Lloyd, S.D., Fletcher, T.D., Wong, T.H.F. and Wootton, R.M. (2001), *Assessment of* ***Pollutant Removal in a Newly Constructed Bio-retention System***, proceedings of the 2nd South Pacific Stormwater Conference, Auckland, New Zealand, 27 – 29 June 2001, pp.20-30.

ASSESSMENT OF POLLUTANT REMOVAL PERFORMANCE IN A BIO-FILTRATION SYSTEM – PRELIMINARY RESULTS

Sara D. Lloyd, Tim D. Fletcher, Tony H.F. Wong and Richard M. Wootton
Department of Civil Eng., Monash University and Cooperative Research Centre for Catchment Hydrology

ABSTRACT

This paper presents the preliminary findings of a series of controlled field experiments investigating the pollutant removal effectiveness of a newly constructed bio-filtration system. A bio-filtration system consists of an infiltration system (e.g. gravel infiltration trench) overlain by a vegetated (normally grass) swale. Flow conditions corresponding to the peak discharges of the 3 month, 1 yr and 5 yr ARI events were simulated. In addition, experiments involving the operation of the swale by itself were undertaken, by discharging flows directly into the swale, with inlets to the underlying infiltration trench blocked. In essence, the system operated as a swale with a relatively high infiltration capacity due to the underlying trench.

Pollutant removal efficiency was investigated by dosing of the system with pollutants of known characteristics and mass. Two pollutant sets were used (differing in mass, to achieve two different concentrations for each flow rate) consisting of Bromide, TSS, PO_4, and NO_X. Bromide (Br) has been used as a conservative tracer, allowing the mass balance of the pollutographs to be calculated.

The results presented in this paper are for the 3 month ARI simulation (~2.5 l/s) for the full bio-filtration system, and the simulation whereby flows were discharged to the swale component of the system only, at a rate of approximately 2 l/s. The results show TSS removal of between 55% and 74%, and TP removal of between 24% and 55%. The relatively low phosphorus removal may in part be attributed to the exclusive use of soluble reactive phosphorus in the dosing mix. While a reduction in NO_X was observed, no effective removal of TN was found.

KEY WORDS

Source control, bio-filtration, pollutant removal efficiency, stormwater

1. INTRODUCTION

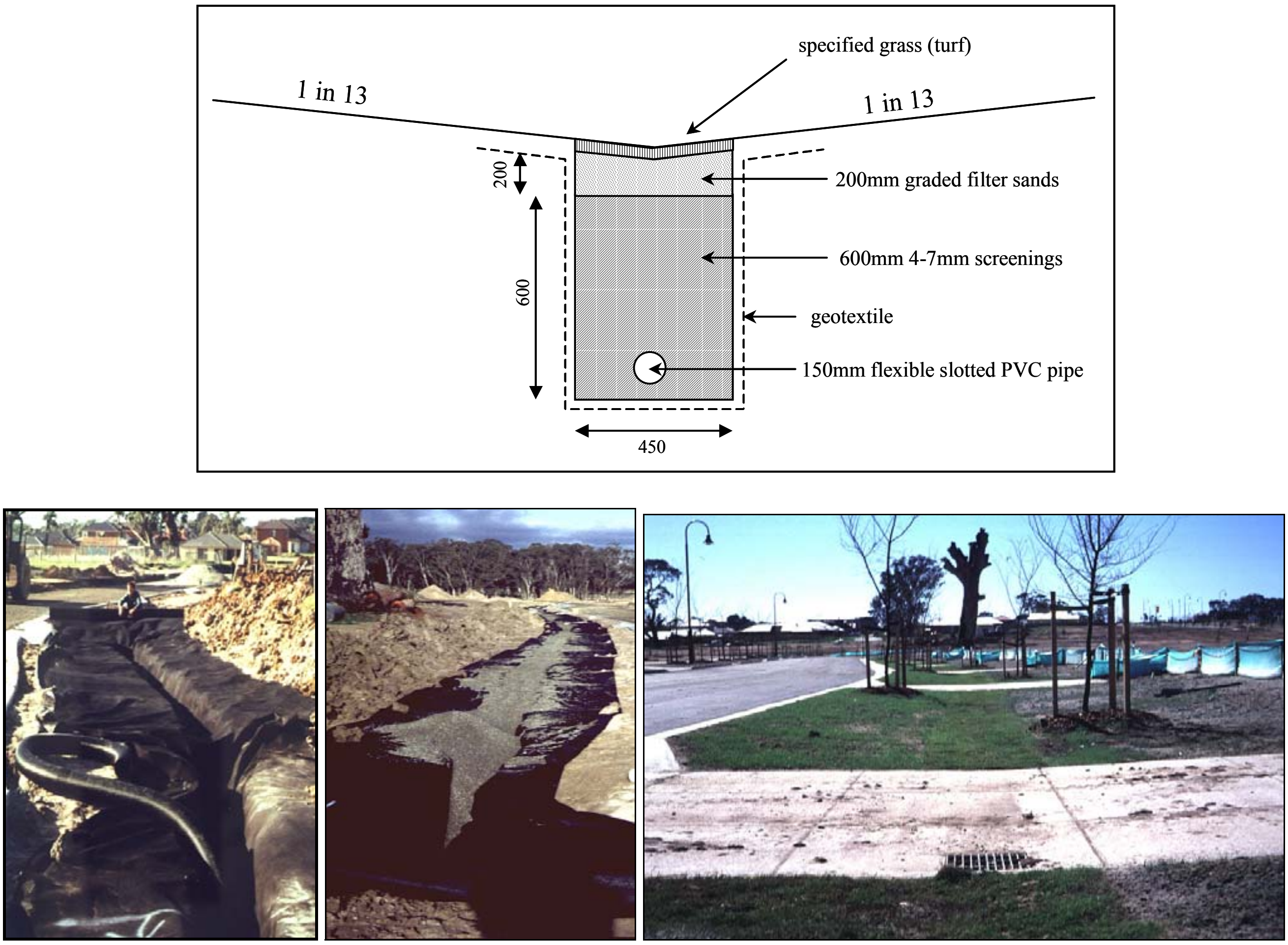
It is widely recognised that increased runoff and the discharge of polluted stormwater resulting from catchment urbanisation have a negative impact on the aquatic ecosystem of receiving waters. The management of urban stormwater for flow control and water quality improvement are now becoming standard design considerations in catchment development. Stormwater drainage solutions involving a combination of source and in-transit best management practices (BMPs) that are integrated into urban design offer a means to protect receiving waters from stormwater discharged from urban development. Controlling stormwater pollutants at their source has the advantages of reduced hydraulic loading, greater ability to attenuate flows, reduced pollutant loads to downstream regional treatment facilities (such as wetlands and waterway protection/restoration works) and, in may cases, lower capital cost. A bio-filtration system is one example of a source control method that can be integrated into the streetscape design to treat road runoff and roof runoff prior to discharging to receiving waters. Bio-filtration systems are a combined detention, infiltration and collection system, and generally integrate a vegetated swale and infiltration trench as part of their design. There are currently limited data on the performance and life cycle cost of bio-filtration systems. This paper describes a series of field experiments undertaken to explore and quantify the water quality treatment efficiency of a bio-filtration system under different hydraulic and pollutant loading conditions.

