Using swales to pre-treat stormwater runoff and prolong the effective life of permeable pavement systems

Utilisation des noues pour pré-traiter les eaux de ruissellement et prolonger la durée de vie effective des systèmes de revètements poreux

Mohamed Ansaf Kachchu Mohamed [1], Terry Lucke[1] & Floris Boogaard[2+3]

[1]School of Science and Engineering, University of the Sunshine Coast, Australia
m_k107@student.usc.edu.au
[2]Delft University of Technology, Faculty of Civil Engineering and Geosciences, Delft, the Netherlands
[3] TAUW, P.O. Box 20748, 111 NS Amsterdam, The Netherlands

RÉSUMÉ

Les revêtements perméables ont démontré leur efficacité comme dispositifs de traitement des eaux pluviales, capables de réduire de façon importante le ruissellement de surface et d'améliorer considérablement la qualité des eaux de ruissellement dans les zones urbaines. Cependant, les problèmes potentiels de colmatage par des sédiments et les besoins d'entretien qui en découlent ont été identifiés comme les principaux obstacles à l'adoption plus répandue des revêtements perméables dans les aménagements urbains. Cette étude porte sur l'efficacité de l’utilisation de noues gazonnées comme prétraitement pour les chaussées perméables afin de réduire l'encrassement et prolonger la durée de vie de ces systèmes, à la fois en Australie et aux Pays-Bas. Les premiers résultats ont démontré qu'entre 50 % et 75 % du total de sédiments en suspension ont été éliminés sur les dix premiers mètres de la rigole. Les résultats de cette étude suggèrent que le prétraitement des eaux de ruissellement par des noues courtes avant qu’elles n'entrent dans les systèmes de chaussée perméable pourrait augmenter considérablement la durée de vie effective des systèmes de chaussée perméables.

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 wide spread adoption of permeable pavements in urban developments. This study will investigate 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 in both Australia and the Netherlands. The initial results demonstrated that between 50% and 75% of the total suspended sediment was removed within the first 10 m of the swale length. The results of this study suggest that pre-treatment of stormwater runoff by short swales before it enters permeable pavement systems could potentially significantly increase the effective life of permeable pavement systems.

KEYWORDS

Clogging, Permeable pavement, Stormwater pollution, Stormwater runoff, Swales

1 INTRODUCTION

Permeable pavements have been recognised as an effective urban stormwater runoff best management practice (BMP) option to assist in returning catchments to their pre-development hydrologic regimes (Chopra et al., 2010; Collins et al., 2008; 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 (Bean et al., 2004; Hunt & Smith, 2010; Scholz & Grabowiecki, 2007). The advantages of permeable pavement as a source control device have been reported in many recent studies and guidelines (Beecham et al., 2010; Brattebo & Booth, 2003; WSUD, 2010). However, in spite of their many stormwater management benefits, there is still some reluctance to the wide spread implementation of permeable pavements among stormwater industry professionals (Gomez-Ullate et al., 2011; Fassman & Blackbourn, 2010; Lucke, 2011). The potential problems with clogging and consequent maintenance requirements have been identified as the main barriers to more wide spread adoption of permeable pavements in urban developments (Hunt & Bean, 2006; Yong et al., 2008; Tan et al., 2003).

A permeable pavement's infiltration capacity is the primary indicator of its operational capability and it should remain above a certain limiting value to still be deemed as functional. 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; Chopra et al., 2010). It has been reported that the finer sediment (silt and clay) brought in with the runoff is the main determinant of the effective lifespan of permeable pavements in the field (Coughlin et al., 2012; Haselbach, 2010; Siriwardene et al., 2007b; Pratt et al., 1995). Siriwardene et al. (2007b) concluded that sediment finer than 6 µm in size is the main cause of clogging in permeable pavements. Therefore, regular maintenance of permeable pavement by means of vacuum sweeping or pressure washing is often recommended to remove this sediment and to help prevent clogging of the pavement surface (Balades et al., 1995).

While maintenance 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, a treatment train arrangement incorporating a swale upstream of the permeable pavement could also be expected to slow down the clogging process that takes place. Swales have been shown to be very efficient in removing sediment particles from urban runoff (Stagge et al., 2012; Deletic, 2005; Barrett et al., 1998; Boogaard et al., 2006). Therefore, it is likely that pre-treating storm runoff upstream of a permeable pavement, specifically targeting sediment removal using a swale, will significantly reduce the sediment loads and increase the effective life of the pavement (Figure 1).

