Preliminary investigation into the pollution reduction performance of swales used in a stormwater treatment train

M. A. Kachchu Mohamed, T. Lucke and F. Boogaard

ABSTRACT

Permeable pavements have been shown to be effective stormwater treatment devices that can greatly reduce surface runoff and significantly improve the quality of stormwater runoff in urban areas. However, the potential problems with sediment clogging and consequent maintenance requirements have been identified as the main barriers to more widespread adoption of permeable pavements in urban developments. This Australian study investigates the effectiveness of using grass swales as pre-treatment devices for permeable pavements in order to reduce clogging and extend the life span of these systems. The results of simulated runoff experiments demonstrated that between 50 and 75% of the total suspended sediment (TSS) was removed within the first 10 m of the swale length. This suggests swales of this length could potentially increase the effective life of permeable pavement systems by reducing clogging, and therefore maintenance. Nutrient removal was also tested in the study and the results indicated the tested swales were of limited effectiveness in the removal of these pollutants. However, in real runoff situations, reduction of TSS will have a direct influence on removing nutrients because a significant proportion of nutrients (and other pollutants) are attached to the sediments.

Key words | clogging, permeable pavement, stormwater pollution, stormwater runoff, swales

M. A. Kachchu Mohamed
T. Lucke (corresponding author)
School of Science and Engineering,
University of the Sunshine Coast,
Australia
E-mail: *tlucke@usc.edu.au*

F. Boogaard
Faculty of Civil Engineering and Geosciences,
Delft University of Technology,
The Netherlands

INTRODUCTION

Permeable pavements have been recognised as an effective urban stormwater runoff best management practice to assist in returning catchments to their pre-development hydrologic regimes (Pezzaniti *et al.* 2009; Ball & Rankin 2010). Permeable pavements' ability to infiltrate stormwater into the ground greatly reduces surface runoff and improves the quality of stormwater runoff in urban areas (Scholz & Grabowiecki 2007). The advantages of permeable pavements as a source control device have been reported in many recent studies and guidelines (Brattebo & Booth 2003; Melbourne Water 2013). However, in spite of their many stormwater management benefits, there is still some reluctance to the widespread implementation of permeable pavements among stormwater industry professionals (Fassman & Blackbourn 2010; Lucke & Beecham 2011). The potential problems with clogging and consequent maintenance requirements have been identified as the main barriers to more widespread adoption of permeable pavements in urban developments (Yong *et al.* 2008).

The sediment transported in stormwater is the main cause of clogging of permeable pavement surfaces and this reduces the permeability and effective life span of pavements (Scholz & Grabowiecki 2007; Shirke & Shuler 2009). It has been reported that the finer sediment (silt and clay) brought in with the runoff is the main determinant of the effective life span of permeable pavements in the field (Pratt *et al.* 1995; Siriwardene *et al.* 2007).

The idea that pre-treatment systems could prevent the risk of clogging in stormwater infiltration systems has been previously proposed in design guidelines and methodologies (Bettess 1996; Wong 2006; Kadurupokune & Jayasuriya 2009). However, Siriwardene *et al.* (2007) asserted that the majority of clogging is caused by very fine particles (less than 6 μm in diameter) and pre-treatment of stormwater may therefore not be as effective as anticipated.

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While regular maintenance such as vacuum sweeping or pressure washing (Balades *et al.* 1995) can be an effective way of reducing clogging and prolonging the effective lives of permeable pavements, other methods of lowering sediment levels have also been explored. For example, swales have been shown to be very efficient in removing sediment particles from urban runoff (Barrett *et al.* 1998; Deletic 2005). Therefore, pre-treating storm runoff upstream of a permeable pavement, specifically targeting sediment removal using a swale, may significantly reduce the sediment loads and increase the effective life of the pavement (Kadurupokune & Jayasuriya 2009).

Swales are shallow vegetated (generally grassed) channels with gentle side slopes (often 1V:13H or more) and longitudinal slopes (typically <1.6%) conveying runoff downstream (Jamil & Davis 2008; Davis *et al.* 2012). These are simple systems and considered to be very cost effective stormwater devices for controlling runoff volumes and pollutants yielded from impervious surfaces (Deletic & Fletcher 2006). The ability of swales to reduce total runoff volumes and for flow attenuation has often been reported in the literature, particularly in low to medium storm events (Deletic & Fletcher 2006; Davis *et al.* 2012). The majority of the research done on swales focuses on their water quality improvement capabilities rather than their flow reduction and attenuation benefits.