2. DESIGN OF THE BIO-FILTRATION SYSTEM

The bio-filtration system used to investigate the hydraulic performance and pollutant removal effectiveness is located at the Lynbrook Estate, Melbourne, Australia. The system forms part of an innovative stormwater drainage scheme of a 300 allotment residential precinct, consisting of two variations of a bio-filtration system (which form part of the streetscape), a constructed wetland and an ornamental pond. For details of the complete stormwater management scheme integrated into the Lynbrook Estate, including information on construction activities and issues, costs and market place acceptance, refer to Lloyd *et al.* (2001).

Figure 1 illustrates the design attributes of the bio-filtration system used for local residential streets in the precinct, and tested in these experiments. The system consists of an underground gravel trench of 0.8 m depth and 0.45m width overlain with a grass swale. The gravels range from 2mm to 7mm in diameter.

Figure 1. Cross Section Design and Construction Images of the Bio-filtration System at the Lynbrook Estate



The system has been designed to notionally operate as a series of individual cells separated by the driveway crossovers into individual residential lots. Roof runoff from adjoining dwellings is connected directly to the gravel trench, whereas road runoff is diverted into the swale using kerb chutes located at the downstream side of each driveway crossover. Road runoff is conveyed as surface flow along the length of each 'cell' of the swale and subjected to infiltration into the gravel trench. At the end of each cell, any runoff remaining as surface flow is discharged directly into the underlying trench via an inlet pit located on each driveway crossover. Each cell is thus subjected to a hydraulic loading from runoff generated from their individual catchment, until the discharge capacity of the subsurface gravel trench system is reached, at which time the swale of the bio-filtration cells operate as a continuous system.

Stormwater infiltrated through the gravel trench is collected by a 150 mm diameter perforated pipe, which conveys the treated water to an underground concrete pipe and then into the receiving waters. Stormwater runoff exceeding the discharge capacity of the 150 mm diameter perforated pipe/gravel trench system is conveyed as open channel flow along the grass swale to a grated entry pit and then directly into the underground pipe to the receiving waters.

3. EXPERIMENTAL DESIGN

A series of 8 experimental runs was undertaken on the newly constructed bio-filtration system. Figure 2 shows the experimental setup used during the field investigations, and Table 1 summarises the details of the 8 experimental runs undertaken. Water from a fire hydrant was discharged into a constant-head tank and redirected, via flow control valves, to three inflow points located along the bio-filtration system. Flow conditions corresponding to the peak discharge of the 3 month, 1 yr and 5 yr ARI events were simulated. At each inflow point to the bio-filtration system, flows were simultaneously distributed to the grass swale and underlying gravel trench using splitter boxes, in order to reflect the design operating conditions for the treatment of road runoff (directed to the swale) and roof runoff from the adjacent catchment (discharged directly to the infiltration trench). A series of holes that could be opened and blocked depending on the experimental run being undertaken enabled predetermined flow rates to be achieved out of each splitter box. Flows rates were measured at the downstream end of the system using a v-notch weir. Water samples were collected from inspection wells in the infiltration trench, using automatic samplers.