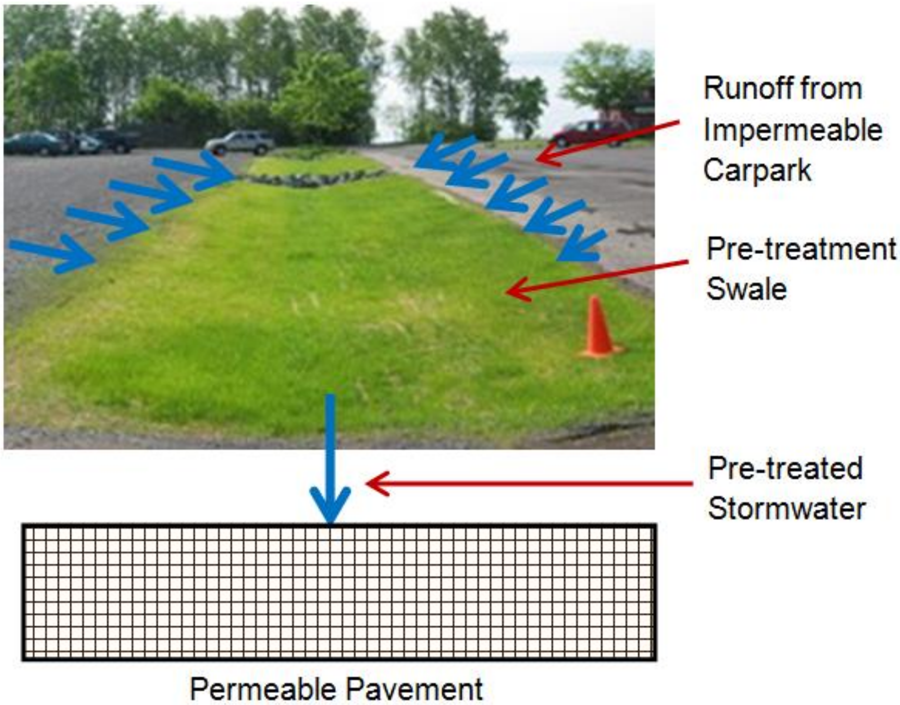

Figure 1. Pre-treatment Swale for Permeable Pavement Concept

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 (Wong, 2006; Bettess, 1996). However, Siriwardene et al. (2007a) 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. This study will investigate 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. This research will be conducted on swales in both Australia and the Netherlands. The initial Australian results are presented here.

1.1 Previous Studies

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 (Davis & Jamil, 2008; Davis et al., 2011). These are simple systems and considered to be very cost effective stormwater best management practice (BMP) devices for controlling runoff volumes and pollutants yielded from impervious surfaces (Yu et al., 2001; Deletic & Fletcher, 2006). The ability of swales to reduce total runoff volumes and for flow attenuation has often been reported in the literature, especially in low to medium storm events (Davis et al., 2011; Rushton, 2001; Deletic & Fletcher, 2006; Kuo et al., 1999).

Traditionally, swales were generally only designed to convey stormwater to downstream water bodies. However, they can be as effective as sedimentation/filtration systems for the removal of pollutant constituents in the runoff (Barrett et al., 1998). 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). The majority of the research done on swales is to do with their water quality improvement capabilities rather than their flow reduction and attenuation benefits.

A 65 m long grassed swale in Brisbane, Australia, was shown to reduce pollutant loads of total nitrogen (TN), total phosphorous (TP) and total suspended solids (TSS) by an average of 56%, 46% and 69%, respectively (Deletic & Fletcher, 2006). As part of the same study, swale testing in Aberdeen, Scotland, showed that the swale reduced inflow sediment concentrations by between 61% and 86%. A statistical compilation of past swale performance studies by Deletic and Fletcher (2006) provided average pollutant reduction efficiency of 72% for TSS, 52% for TP and 45% for TN. Simulated runoff testings on nine swales by Bäckström (2002) demonstrated TSS removal rates of between 79% and 98%. He also observed greater levels of particle trapping occurred when a swale had dense and fully developed turf.

A well designed field study on two major highway median swales showed pollutant mass reductions of above 85% for TSS and between 36% and 61% for TP and nitrate (Barrett et al., 1998). Field tests on a 60 m long swale that treated the runoff from a 6.27 ha suburban drainage basin at Mountlake Terrace, Washington revealed an average suspended solids concentration reduction of 83% from six storms events (Khan et al., 1992). Deletic (2005) found that suspended particles tend to settle out in the grass swale during shallow runoff conditions and swales also remove pollutants that adhere to the sediments such as heavy metals.

