View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Hanze UAS repository

AMSTERDAM INTERNATIONAL WATER WEEK

Investigation into the long-term stormwater pollution removal efficiency of bioretention systems

Terry Lucke*, Rick Jaeger, Carsten Dierkes***, Floris Boogaard******

* Stormwater Research Group, University of the Sunshine Coast, Australia. tlucke@usc.edu.au
** Water Engineering, Technical University of Munich, Germany. Rick.jaeger@tum.de
*** Water Engineering, Frankfurt University of Applied Sciences, Germany. Carsten.Dierkes@fb1.fra-uas.de
*** Built Environments, Hanze University of Applied Sciences, Groningen, Netherlands. floris.boogaard@tauw.nl

Abstract: In recent years, there has been a steady increase in the number of bioretention systems installed worldwide. However, there has only been limited research on the long-term effectiveness of these sustainable urban drainage system devices. This paper presents the results of a series of controlled field experiments investigating the pollutant removal efficiency of three bio-filtration system that have been in service for over five years in the Sunshine Coast in Australia. The results of this study suggest that the long-term pollution removal performance of these systems may not be as effective as previously thought and further research is needed.

Keywords: bioretention systems; stormwater pollution; sustainable urban drainage systems (SUDS)

Introduction

The increase in impervious surface accompanying urban development over recent decades has increased both the volume of stormwater runoff, and the amount of pollution flowing downstream to receiving waters (Dietz, 2007; Lucke and Beecham, 2011). Consequently, the management of stormwater in urban areas has become a priority issue for those responsible for planning and construction of new developments, and maintenance of existing stormwater infrastructure (Nichols et al, 2015).

Bioretention (biofitration) systems (Figure 1) have been widely implemented in urban areas over the past decade to manage stormwater by reducing peak flows and downstream pollution loads (Davis, 2008; Hunt et al, 2008; Le Coustumer et al, 2012). This has generally been in response to various stormwater management initiatives, such as water sensitive urban design (WSUD) in Australia, sustainable urban drainage systems (SUDS) in Europe and low impact development (LID) in the USA, to reduce stormwater pollution and downstream flows.

Part of the reason for the recent popularity of bioretention systems is the flexibility in their design which assists with their relatively simple integration (retrofitting) into existing urban areas (Bratieres et al, 2008). They are also considered to contribute a range of benefits beyond the conventional stormwater quality and quality functions, including aesthetic and social benefits (Deletic et al, 2014; Mullaney et al, 2015). Smaller sized bioretention system are often incorporated into existing roadways in place of a traditional grassed nature strip or verge.

Figure 1 One of the three bioretention basins evaluated in the study

Bioretention systems (Figure 1) are generally soil-plant based systems that typically consist of a filter medium (usually sandy), underlain by a gravel drainage layer (Dietz, 2007; Deletic et al, 2014). Bioretention systems may be lined with some type of geofabric to allow infiltration, or include an impermeable liner to assist in stormwater capture and reuse (FAWB, 2009). Bioretention systems treat stormwater via a range of physical, chemical and biological processes. These include mechanical filtration, sedimentation, adsorption, and plant and microbial uptake (Deletic et al, 2014).

Many of the previous studies investigating the performance of bioretention systems have been laboratory scale studies (Hatt et al, 2009; Bratieres et al, 2008; Le Coustumer et al, 2012; Deletic et al, 2014). The studies that have incorporated field-based testing have reported varied results, particularly in relation to the treatment of soluble forms of nutrients (N and P) and areas subject to high contaminant loading such as fuel stations or waste recycling sites (Dietz, 2007). The capacity of bioretention systems to treat the peak flow rates of stormwater generated by high-intensity rainfall events is also limited by the relatively small bioretention area to catchment area ratio of approximately 2-4% (Dietz, 2007; Hunt et al, 2008; Hatt et al, 2009). In addition to the challenge of basin sizing, bioretention system hydrologic and nutrient pollution removal performance have been shown to be dependent on the antecedent dry period before storm events (Mangangka et al, 2015; Hunt et al, 2008).