In actual operating conditions, the gravel trench conveys stormwater generated from the total catchment of all the individual bio-filtration cells. Hydrologic computation shows that saturated flow conditions occur in the infiltration trench for events larger than the 6 month ARI event, corresponding to the discharge capacity of the underlying perforated pipe (ie. approx. 22 l/s). Due to the limited capacity of the water supply, it was not possible to provide the necessary inflow rate of to achieve saturated flow conditions when simulating the 1 year and 5 year ARI flow conditions. Simulation of these conditions was achieved by choking the perforated pipe at the outfall using a riser.

To gain a greater understanding of how the swale component of the bio-filtration system works, the inlet pits to the underlying trench were sealed and water was discharged directly onto the swale at two flow rates of 2 l/s and 4 l/s. Samples were collected at 5 locations along the swale as well at the outfall using auto-samplers.

Figure 2. Experimental Design of Bio-filtration Experiments

Samples were collected at each sampling location prior to the dosing of the system for all experimental runs, to determine pollutant background concentrations. The background concentration of pollutant level was subtracted from the instantaneous pollutant concentrations measured during the experiments, so as not to underestimate pollutant removal efficiencies. Pollutant dosing occurred over a 10 minute period with the pollutants being released directly into the splitter boxes. Two pollutant sets, providing two pollutant concentrations for each flow condition, were used (Table 2). Each pollutant set consisted of Bromide (Br), Total Suspended Solids (TSS), soluble phosphorus (PO_4) and soluble nitrogen (NO_X). The particle size distribution of TSS ranged from 0.4 μm (5 percentile) to 15 μm (95 percentile).

The speciations of these pollutants are not typical of urban stormwater pollutants. For example, TSS generated from a typical urban catchment would have particle size ranging up to 100 μm and larger, and only 10%-15% of TP in urban stormwater is in soluble form. The speciation of TN is more varied, but NO_X is not normally the dominant form of nitrogen in urban stormwater. The derived treatment efficiencies of the bio-filtration system for the various pollutants are consequently expected to be lower than for normal operating conditions.

Bromide is a conservative tracer that enables the pollutographs to be tracked through the system providing the basis for calculating a mass balance for the pollutographs. Laboratory analysis of Br, TSS, TP, TN, PO_4 and NO_x concentrations was undertaken by a registered laboratory.

Table 1. Summary of the Experimental Program

EXPERIMENT RUN NO.	HYDRAULIC & POLLUTANT LOADING	REMARKS
1	▪ Operating as a bio-filtration system ▪ 3 month ARI ▪ Pollutant Set#1	▪ Conducted in 3 cells with flow distributed into property crossover inlet pit (67%) and kerb chute (33%); ▪ 10 minute dosing after establishment of unsaturated steady state conditions.
2	▪ Operating as a bio-filtration system ▪ 3 month ARI ▪ Pollutant Set#2	▪ Conducted in 3 cells with flow distributed into property crossover inlet pit (67%) and kerb chute (33%); ▪ 10 minute dosing after establishment of unsaturated steady state conditions.
3	▪ Operating as a bio-filtration system ▪ 1 year ARI ▪ Pollutant Set#1	▪ Conducted in 3 cells with flow distributed into property crossover inlet pit (60%) and kerb chute (40%); ▪ 10 minute dosing after establishment of unsaturated steady state conditions; ▪ Choke discharge capacity of perforated pipe and dose over 10 minute after establishment of saturated steady state conditions.
4	▪ Operating as a bio-filtration system ▪ 1 year ARI ▪ Pollutant Set#2	▪ Conducted in 3 cells with flow distributed into property crossover inlet pit (60%) and kerb chute (40%); ▪ 10 minute dosing after establishment of unsaturated steady state conditions; ▪ Choke discharge capacity of perforated pipe and dose over 10 minute after establishment of saturated steady state conditions.
5	▪ Operating as a bio-filtration system ▪ 5 year ARI ▪ Pollutant Set#1	▪ Conducted in 2 cells with flow distributed into property crossover inlet pit (33%) and kerb chute (67%); ▪ 10 minute dosing after establishment of saturated steady state conditions.
6	▪ Operating as a bio-filtration system ▪ 5 year ARI ▪ Pollutant Set#2	▪ Conducted in 2 cells with flow distributed into property crossover inlet pit (33%) and kerb chute (67%); ▪ 10 minute dosing after establishment of saturated steady state conditions.
7	▪ Operating as a swale with a high infiltration capacity ▪ Discharge rate - 4 l/s ▪ Pollutant Set#2	▪ Conducted along a 35m length of swale with property crossover inlet pits blocked; ▪ Flow discharged from single point; ▪ 10 minute dosing after establishment of unsaturated steady state conditions.
8	▪ Operating as a swale with a high infiltration capacity ▪ Discharge rate - 2 l/s ▪ Pollutant Set#2	▪ Conducted along a 35m length of swale with property crossover inlet pits blocked; ▪ Flow discharged from single point; ▪ 10 minute dosing after establishment of unsaturated steady state conditions.