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 were effectively trapped by the swales, while the swale's trapping efficiency of particles less than 6 µm was very low (Deletic, 2005). Deletic, (2005) also observed that large particles settled out within the first few meters of the swale, while smaller particles travelled further downstream. These results showed that the runoff sediment concentration is rapidly reduced after entering the swale.

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 phosphorous is not so well known (Wright et al., 2010). Despite the relatively large number of studies that have demonstrated positive pollution removal performance by swales, very few of the studies have analysed in any detail, the particle sizes removed by the swale and the particle size distribution (PSD) of the outflow. This study will investigate the pollution removal performance of grass swales used as pre-treatment devices for permeable pavements in Australia and the Netherlands. As part of the study, an in-depth analysis will be undertaken on the nutrient removal processes and on both, the sediments that are trapped within the swales, and the sediments that are released by the swales.

2 METHODS

The objective of the study is to determine the optimum relationship between impervious area, swale treatment area and permeable pavement area to improve the effective life span of permeable pavements. A study of the literature has revealed that the sediment removal efficiency of swales generally decreases exponentially with respect to the length of the swale. Therefore, the specific objective of this study is to find the optimum length of swale to trap the maximum amount of sediment. A series of experimental investigations on a variety of different operational swales will be undertaken to determine the optimum swale length for pre-treatment of stormwater for permeable pavement systems.

Once a method of establishing the optimum swale length is determined from the experiments, this will enable a relationship between the ratio of impervious surface to swale treatment area to be derived based on the expected runoff volumes. Based on these two parameters, an optimised design method for the pre-treatment of stormwater runoff by swales for permeable pavements systems can be developed which minimises cost and required land area, while maximising stormwater treatment efficiency.

2.1 Study Approach

A research methodology has been developed to assess the conceptual performance of a treatment-train approach for pre-treating stormwater for permeable pavement systems using swales. Due to practical reasons, both treatment devices will be studied separately and the treatment train performance will be simulated. A detailed assessment of the stormwater runoff pollutant removal characteristics of swales in Australia and Holland will be performed in the initial phase of the study. The swale performance testing was undertaken as controlled field experiments using simulated stormwater runoff events. The experimental results of the swale treatment performance will be used to develop a regional best management practices (BMP) database for both locations. The inflow and outflow pollution concentrations and particle size distributions (PSD) of the stormwater treated by the swales will be analysed as part of the study. The outflow stormwater from the swales will then be used as the inflow water for the permeable pavement performance testing.

Laboratory-scale permeable pavement models (designed as sand columns) will be developed and the clogging performance of these models will be tested. The outflow sediment conditions from swale testing results will be replicated in these tests using storm simulation techniques previously presented by and Siriwardene et al. (2007a;2007b), Hatt et al. (2007) and Yong and Deletic (2012). A field-scale permeable pavement testing facility at the University of the Sunshine Coast (USC), Australia will also be evaluated using similar simulation conditions to verify the experimental laboratory results. This paper describes a series of controlled field experiments undertaken to explore and quantify the water quality treatment efficiency of swales under different pollutant loading conditions.

2.2 Experimental Methodology

Controlled field experiments on swales consisted of the following steps;

Selecting appropriate swales for testing: As the objective of this part of the study was to investigate the variation in pollutant removal performance along the length of the swales, the swale length was the primary selection criterion. Three different vegetated swales of at least 30 m in length were selected for evaluation in this study (Figure 2). The swales were also selected so that they had common cross-sectional profiles, soil characteristics and vegetation conditions in order to allow for an appropriate comparison to be made between the swales.

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

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

Figure 2. Selected Australian swales in the study: (a) USC Engineering swale-35 m long, (b) Innovation Centre swale- 30 m long, and (c) Sports Complex swale- 45 m long

Table 1. Pollutant Constituent Concentrations Used in the Simulation Experiments

Pollutants	**Concentrations (mg/l)**			
Test	**A**	**B**	**C**	**D**
Total suspended solid (TSS)	-	150	750	1500
Total nitrogen (TN) - KNO_3	-	1	5	10
Total phosphorous (TP) - KH_2PO_4	-	1	5	10

Runoff simulations were performed with four different pollutant concentrations (Table 1). One experimental run without any pollutants (A) was performed as a control to determine the background concentrations found in the swales. The other three runs were simulated with typical Australian (Duncan, 1999) urban runoff pollutant concentrations (B), five times the typical concentrations (C) and ten times the typical concentrations (D). The nutrient concentrations used for the synthetic stormwater testing were slightly higher than the 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.