This paper presents the pollution removal and hydrologic performance results of field-based experiments undertaken on three, 10-year old street-side bioretention systems. The bioretention basins, located in Caloundra, on the Sunshine Coast in Australia, were subjected to a series of simulated rainfall events using synthetic stormwater. Four different synthetic stormwater pollutant concentrations were used in the study. Tests were also undertaken to determine the levels of contaminant and heavy metals build-up that occurred in the filter media over the 10 year operational life of the bioretention systems.

Material and Methods

The three bioretention systems evaluated in this study were installed in 2005 to treat stormwater road runoff from a mixed commercial and industrial catchment of approximately 0.6 ha in area. The bioretention basins were located directly adjacent to the roadway which runs centrally through the catchment (Figure 1). The bioretention basins were designed to have an operational hydraulic conductivity of 180 mm/h and achieve the recommended regulatory pollution reduction objectives of 80% of Total Suspended Solids (TSS), 60% of Total Phosphorus (TP), and 45% of Total Nitrogen (TN) (ANZECC, 2000).

In order to reduce the variability, uncertainty and difficulty in monitoring pollution removal performance during natural rainfall events, simulated rainfall runoff techniques were used in this study. Using a purpose-built stormwater simulation test rig, each bioretention basin was subjected to the equivalent runoff inflow rate (Figure 2) that would be generated from a 54.8 m^2 roadway catchment emanating from a 30 minute duration, two year average recurrence interval (ARI) rainfall intensity event at the test location based on procedures outlined in Australian Rainfall and Runoff (Pilgrim, 1987). Two 1,000 litre tanks with adjustable outlet control were used to simulate the inflow volumes from the 30 minute duration, two year average recurrence interval test storm (total inflow volume = 2,000 L).

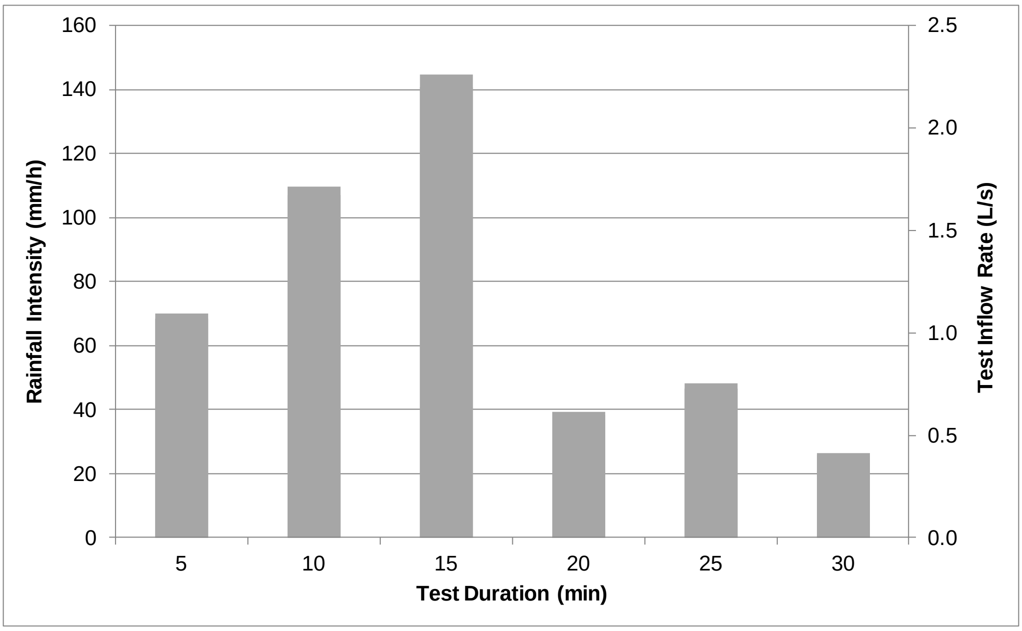

Figure 2 Rainfall intensities and equivalent test inflow rates used in the study

The three identically-sized basins were fitted with flow monitoring and water sampling equipment (Figure 3). Metal spouts were attached below the bioretention outlet pipes to collect the outflow from the basins and direct it through the 50 mm diameter flow meters (Octave Ultrasonic Water Meter DN50) to measure flowrates (Figure 3). An ISCO GLS auto-sampler was used to collect outflow samples in each pit. Sampling equipment also included a Datataker (DT80) datalogger, battery pack and battery charger. Flow-weighted water samples were taken by the autosamplers after every 50L of water had passed through the flowmeter. The water samples were collected through a tube connected to a tapping point on the underside of the flowmeter pipework. Composite water samples comprising were collected and analysed for the inflow and outflow results.