Table 2. Pollutant Concentrations for Experimental Program

	Concentration	
Pollutant	Pollutant set # 1	Pollutant set # 2
Bromide (KBr)	1.5 mg/l	1.5 mg/l
TSS (Eckalite 2)	200 mg/l	1000 mg/l
Soluble Phosphorus (KH_2PO_4)	0.01 mg/l	1 mg/l
Soluble Nitrogen (KNO_3)	0.1 mg/l	3 mg/l

Additional work was also undertaken to investigate the presence of bio-films within the gravel trench. This work confirmed their presence and further investigations are planned to identify forms (ie. algae and bacteria) and quantify their abundance.

4. RESULTS FOR THE 3 MONTH ARI EVENT FLOW SIMULATIONS

Flow rates for the experimental runs simulating the 3 month ARI event were approximately 2.5 l/s, with 67% of this flow directed into the gravel trench to represent that component of stormwater runoff generated from the residential allotments. The wetted front along the swale component of the bio-filtration system typically travelled 8 m downstream of each inflow point, being subsequently infiltrated to the underlying trench. The flow path of water in the gravel trench is predominantly in the vertical direction through the 0.8 m layer to the perforated pipe before water flows in the longitudinal direction along the length of the bio-filtration system.

The results for Experimental Run Number 1 (the 3 month ARI simulations dosing with pollutant set #1) were difficult to interpret due to excessive noise in the data. This was due to the dosing concentrations being similar to the background nutrient concentrations within the system. The high background concentrations of pollutant within the system are believed to be the result of the fertiliser application required to rapidly establish grass cover within the swale component of the bio-filtration system. Rapid grass establishment was undertaken by the developers to stabilise the system and protect it from excessive sediment-laden runoff from the adjacent construction site. These high background nutrient concentrations are expected to reduce as the system matures.

Experimental Run Number 2 consisted of much larger pollutant masses dosed into the system and consequently the results were easier to interpret. Figure 3 shows the change in pollutant loads (adjusted for background concentrations) within the bio-filtration system for the 3 month ARI event flow simulation. Analysis of bromide showed a 23% reduction in mass. The loss of bromide is believed to be attributed to a combination of the following factors;

1. minor errors in measuring flow rates out of the splitter boxes and over the downstream v-notch weir, and
2. exfiltration from the bio-filtration system (ie swale and/or trench component) to the underlying soils.

Of the two primary factors listed above, inaccuracy in the estimation of flows at the inlet and outlet of the bio-filtration system is considered the more dominant. Adjustments to the pollutant loads recorded at the sampling stations were made to account for the loss in bromide load when calculating pollutant removal efficiency, since bromide is a conservative tracer and the loss of bromide can not be attributed to pollutant removal mechanisms operating within the bio-filtration system. Without accounting for this loss, an over-estimation of pollutant removal efficiencies would occur. Having adjusted the pollutant loads of TSS, TP and TN for the 23% loss of pollutants from the system, pollutant removal efficiencies for these pollutants were found to be 55%, 24% and 0% respectively. It is evident from Figure 3 that whilst no removal of TN was observed, there was a significant reduction in NO_X (~50%) and suggests that the bio-filtration system may have been a source of organic nitrogen.

Figure 3. Pollutant Removal Effectiveness of a Bio-filtration System (flow rate ~ 2.5 l/s)