Water quality treatment in a swale occurs through the process of sedimentation, filtration, infiltration and biological and chemical interactions with the soil (Winston *et al.* 2012). Swale performance studies by Deletic & Fletcher (2006) demonstrated average pollutant reduction efficiency of 72% for total suspended sediment (TSS), 52% for total phosphorus (TP) and 45% for total nitrogen (TN). Simulated runoff testing on nine swales by Bäckström (2002) demonstrated TSS removal rates between 79 and 98%. He also observed more particles were trapped when a swale had dense and fully developed turf. Bäckström (2003) reported that a 110 m long grass-covered swale removed sediments of particle sizes greater than 25 μm. He also found that small particles (between 9 and 15 μm in diameter) were exported from the swale. The sediment capturing performance of swales was found to reduce exponentially with the length of the swale, often reaching a constant value (Deletic 2005; Deletic & Fletcher 2006). A significant quantity of particles above 57 μm in diameter was effectively trapped by the swales, while the swale's trapping efficiency of particles less than 6 μm was very low. Deletic (2005) also observed that large particles settled out within the first few metres of the swale, while smaller particles travelled further downstream. These results showed that the runoff sediment concentration is rapidly reduced after entering the swale. A more detailed analysis of particle size distribution (PSD) will be addressed in future investigations.

The primary focus of this investigation was to determine the optimum swale length for pre-treatment of stormwater for permeable pavement systems to prolong the life span of these systems by reducing sedimentation and required maintenance. To determine the optimum swale length, an analysis was undertaken to quantify the amount of sediments that are trapped and released within the swales under controlled conditions. This investigation also collected data on the efficacy of swales in nutrient removal in simulated runoff conditions. This paper will explain the field testing methodologies, detail the procedures of the field tests, discuss the results, and propose future areas of investigation.

METHODS

A series of controlled field experiments were undertaken to explore and quantify the water quality treatment efficiency of swales under different pollutant loading conditions.

A detailed assessment of the stormwater runoff pollutant removal characteristics of swales was performed in the initial phase of this study. The swale performance testing was undertaken as controlled field experiments using simulated stormwater runoff events. The inflow and outflow pollution concentrations of the stormwater treated by the swales was analysed as part of the initial study. The outflow stormwater from the swales was used as the inflow water for the permeable pavement performance testing in the later part of this study.

The outflow sediment conditions from swale testing results were replicated in these tests using storm simulation techniques previously presented by Siriwardene *et al.* (2007), Hatt *et al.* (2007), and Yong & Deletic (2012). A field-scale permeable pavement testing facility at the University of the Sunshine Coast (USC), Australia was also evaluated using similar simulation conditions to verify the experimental laboratory results.

Experimental methodology

Three different vegetated swales of at least 30 m in length were selected for evaluation to investigate the variation in TSS and pollution removal performance (Figure 1). The swales had common cross-sectional profiles, soil