Figure 3 Flow monitoring and water sampling setup

In order to replicate typical stormwater pollution loads found in urban runoff, the synthetic stormwater was dosed with pollutants using a similar methodology to that used by Lloyd et al (2001), and Deletic and Fletcher (2006) with pollutant concentrations as identified by Duncan (1999) occurring in land used for industrial purposes. Four different pollution concentrations were tested on each of the three bioretention basins (Table 1). The four concentrations tested were: A) no pollution; B) typical Australian urban pollutant loads (TSS 150 mg/L; N 2.6 mg/L, and; P 0.35 mg/L) (Duncan, 1999; Hatt et al, 2007; Liu et al, 2014); C) double the typical pollution loads, and; D) five times the typical pollution loads. While the higher pollution loads would not be expected to occur naturally aside from possibly resulting from extremely long antecedent dry periods, they were included in this study in order to help identify any distinctive trends that may otherwise be difficult to measure. Silica sediment (Sibelco 60G), phosphorus (KH_2PO_4) and nitrogen (KNO_3) was added to 2,000L of municipal water to produce the simulated pollutant concentrations (Ansaf et al 2014).

Table 1 Mass of pollutants added to 2,000L of municipal water used in study (A - Nil pollution; B - typical Australian pollutant loads; C – 2 X typical loads; D – 5 X typical loads).

Pollutant	**Synthetic additive**	**Test**			
		A	**B**	**C**	**D**
TSS	60G Silica	0	300g	600g	1500g
TP	KH_2PO_4	0	8.79g	17.58g	43.95g
TN	KNO_3	0	14.44g	28.88g	72.2g

The calculated average (mean) was used during analysis. Concentration Reduction Efficiency (CRE) was calculated for each simulated event as the percentage reduction in concentration with respect to inflow concentration for each pollutant (TSS, TN, and TP). Average CRE was calculated as shown in Equation 1 below. Total pollutant loads and Event Mean Concentrations (EMCs) (Equation 2) were determined for each test flow event.

$$Avg.CRE = \frac{\sum\left[\frac{\{EMCinflow - EMCoutflow\}}{EMCin}\right]}{no.of\ events} \quad \ldots\text{Eqn.1}$$

$$EMC = \frac{\sum_{i=1}^{n} V_i C_i}{\sum_{i=1}^{n} V_i} \quad \ldots\text{Eqn.2}$$

Where,
V_i = Volume of flow during period i
C_i = Concentration associated with period i
n = Total number of aliquots collected during event

Student t-tests were undertaken on measured inflow and outflow pollution concentration results (unequal variances) to determine whether inflow pollution concentrations varied significantly between outflow and inflow ($p<0.05$).

Results and Discussion

Pollution removal performance, as measured by event mean concentrations (EMC) for the three regulated pollutants, varied significantly across the three basins. The student t-test results (Table 2) for the differences in pollution concentrations between inflow and outflow varied significantly for TSS ($p<0.03$) and TP ($p<0.01$). However, the TN removal was not significant ($p=0.18$) across all three basins. The individual basin nutrient pollution removal performances are shown in Figure 4.

Table 2 Student t-test results of bioretention basin nutrient pollution removal performance

Pollution concentration dosage	**TSS (*p*)**	**TN (*p*)**	**TP (*p*)**
Nil (Test A)	<0.05*	0.11	0.43
Single (Test B)	0.72	0.75	0.17
Double (Test C)	<0.03*	0.73	<0.001*
X 5 (Test D)	<0.001*	<0.01*	<0.05*

** significant*

Average bioretention basin pollution removal results for Tests A-C were highly variable (Figure 4). Tests D, with five times the standard pollution concentrations, were the only tests that demonstrated significant pollution reduction performance by the bioretention basins for all three pollutants (Figure 4). Test A results (Nil concentrations) showed that the bioretention basins exported both TSS and TN, while TP was found to show a modest pollution removal performance (26.8%). Although this was an unexpected result, it was thought that this may have been potentially due to test apparatus contamination from previous tests. Although every endeavour was made to wash and remove all remnant contaminants from the supply tanks between tests, this was practically impossible to achieve in the field. Consequently, it was accepted that some of the study inflow samples may have contained trace amounts of pollutants from previous tests. However, the measured trace contaminant concentrations were very small and it was considered unlikely that they would significantly affect the study results. Similar issues have been found in previous studies that have incorporated synthetic stormwater (particularly involving sediment), where delivery of the synthetic stormwater is sometimes problematic (Hatt et al, 2011).