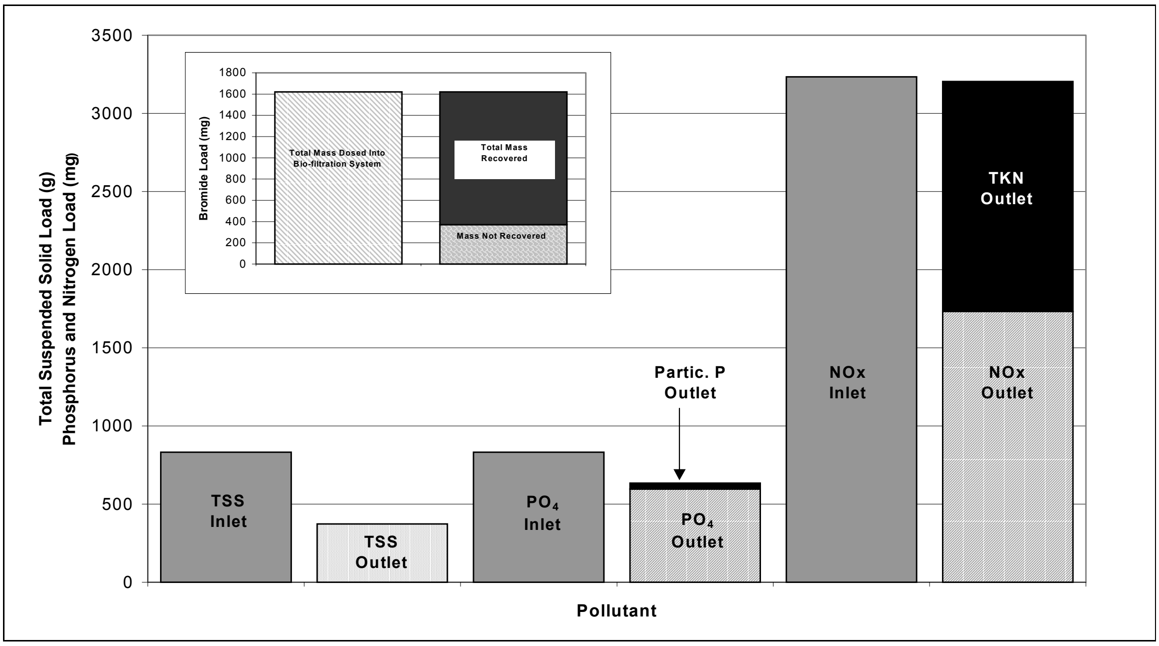
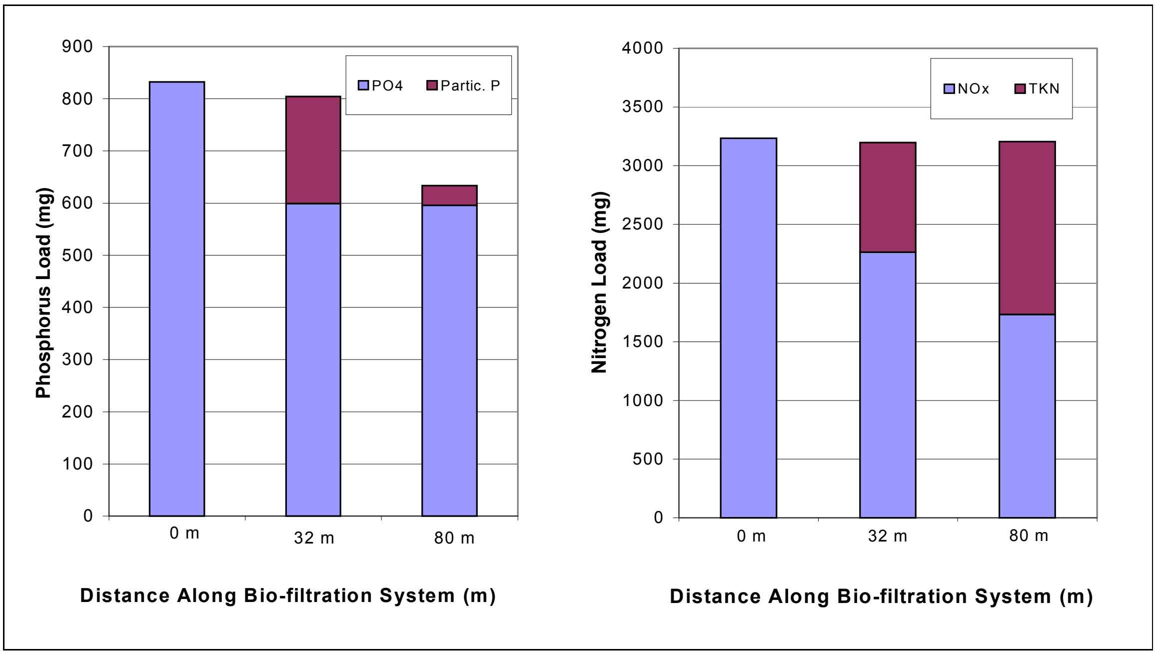


Figure 4 shows the relative proportion of soluble phosphorus and nitrogen to other forms of the nutrients. The mass of soluble phosphorus, which represents the entire phosphorus load dosed into the system, dropped from 830 mg to approximately 600 mg by 32 m downstream from the first dosing point. This soluble load of phosphorus remained constant, thereafter, to the outfall of the system. Approximately 25% of the phosphorus load dosed into the system has presumedly been rapidly bound to the suspended sediment, and subsequently removed via the sedimentation and filtration processes operating in the bio-filtration system.

Figure 4. Relative Proportions of Soluble Nutrient Loads Through the Bio-filtration System



5. RESULTS FOR THE SWALE COMPONENT

The second set of results presented in this paper are for Experimental Run Number 8, where flows were discharged directly into a 35 m section of the swale component of the bio-filtration system, with the pit inlets (located at the crossovers to residential allotments) to the underlying trench blocked. The notional flow path of water is initially that of open channel flow but with progressive infiltration of water through the grass swale and graded sand layer into the gravel trench.

Figure 5 shows 27% the bromide dosed into the bio-filtration system was not recorded 5 m downstream. The plot shows a progressive increase in the proportion of bromide recovered from the gravel trench, reflecting the progressive transfer of flow from the surface flow (swale) component to the sub-surface flow (trench) component of the bio-filtration system. Over the 35 m section of the swale, the proportion of flow conveyed by the sub-surface component of the bio-filtration system increased from zero to in excess of 50%. Adjustments to the observed pollutant loads along the swales were made to account for the 27% discrepancy in the bromide load in calculating the treatment efficiency of TSS, TP and TN.