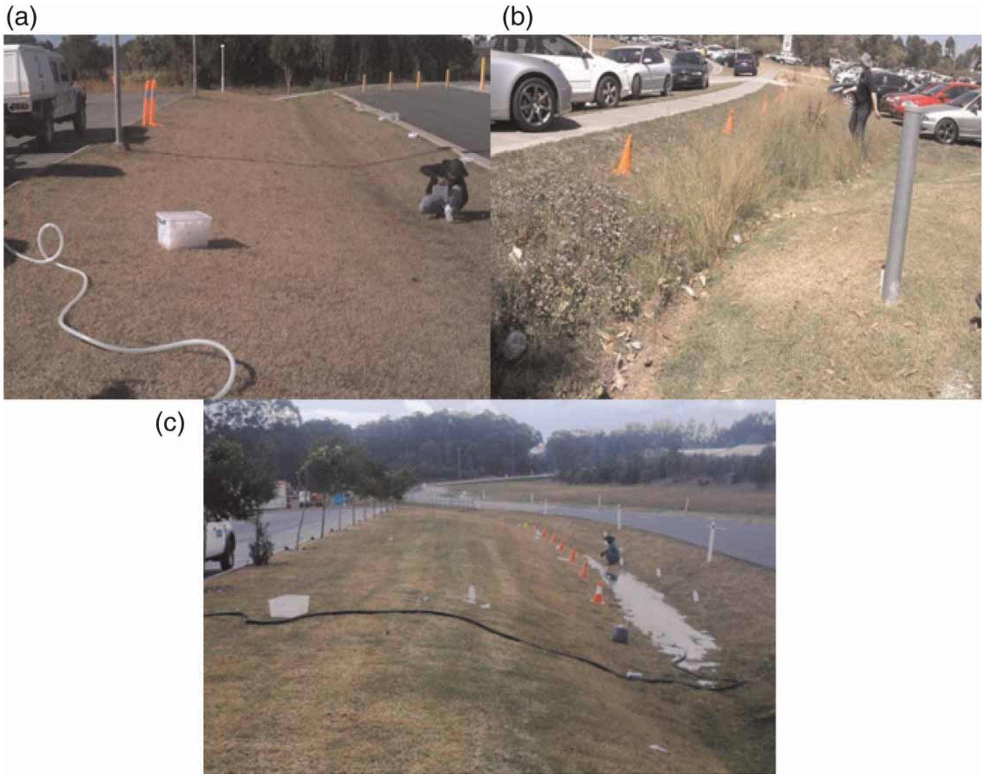

Figure 1 | Selected swales in the study. (a) Engineering swale — 35 m long, (b) Innovation Centre swale – 30 m long, and (c) Sports Complex swale – 45 m long.

characteristics and vegetation cover (short, mown grass). However, in addition to the mown grass, the Innovation Centre swale was planted with native grasses approximately 500 mm in height (Figure 1(b)).

The USC campus is generally very flat and has a relatively high water table. Drainage is therefore a big issue at USC and swales are used extensively there to help prevent localised flooding during heavy rain events. The Innovation Centre swale (Figure 1(b)) is next to the main entrance to the University and is particularly prone to flooding. Both the Engineering swale and the Sports Complex swale (Figure 1(a) and 1(c)) are on flat areas of land adjacent to storage lakes and natural wetlands. In other words, it is a perfect environment to carry out the field tests on swales based on heavy sedimentation and flooding events.

Monitoring the performance of full-scale stormwater treatment devices during real storm events is extremely difficult to do accurately. Literature suggests that controlled tests are more reliable, simpler to undertake, and more consistent, due to the ability to control the flow duration and water quality (Lloyd *et al.* 2001; Deletic & Fletcher 2006; Hatt *et al.* 2007). Therefore, performance monitoring of a field installation using simulated rainfall events is a more common approach. Field testing experiments can be done using either 'natural' or 'synthetic' stormwater (Hatt *et al.* 2007). Synthetic pollutant constituents were used in this study to promote consistency throughout the experiments.

Pollutant concentrations were introduced in the synthetic stormwater used in this study based on literature values for typical Australian urban runoff quality data (Duncan 1999; Lloyd *et al.* 2001; Wong 2006; Bratieres *et al.* 2008). Table 1 shows the selected pollutant constituents and concentrations used in the experiments.

Runoff simulations were performed with four different pollutant concentrations (Table 1). Experiment A was performed without any pollutants as a control to determine the background concentrations found in the swales. The other three experiments were simulated with typical Australian (Duncan 1999) urban runoff pollutant concentrations

Table 1 | Pollutant constituent concentrations used in the simulation experiments

Pollutants	Concentrations (mg/L)			
Test	A	B	C	D
TSS – Silica	–	150	750	1,500
TN – KNO_3	–	1	5	10
TP – KH_2PO_4	–	1	5	10

(B), five times the typical concentrations (C), and 10 times the typical concentrations (D). Experiments C and D were included to replicate 5 and 10 years' worth of sediment loading in one test, respectively. This was done to ensure measureable results would be obtained in the tests. However, these pollutant concentrations are not representative of typical Australian stormwater conditions.

The nutrient concentrations used for the synthetic stormwater testing were slightly higher than typical values due to the difficulty in measuring such low concentrations. The experiments were designed with different pollutant concentrations in order to help understand the performance of swales under varying pollution loads.

The 100G type silica (Unimin, Australia) was used to produce the synthetic stormwater sediment used in this study. The gradation of the 100G was considered to best represent the PSD of typical urban stormwater sediments in Australia (Duncan 1999). The nutrient concentrations were reproduced in the synthetic stormwater through the addition of soluble chemical reagents KNO_3 and KH_2PO_4, for TN and TP respectively (Table 1).

A mobile stormwater quality testing rig was constructed for the purpose of testing stormwater treatment devices in the field. The test rig consisted of a 2,000 L tank with a piezometer mounted on a trailer. The tank was filled with potable water. The outflow from the tank was adjusted using a flow control valve set to a continuous average flow rate of 1.6 L/s. This flow rate was chosen to represent the average runoff from a 100 m^2 carpark area upstream of the swale during a typical 1 hour storm at the site.