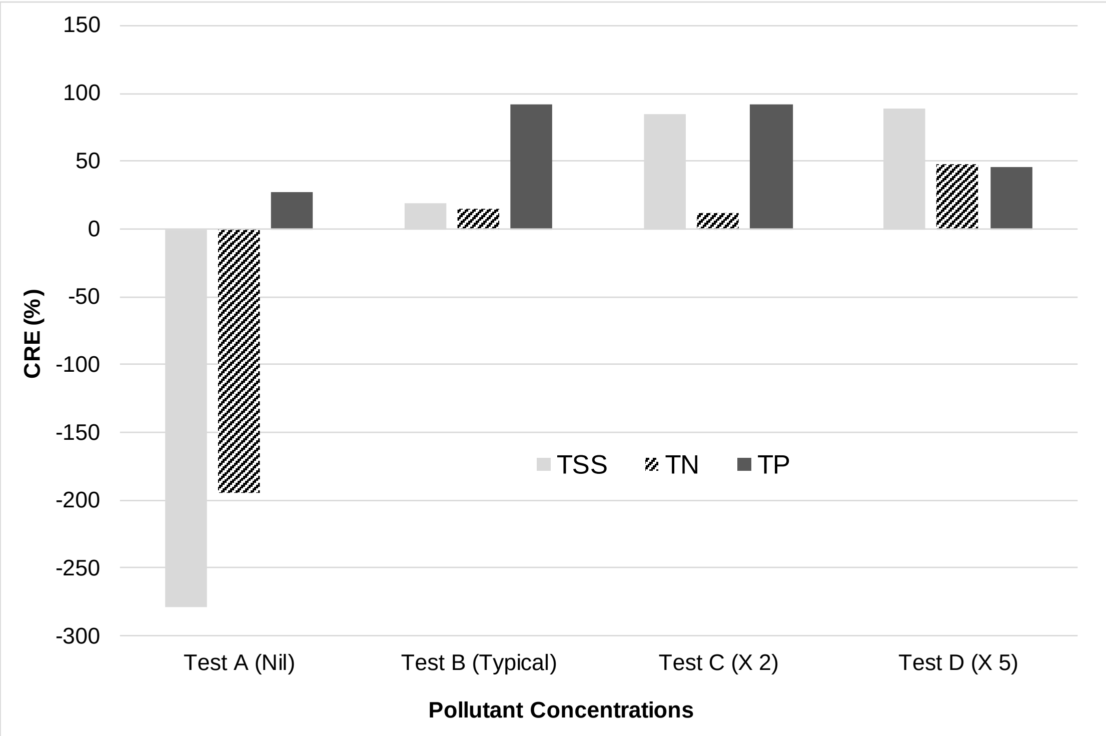

Figure 4 Average bioretention pollution removal performance (CRE) across basins

The results of this study suggest that the long-term pollution removal performance of bioretention systems may not be as effective as previously assumed. While this study was limited to evaluation of only three systems in Australia, the study results suggest that further investigation of these systems is warranted.

Conclusions

This study evaluated the pollution removal performance of three, 10-year old street-side bioretention systems. The bioretention basins were subjected to a series of simulated rainfall events using synthetic stormwater and four different pollution concentrations were tested. The study found:

- TSS removal performance was variable for all tests and no correlation was found between performance and dosage;
- TN removal was positive for Tests B, C and D. However, the TN removal results for Test A were found to be negative;
- TP was the only pollutant to be effectively removed from all basins for all four synthetic stormwater tests;
- The study bioretention basins were found to export pollutants during tests where no pollutants were added to the simulated inflow water (Test A).

While this study has added to the current knowledge about the long-term pollution removal and stormwater reduction performance of street-side bioretention basins, further research is required in future order to fully understand the potential stormwater management benefits of these systems.