As is evident in Figure 6, the removal rate of TSS and TP can be described as a function of exponential decay along the bio-filtration system. In total, a 74% reduction in TSS and 55% reduction in TP were achieved. Hence, under these loading conditions the swale component of the bio-filtration system is very efficient at removing TSS, particularly given the finely graded nature of the material used for the experiment. No effective removal of TN was found.

Figure 7 further examines the reduction in TSS along the swale and trench components of the bio-filtration system. Approximately one third of the TSS load at the outfall of the system was recovered from flows that had been infiltrated into and subsequently conveyed within the trench (compared to over 50% of the bromide). It is therefore assumed that the majority of TSS remains within the swale component of the bio-filtration system and that the TSS fraction conveyed within the trench largely represents the colloidal clay fractions (ie, the 5% of original TSS which was less than 0.4 μm in diameter). The migration of this finely graded particulate material into the underlying gravel trench has important consequences for other pollutants bound to their surface.

Figure 5. Bromide Loads Recovered at Each Sampling Point Along the Bio-filtration System

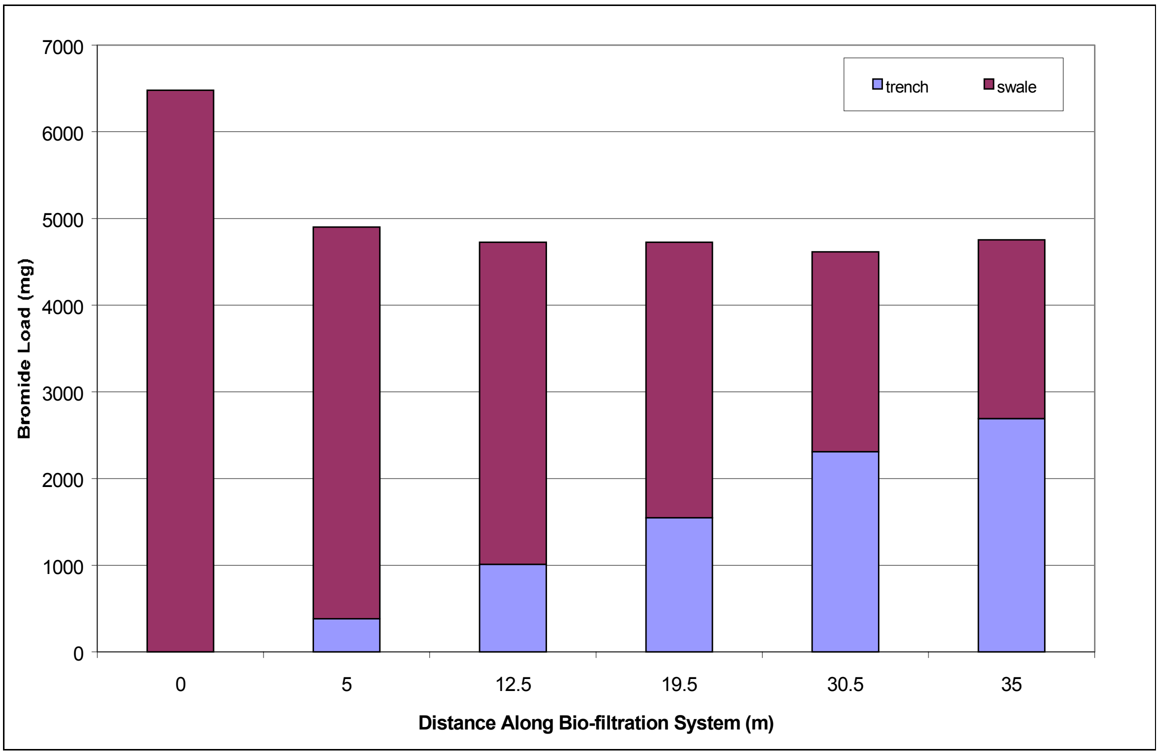


Figure 6. Removal of TSS, TP and TN Along the Bio-filtration System

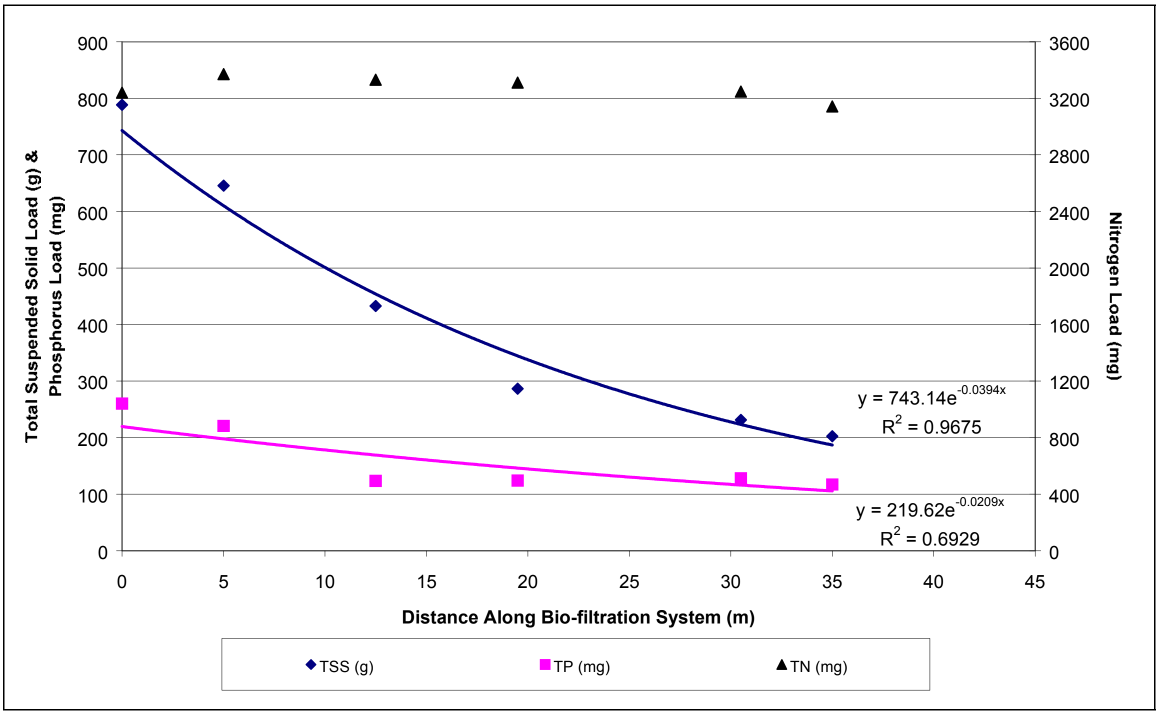


Figure 7.Total Suspended Solid Load Recovered at Each Sampling Point Along the Bio-filtration System

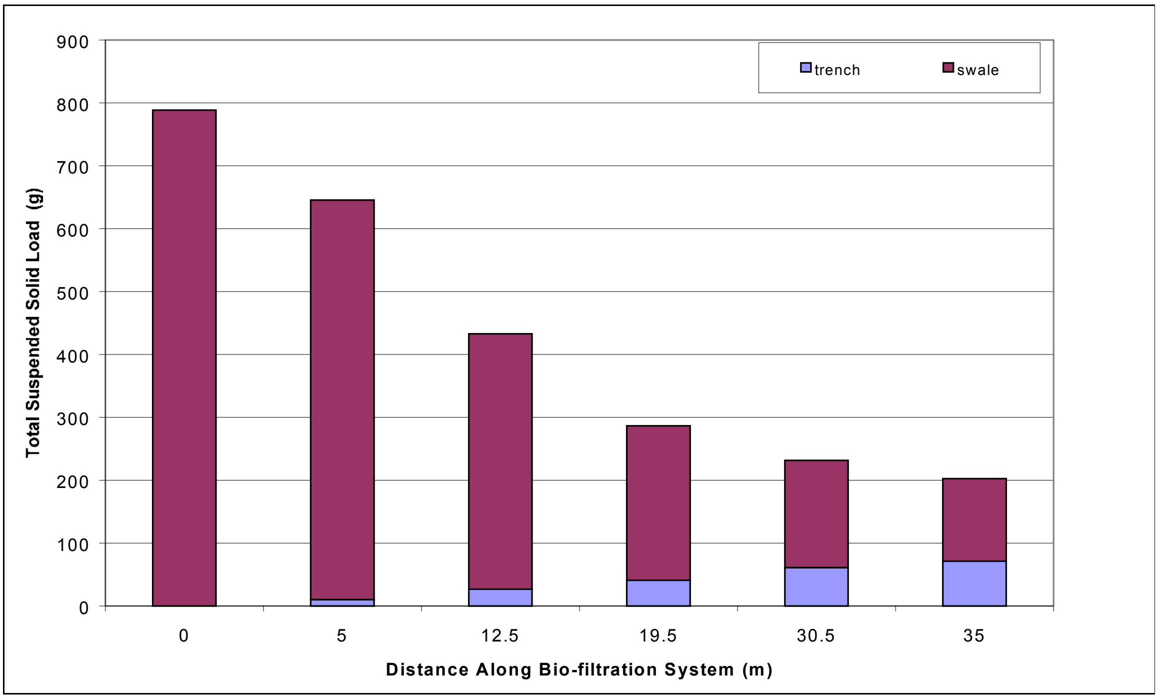
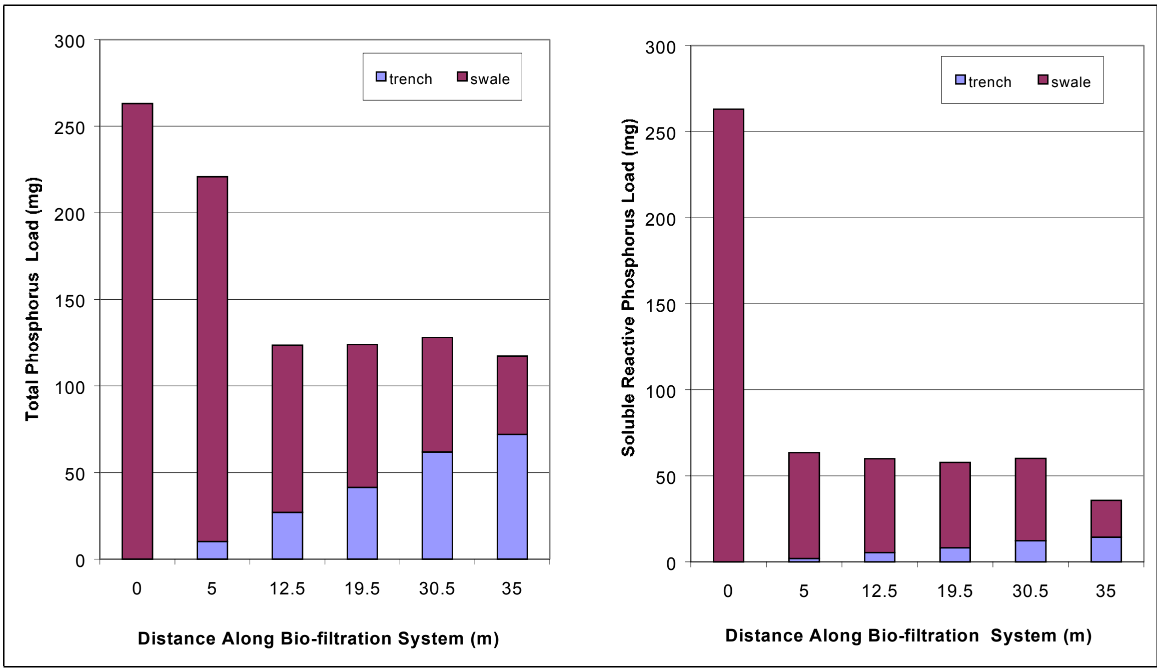