In addition to the concentration of the pollutants, the particle size distribution (PSD) of the sediment is also an important parameter to be considered when using synthetic stormwater for testing purposes. The PSD of typical Australian urban stormwater sediment (Wong, 2006; Ball & Abustan, 1995; Duncan, 1999) was plotted against the PSDs of different grades of commercially available special silica (Sibelco, 2012) to identify the most suitable type for testing. The specially manufactured silica is available in various product ranges from 60G to 500G (Sibelco, 2012). The 100G type silica was considered to be most appropriate match with the PSD of urban stormwater sediments in Australia (Figure 3). 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, as shown in the Table 1.

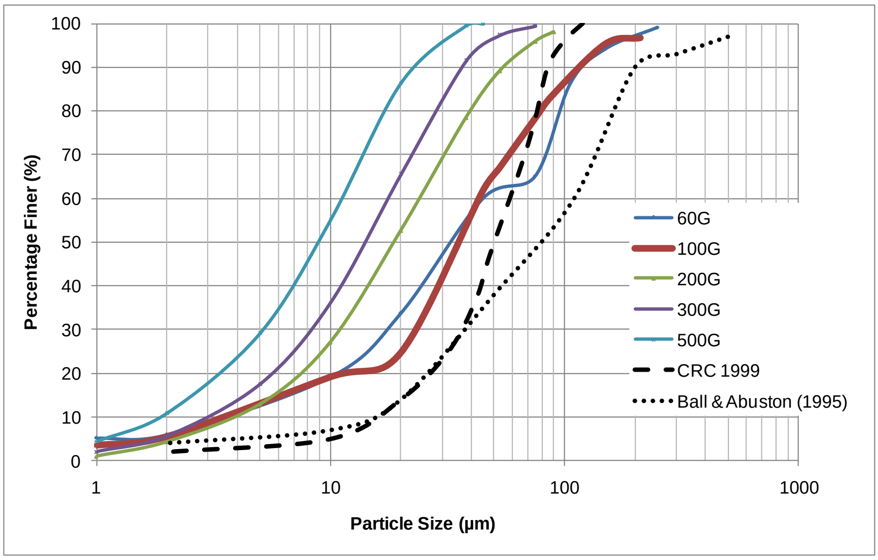

Figure 3. Particle size distribution (PSD) of artificial sediments and natural urban stormwater sediments

A mobile stormwater quality testing rig was constructed for the purpose of testing stormwater treatment devices in the field. The test rig consists of a 2000 litre tank with a piezometer attached mounted on a trailer. The tank was filled with potable water. The outflow from the tank can be adjusted using a control valve and for this swale testing study the outflow was set to a continuous average flowrate of 1.6 l/s.

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 a specially 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 4kW 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.

2.3 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 minutes 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 (Figure 6). It required approximately 21 minutes to fully drain the 2kL tank. Grab samples of the runoff were collected every 5 m along the length of the swale to determine the change in pollutant concentrations (Figure 2). Three samples were collected at each sampling location throughout the duration of the test and these were combined to form composite samples.

3 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 4 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). Figure 4 also shows a trendline for all three sets of TSS removal results. The trendline 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 4.

The results from Test B (typical) also showed an exponential decay along the length of the swale, although this was less pronounced. In addition one of the swales results showed an increased 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.