References

Ansaf, K.M.M., Lucke, T., & Boogaard, F. (2014) Preliminary investigation into the pollution reduction performance of swales used in a stormwater treatment train. Water Sci. & Tech.69 (5): 1014-1020.

ANZECC and ARMCANZ (2000) Australian and New Zealand guidelines for fresh and marine waters. National Water Quality Management Strategy Paper No 4, Australian and New Zealand Environment and Conservation Council & Agriculture Resource Management Council of Australia and New Zealand, Canberra.

Bratieres, K., Fletcher, T.D., Deletic, A., & Zinger, Y. (2008) Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study. Water Research. 42, 3930-3940.

Davis, A. (2008) Field Performance of Bioretention: Hydrology Impacts. Journal of Hydrologic Engineering 13(2), 90-95. DOI: 10.1061/(ASCE)1084-0699(2008)13:2(90)

Deletic, A. & Fletcher, T.D. (2006) Performance of grass filters used for stormwater treatment—a field and modelling study. Journal of Hydrology 317(3): 261-275.

Deletic, A., McCarthy, D., Chandresena, G., Li, Y., Hatt, B., Payne, E., Zhang, K., Henry, R., Kolotelo, P., Randjelovic, A., Meng, Z., Glaister, B., Pham, P., & Ellerton, J. (2014). Biofilters and wetlands for stormwater treatment and harvesting (pp. 67). Melbourne: Cooperative Research Centre for Water Sensitive Cities, Monash University, October, 2014.

Dietz, M. E. (2007) Low Impact Development Practices: A Review of Current 17 Research and Recommendations for Future Directions. Water Air Soil Pollution, 186: 351-363.

Duncan, H. (1999) Urban stormwater quality: a statistical overview: Clayton Victoria: CRC for Catchment Hydrology.

FAWB (2009). Adoption Guidelines for Stormwater Biofiltration Systems. Faculty for Advancing Water Biofiltration. Monash University. June 2009.

Hatt, B.E., Fletcher, T.D., & Deletic, A. (2009) Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. Journal of Hydrology, 365(3): 310-321.

Hatt, B.E., Fletcher, T.D., Deletic, A. (2007) Hydraulic and pollutant removal performance of stormwater filters under variable wetting and drying regimes. Water Science & Technology 56(12): 11-19.
Hatt, B.E., Steinel, A., Deletic, A., & Fletcher, T.D. (2011) Retention of heavy metals by stormwater filtration systems: Breakthrough analysis. Water Science & Technology, 64: 1913-1919.
Hunt, W., Smith, J., Jadlocki, S., Hathaway, J., & Eubanks, P. (2008). Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, N.C. Journal of Environmental Engineering, 134(5): 403-408.
Le Coustumer, S., Fletcher, T.D., Deletic, A., Barraud, S., & Poelsma, P. (2012). The influence of design parameters on clogging of stormwater biofilters: a large-scale column study. Water Research, 46(20): 6743-6752.
Liu, J., Sample, D., Bell, C., & Guan, Y. (2014). Review and Research Needs of Bioretention Used for the Treatment of Urban Stormwater. Water 6(4): 1069-1099.
Lloyd, S.D. (2001) Water Sensitive Urban Design in the Australian Context. Synthesis of a Conference held 30–31 August 2000, Melbourne, Australia (Technical Report No. 01/7) Cooperative Research Centre for Catchment Hydrology, Melbourne, Australia (2001)
Lucke, T., & Beecham, S. (2011) Field investigation of clogging in a permeable pavement system. J. Build. Res. Inf. 39(6): 603–615.
Mangangka, I.R., Liu, A., Egodawatta, P., & Goonetilleke, A. (2015). Performance characterisation of a stormwater treatment bioretention basin. Journal of Environmental Management, (150): 173-178.
Mullaney, J., Lucke, T., & Trueman, S.J. (2015) A review of benefits and challenges in growing street trees in paved urban environments. Landscape and Urban Planning, 134: 157-166.
Nichols, P.W.B., White, R., & Lucke, T. (2015) Do sediment type and test durations affect results of laboratory-based, accelerated testing studies of permeable pavement clogging? Sci.Tot.Env. (511): 786-791.
Pilgrim, D.H., (ed). (1987) Australian Rainfall & Runoff – A Guide to Flood Estimation, Institution of Engineers, Australia, Barton, ACT, 1987.