Figure 8 shows that up to 75% of the soluble phosphorus dosed into the system was converted to particulate form within the first 5 m of the swale. This is a significant increase from the 25% conversion of soluble to particulate phosphorus of Experiment Run 2 and may be attributed to the fact that 67% of the flow in Experiment 2 was directly discharged into the gravel trench. The results may suggest that the sediment used in the dosing may not be a suitable binding material for phosphorus and that a higher proportion of phosphorus was binding to in-situ graded sand of the swale. This is a topic for further investigation.

Figure 8. Phosphorus Load Recovered at Each Sampling Point Along the Bio-filtration System



6. CONCLUSION AND RECOMMENDATIONS

The preliminary results discussed in this paper suggest that bio-filtration systems can be an effective stormwater treatment measure. The detention time within the bio-filtration system is only sufficient to promote physical treatment mechanisms and the high pollutant removal rates achieved for TSS and TP are predominantly the result of enhanced sedimentation processes (via filtration and adhesion), along with the adsorption of soluble phosphorus onto finely graded particulates, and their subsequent removal. The results of this study indicate ineffective treatment of soluble nutrients within the bio-filtration system (other than the fraction of soluble phosphorus that binds to available TSS sites). This is not considered to be a serious impediment to effective stormwater treatment as it is well established that a high proportion of phosphorus and metals are transported in urban stormwater in a particulate form. These systems could serve as pre-treatment for the removal of soluble pollutants by downstream treatment facilities such as wetlands. Alternatively, modification of the bio-filtration system design to promote longer detention period and high biofilm growth could be adopted to increase the treatment of soluble pollutants. The consequence of such a modification is the significant increase in the size of these systems.

Bio-filtration systems are shown to have potential water quality benefits within an integrated stormwater management scheme. However, further investigations and refinements are needed to maximise their potential and efficiency. Recommendations for further investigation include;

- assessment of treatment efficiencies of bio-filtration systems with modified design parameters (ie. other forms of swale vegetation, variation in infiltration medium, extended surface ponding, so that filtration and detention times are increased),
- confirm the significance of insitu graded sand in the adsorption of soluble phosphorus, and its implications on bio-filtration design and pathways for stormwater discharging into these systems.

ACKNOWLEDGEMENTS

Many thanks to Andrew Barton who at the time of the fieldwork program was a vacation student working in the Cooperative Research Centre for Catchment Hydrology. Andrew assisted with organising the equipment required to undertake the fieldwork program and helped in the collection of samples during the undertaking of the experimental runs. Thanks also to Tanya Mueller for feedback on the bio-film investigation and willingness to assist with the fieldwork program. Finally, the extensive nature of this field work program could not be undertaken without the help of many hands to assist with the daily set up of the experimental runs and the collection of samples during the undertaking of the experiments. Thanks to Hugh Duncan, Justin Lewis, Anna Wilson, Jane Catford, Lucy Peljo and Matthew Wong for providing assistance in the field when required.

REFERENCES

Lloyd, S.D., Wong, T.H.F., Porter, B. (2001) Implementing an Ecological Sustainable Stormwater Drainage System in a Residential Development, *Proceedings of NOVATECH 2001, 4th International Conference on Innovative Technologies in Urban Drainage*, Lyon, France, June 25-27th, in press.