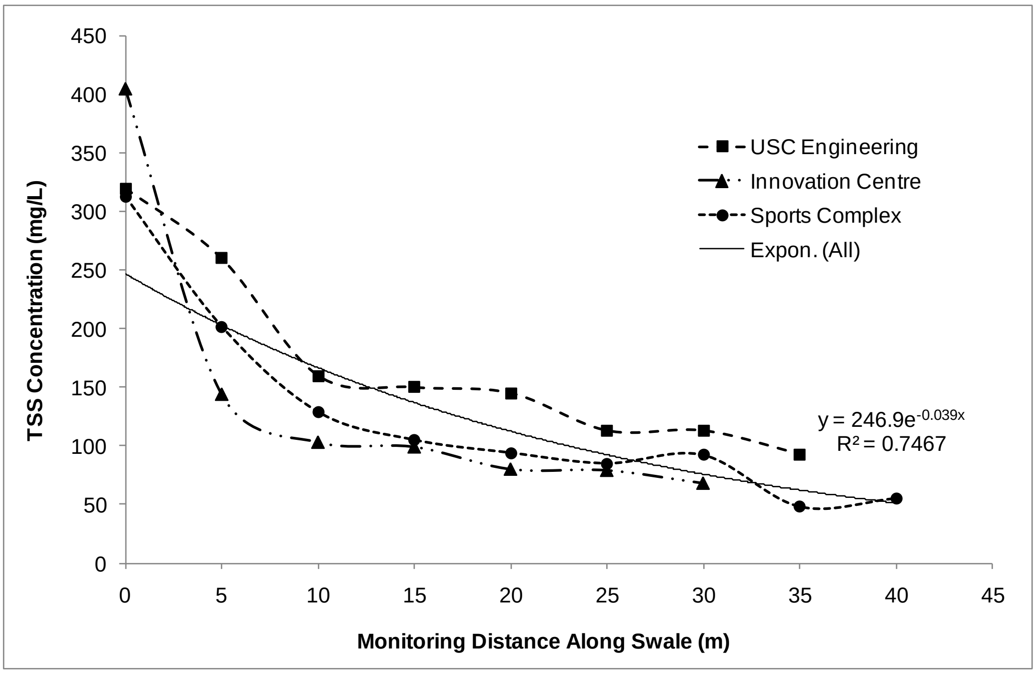

Figure 4. Reduction in TSS along Swales for Test C

Figure 4 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. Schueler & Holland (2000) 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 15m long. Removing over 50% of the TSS from stormwater before it enters permeable pavement systems could significantly increase the effective life of the pavements.

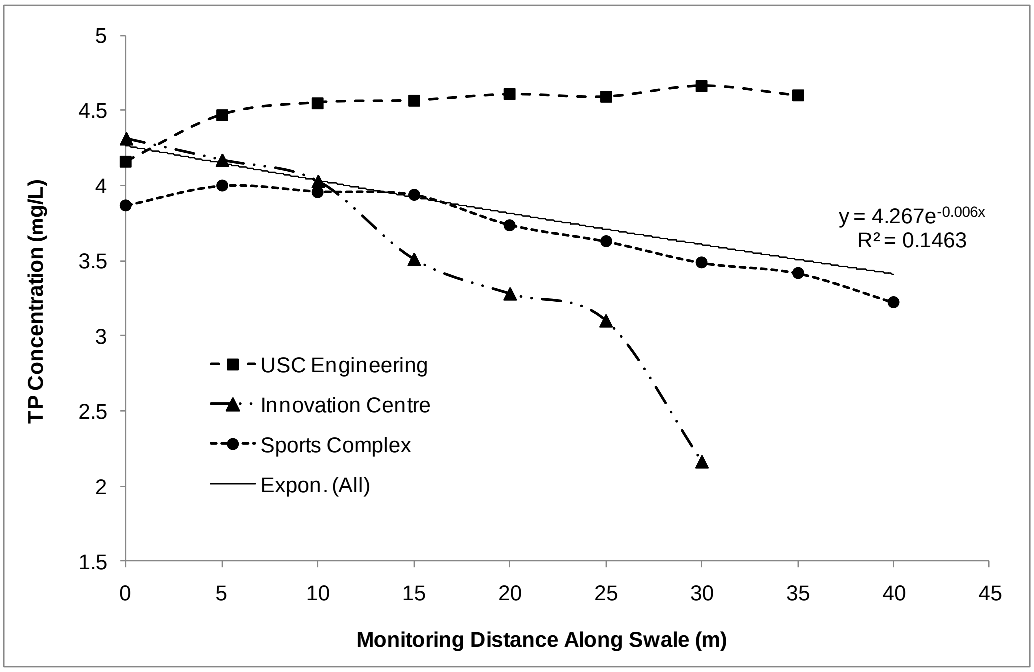

Figure 5. Reduction in TP along Swales for Test C

Figures 5 and 6 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 experimental results showed that swales were only of limited effectiveness in the removal of nutrients from the synthetic stormwater used in this study. The swales' TP and TN reduction performance were both highly variable. A consistent reduction trend was observed along the length of the swale for the higher concentrations of TP used in Tests C (Figure 5) 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 6) and D and was negative in Test A. It is thought that leaching of phosphorous and nitrogen from the swale was responsible for the increases in concentrations seen in the Test A results.