It was very important to keep the pollutant concentration of the tank outflow consistent throughout the swale testing. A special mixing system was designed for this purpose using a submersible pump fitted with an especially designed directional flow system that generated high powered water jets which enabled continuous mixing of the synthetic stormwater within the tank throughout the duration of the testing. The pump was powered by a 4 kW portable generator. The tank mixing system proved to be very reliable with outflow sediment concentrations only varying by ±10%. There was no difference in outflow nutrient concentrations as the nutrients used for testing were fully soluble.

Experimental procedure

The submersible pump was first activated in the full tank in order to allow a thorough mixing action to develop. Once the mixing action was functioning correctly, the appropriate amounts of pollutants were added for each test (Table 1). The pollutants were allowed to mix for a period of between 10 and 15 min to ensure that they were thoroughly mixed. The tank hose was placed at the beginning of the swale test section. The valve was opened and the outflow from the tank hose was set to 1.6 L/s. It required approximately 21 min to fully drain the 2 kL tank. Grab samples of the runoff were collected every 5 m along the length of the swale to determine the change in pollutant concentrations. Three samples were collected at each sampling location throughout the duration of the test and these were combined to form composite samples for each location.

RESULTS AND DISCUSSION

Results from all three test sites have confirmed that grass swales are an effective means of sediment removal from urban runoff. Figure 2 shows the reduction in TSS concentrations along each of the three swales for an initial TSS concentration of approximately five times the typical Australian urban runoff concentration (Test C in Table 1). It can be seen from the results in Figure 2 that the Innovation Centre swale was the most effective at removing the sediment from the stormwater. It is hypothesised that this was due to the native grasses contained in the swale. Figure 2 also shows a trend line for all three sets of TSS removal results. The trend line demonstrates an exponential decay along the length of the swale which agrees with results presented by Deletic (2005). The results from Test D were similar to those shown in Figure 2.

The results from Test B (typical) also showed an exponential decay along the length of the swale, although this

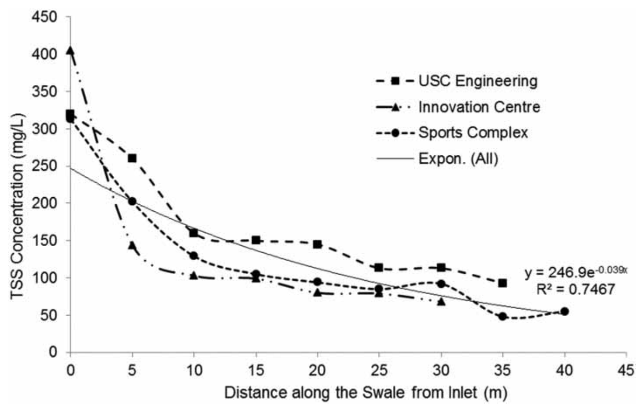

Figure 2 | Reduction in TSS along swales for Test C.

was less pronounced. Additionally, the results from one of the swales results showed an increase in TSS concentrations at one point. The results from the control (Test A) showed also an increase in TSS concentrations along the length of one of the swales. It is thought that the water used in these two tests may have dislodged sediment from the base of the swales and this caused the unexpected increases. The results of Test A and B demonstrate the difficulty in quantifying the effects of stormwater treatment devices on stormwater with very low pollution concentrations. It should also be noted that although a sediment load mass of 750 mg/L was mixed into the synthetic stormwater, the sediment load recorded at the inlet to the swale was up to 50% lower. It was hypothesised that this was due to heavier sediment particles settling out in the tank and the hose, despite the rigorous mixing action supplied by the mixing pump.

Figure 2 shows that between 50 and 75% of the TSS was removed within the first 10 m of the swale length. It can also be seen that there was a significant decline in the TSS removal efficiency after the first 10 m and the removal rate was minimal from that point on. These results suggest that installation of excessively long swales to treat stormwater TSS pollution may not be the most cost effective solution. Scheuler (1996) proposed that there is a finite effective length or area for stormwater treatment devices after which the performance does not change owing to what they called the 'irreducible sediment concentration'. The results shown here also suggest that swales used to pre-treat stormwater for permeable pavement systems need not be longer than approximately 10 to 15 m long. Swales of these lengths can remove more than 50% of the TSS from stormwater before it enters permeable pavement systems and therefore could significantly increase the effective life of the pavements by reducing clogging

The experimental results showed that swales were only of limited effectiveness in the removal of nutrients from the synthetic stormwater used in this study. Figures 3 and 4 show the reduction in TP and TN concentrations respectively along each of the three swales for an initial concentration of approximately five times the typical Australian urban runoff concentration (Test C in Table 1). The swales' TP and TN reduction performance were both highly variable. However, it appears that the Innovation Centre swale was also the best forming swale for TP and TP removal, probably again due to the native grasses. A consistent reduction trend was observed along the length of the swale for the higher concentrations of TP

