively. Use of 'semi-natural' stormwater allowed us to minimise variations in inflow concentration whilst maintaining realistic composition: sediment was collected from a stormwater inlet pond, sieved through a 300 μm sieve and mixed with dechlorinated tap water to achieve the target TSS concentration. Any deficit in other pollutants was made up by adding appropriate chemicals. The stormwater was continuously mixed in a tank to ensure even dispersion of constituents and was further conveyed through pipelines into the greenhouse. To achieve consistent input concentrations for each column, the target volume was delivered via five 'passes' (i.e. 5 L each time for most configurations and 10 L each time for columns sized to 1% of the catchment area).