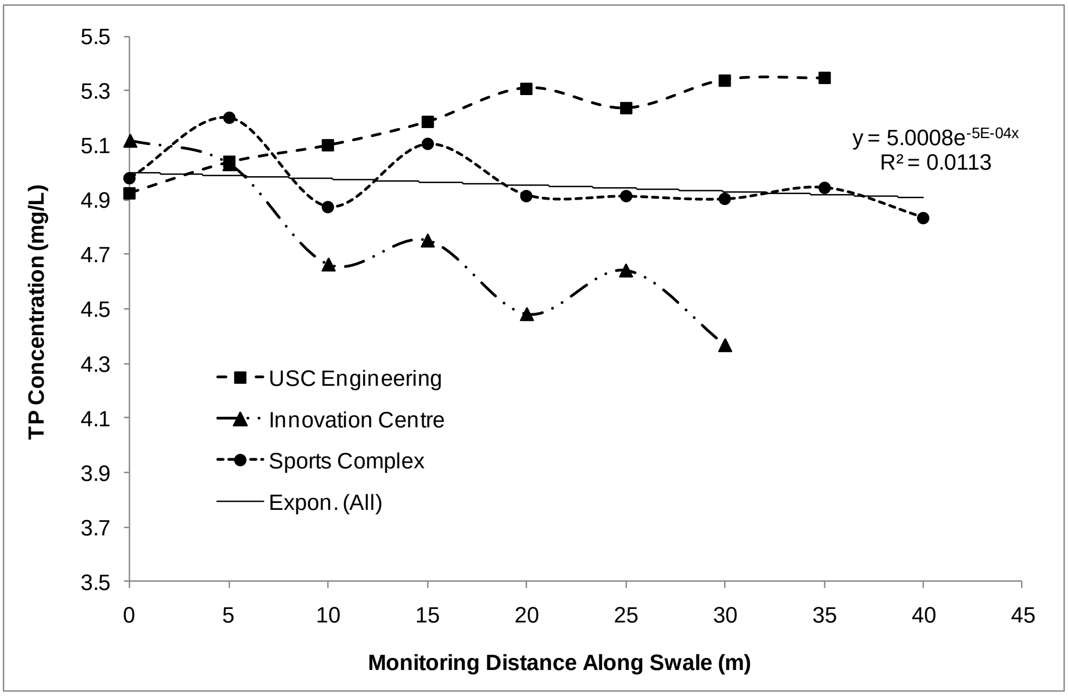

Figure 6. Reduction in TN along Swales for Test C

Swale nutrient removal performance results obtained in this study were inconsistent with previous research findings (Deletic & Fletcher, 2006; Barrett et al., 1998). 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.

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.

The results of this study suggests that pre-treatment of stormwater runoff by short swales before it enters permeable pavement systems could potentially 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.

4 CONCLUSION

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 suggests that pre-treatment of stormwater runoff by short swales before it enters permeable pavement systems could potentially increase the effective lives of permeable pavement systems significantly. Further research is underway to try to confirm this hypothesis.

ACKNOWLEDGMENTS

The authors would like to thank Mr Graham Bebington and the rest of the Sunshine Coast Council for their support and assistance with this project. We would also like to thank the USC laboratory technicians, Hugh Allen and Bernhard Black for all their help with this project. And finally we would like to thank Mr Liam Owen for all his enthusiasm and assistance with this project.

LIST OF REFERENCES

Bäckström, M. (2003). *Grassed Swales for Stormwater Pollution Control during Rain and Snowmelt*. Water Science and Technology, 48(9), 123-132.

Bäckström, M. (2002). *Sediment Transport in Grassed Swales during Simulated Runoff Events*. Water Science and Technology, 45(7), 41-49.

Balades, J.D., Legret, M. & Madiec, H. (1995). *Permeable Pavements: Pollution Management Tools*. Water Science and Technology, 31(1), 49-56.

Ball, J.E. & Abustan, I. (1995). *An investigation of the particle size distribution during storm events on an urban catchment*. 2nd International Symposium on Urban Stormwater Management, IEAust, Melbourne, Australia. 531-535.

Ball, J.E. & Rankin, K. (2010). *The hydrological performance of a permeable pavement*. Urban Water Journal, 7(2), 79-90.