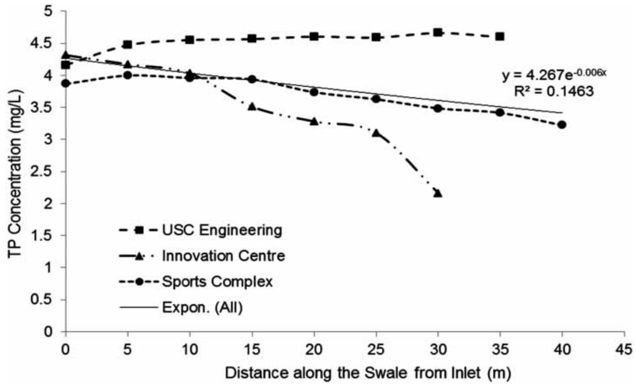

Figure 3 | Reduction in TP along swales for Test C.

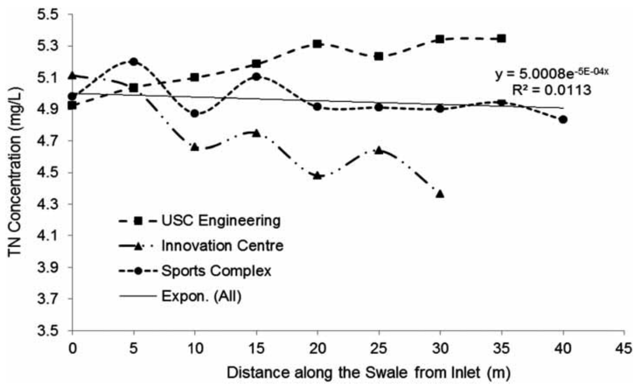

Figure 4 | Reduction in TN along swales for Test C.

used in Tests C (Figure 3) and D. However, for the lower concentrations used in Tests A and B, the removal performance was relatively neutral for Test B and was negative in Test A. TN removal performance was neutral for tests B, C (Figure 4) and D and was negative in Test A. The reasons for these results are unclear. However, it is thought that leaching of phosphorus and nitrogen from the swale may have been responsible for the unexpected variations in concentration results observed in ths study.

Swale nutrient removal performance results obtained in this study were inconsistent with previous research findings (Barrett *et al*. 1998; Deletic & Fletcher 2006). The reason for this discrepancy may be that the fully soluble chemicals used in the experiments may have influenced the performance of the swales at the lower concentrations as suggested by Lloyd *et al*. (2001). In natural storm runoff events, a significant proportion of nutrients (and other pollutants) are attached to the sediments. Therefore, a reduction of TSS will have a direct influence on nutrients removal in real runoff situations.

CONCLUSIONS

Three field swales were monitored during a range of synthetic runoff events to determine their stormwater pollutant removal performances. Results verified a distinctive exponential decrease of TSS concentration along the grass swale and demonstrated that between 50 and 75% of the TSS was removed within the first 10 m of the swale length. Beyond 10 m, only a further approximately 20% reduction can be expected, regardless of the total length. The results suggest that installation of excessively long swales to treat stormwater TSS pollution may not be the most cost effective solution.

The experimental results showed that swales were only of limited effectiveness in the removal of nutrients from the synthetic stormwater used in this study and this is inconsistent with previous research findings. However, for very high concentrations of TP and TN, swales were shown to perform satisfactorily.

The results of this study suggest that pre-treatment of stormwater runoff by short swales before it enters permeable pavement systems could significantly increase the effective lives of permeable pavement systems. While no definitive conclusion can be drawn about this hypothesis at this stage, the research work outlined in this paper is ongoing and is expected to produce some valuable results in the near future that will enable this hypothesis to be fully investigated.

Research results clearly show that swales are very effective in reducing the levels of TSS contained within stormwater. However, the performance of swales in treating nutrients such as nitrogen and phosphorus is not so well known (Winston *et al*. 2010). Despite the relatively large number of studies that have demonstrated positive pollution removal performance by swales, very few of these studies have analysed in any detail, the particle sizes removed by the swale and the PSD of the outflow.

Future work will include a complete analysis of the inlet and outlet swale water samples including sediment PSD using a laser particle size analyser. This detailed analysis of the influent and effluent will identify the size fraction of sediments that are effectively retained in swales. These results will be required to accurately model the permeable pavement inlet water quality parameters.

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