Barrett, M.E., Walsh, P.M., Malina Jr, J.F. & Charbeneau, R.J. (1998). *Performance of Vegetative Controls for Treating Highway Runoff*. Journal of Environmental Engineering, 124(11), 1121-1128.

Bean, E.Z., Hunt, W.F., Bidelspach, D.A. & Burak, R.J. (2004). *Study on the Surface Infiltration Rate of Permeable Pavements*. 1st Water and Environment Speciality Conference of the Canadian Society for Civil Engineering, Saskatoon, Canada.

Beecham, S., Lucke, T. & Myers, B. (2010). *Designing Porous and Permeable Pavements for Stormwater Harvesting and Reuse*. First European Congress of the International Association for Hydro-Environment Engineering and Research (IAHR), Edinburgh, United Kingdom.

Bettess, R. (1996). *Infiltration Drainage - Manual of Good Practice*. Report no. 156, CIRIA London.

Boogard, F.C., Bruins, G. & Wentink, R. (2006). *Wadi's: aanbevelingen voor ontwerp, aanleg en beheer*. Stichting RIONED.

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(14), 3930-3940.

Brattebo, B.O. & Booth, D.B. (2003). *Long-term stormwater quantity and quality performance of permeable pavement systems*. Water Research, 37(18), 4369-4376.

Chopra, M., Kakuturu, S., Ballock, C., Spence, J. & Wanielista, M. (2010). *Effect of Rejuvenation Methods on the Infiltration Rates of Pervious Concrete Pavements*. Journal of Hydrologic Engineering, 15(6), 426-433.

Collins, K.A., Hunt, W.F. & Hathaway, J.M. (2008). *Hydrologic and Water Quality Evaluation of Four Permeable Pavements in North Carolina, USA*. 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK.

Coughlin, J., Campbell, C. & Mays, D. (2012). *Infiltration and Clogging by Sand and Clay in a Pervious Concrete Pavement System*. Journal of Hydrologic Engineering, 17(1), 68-73.

Davis, A.P. & Jamil, N.E.E. (2008). *Field Evaluation of Hydrologic and Water Quality Benefits of Grass Swales with Check Dams for Managing Highway Runoff*. In: Low Impact Development for Urban Ecosystem and Habitat Protection, 1-8.

Davis, A.P., Stagge, J.H., Jamil, E. & Kim, H. (2011). *Hydraulic performance of grass swales for managing highway runoff*. Water Research, DOI:10.1016/j.watres.2011.10.017.

Deletic, A. (2005). *Sediment transport in urban runoff over grassed areas*. Journal of Hydrology, 301(1/4), 108-122.

Deletic, A. & Fletcher, T.D. (2006). *Performance of grass filters used for stormwater treatment—a field and modelling study*. Journal of Hydrology, 317(3/4), 261-275.

Duncan, H.P. (1999). *Urban Stormwater Quality: A statistical Overview*. Report no. 99/3, Cooperative Research Centre for Catchment Hydrology, Melbourne, Australia.

Fassman, E. & Blackbourn, S. (2010). *Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils*. Journal of Hydrologic Engineering, 15(6), 475-485.

Gomez-Ullate, E., Castillo-Lopez, E., Castro-Fresno, D. & Bayon, J. (2011). *Analysis and Contrast of Different Pervious Pavements for Management of Storm-Water in a Parking Area in Northern Spain*. Water Resources Management, 25(6), 1525-1535.

Haselbach, L. (2010). *Potential for Clay Clogging of Pervious Concrete under Extreme Conditions*. Journal of Hydrologic Engineering, 15(1), 67-69.

Hatt, B.E., Fletcher, T.D. & Deletic, A. (2007). *Treatment performance of gravel filter media: Implications for design and application of stormwater infiltration systems*. Water Research, 41(12), 2513-2524.

Hunt, W.F. & Bean, E.Z. (2006). *NC State University Permeable Pavement Research and Changes to the State of NC Runoff Credit System*. 8th International Conference on Concrete Block Paving, San Francisco, California, USA.

Hunt, W.F. & Smith, D.R. (2010). *Structural/Hydrologic Design and Maintenance of Permeable Interlocking Concrete Pavement*. In: Low Impact Development 2010, 1499-1514.

Khan, Z., Thrush, C., Cohen, P., Kulzer, L., Franklin, R., Field, D., Koon, J. & Horner, R. (1992). *Biofiltration swale performance: Recommendations and Design Considerations*. Seattle Metro and Washington Ecology.

Kuo, J.-T., Pan, H., Yu, S.L. & Fassman, E.A. (1999). *Field Test of Grassed Swale Performance in Removing Runoff Pollution*. In: WRPMD'99 - Preparing for the 21st Century, E.M. Wilson (Ed.), ASCE, 1-9.

Lloyd, S.D., Fletcher, T.D., Wong, T.H.F. & Wootton, R.M. (2001). *Assessment of Pollutant Removal in a Newly Constructed Bio-retention System*. 2nd South Pacific Stormwater Conference, Auckland, New Zealand, 20-30.

Lucke, T. (2011). *Investigation into the Sediment Accumulation Processes that Occur in Permeable Interlocking Concrete Paving Systems in Australia*. SIA Queensland State Conference, Gold Coast, Australia.

Pezzaniti, D., Beecham, S. & Kandasamy, J. (2009). *Influence of Clogging on the Effective Life of Permeable Pavements*. Proceedings of the Institution of Civil Engineers - Water Management, 162(3), 211–220.

Pratt, C.J., Mantle, J.D.G. & Schofield, P.A. (1995). *UK research into the performance of permeable pavement, reservoir structures in controlling stormwater discharge quantity and quality*. Water Science and Technology, 32(1), 63-69.

Rushton, B.T. (2001). *Low-Impact Parking Lot Design Reduces Runoff and Pollutant Loads*. Journal of Water Resources Planning and Management, 127(3), 172-179.

Scholz, M. & Grabowiecki, P. (2007). *Review of permeable pavement systems*. Building and Environment, 42(11), 3830-3836.

Schueler, T.R. & Holland, H.K. (2000). *Article 65: Irreducible Pollutant Concentrations Discharged from Stormwater Practices*. The Centre for Watrshed Protection, Ellicott City.

Shirke, N. & Shuler, S. (2009). *Cleaning Porous Pavements Using a Reverse Flush Process*. Journal of Transportation Engineering, 135(11), 832-838.

Sibelco (2012). Company Products Website: *http://www.sibelco.com/index.php/products*.

Siriwardene, N., Deletic, A. & Fletcher, T.D. (2007a). *Application of Laboratory Experiment Results into Practice: Clogging of Stormwater Infiltration Systems*. 13th International Conference on Rainwater Catchment Systems, Sydney, Australia.

Siriwardene, N.R., Deletic, A. & Fletcher, T.D. (2007b). *Clogging of Stormwater Gravel Infiltration Systems and Filters: Insights from a Laboratory Study*. Water Research, 41(7), 1433-1440.

Stagge, J.H., Davis, A.P., Jamil, E. & Kim, H. (2012). *Performance of Grass Swales for Improving Water Quality from Highway Runoff*. Water Research, DOI: 10.1016/j.watres.2012.02.037.

Tan, S., Fwa, T. & Han, C. (2003). *Clogging Evaluation of Permeable Bases.* Journal of Transportation Engineering, 129(3), 309-315.

Winston, R.J., Hunt, W.F., Kennedy, S.G., Wright, J.D. & Lauffer, M.S. (2012). *Field Evaluation of Storm-Water Control Measures for Highway Runoff Treatment*. Journal of Environmental Engineering, 138(1), 101-111.

Wong, T.H.F. 2006, *Australian Runoff Quality: A Guide to Water Sensitive Urban Design*, Engineers Australia, NSW.

Wright, J.D., Hunt, W.F. & Winston, R.J. (2010). *Evaluation of Roadside Filter Strips, Dry Swales, Wet Swales, and Porous Friction Course for Stormwater Treatment*. In: Low Impact Development 2010, 1258-1269.

WSUD (2010). *Water Sensitive Urban Design Technical Manual for Greater Adelaide Region*. Government of South Australia, Adelaide.

Yong, C. and Deletic, A. (2012). Factors that Predict Clogging through Porous Pavements, 7th International Conference on Water Sensitive Urban Design, Melbourne, Australia.

Yong, C.F., Deletic, A., Fletcher, T.D. & Grace, M.R. (2008). *The Clogging Behaviour and Treatment Efficiency of a Range of Porous Pavements*. 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK.

Yu, S.L., Kuo, J.T., Fassman, E.A. & Pan, H. (2001). *Field Test of Grassed-Swale Performance in Removing Runoff Pollution*. Journal of Water Resources Planning and Management, 127(3), 168-171.