SUSTAINABLE MANAGEMENT OF STORMWATER USING PERVIOUS PAVEMENTS

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Nilmini P.W.K. Kadurupokune

B.Eng.

School of Civil, Environmental and Chemical Engineering

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RMIT University

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Statement of originality

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program, and any editorial work, paid or unpaid, carried out by a third party is acknowledged.

Nilmini Kadurupokune

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Abstract

Water Sensitive Urban Design (WSUD) is a practice that is emerging throughout the world as a cutting edge initiative adopted to deliver sustainable use of water resources by urban communities. WSUD is a structural initiative that is used for a given set of conditions to reduce the quantity and improve the quality of stormwater runoff in the most cost-effective manner. Pervious pavements have been identified as a successful element of the WSUD concept.

The introduction of pervious pavements for car parks and driveways reduces the runoff volume discharged into urban drains, delays peak flow and improves the water quality by trapping the sediments in the infiltrated water. As a result, the risk to rivers and natural water bodies from pollutants such as suspended solids, phosphorous, nitrogen, heavy metals, oils and hydrocarbons is reduced. Researchers in the UK, Japan, and the USA have noted a significant reduction in runoff volume and improvements to water quality parameters as a result of the use of pervious pavements in place of conventional impervious asphalt pavements. However, the design and application of pervious pavements is site specific and hence it is important to research pervious pavements to adapt them to Australian field conditions.

The key objective of the study reported herein is to establish relationships between rainfall and pervious pavement runoff and quantify improvements to the quality of stormwater infiltrated through the pervious pavement. The objectives of the study include:

- Quantification of the amount of stormwater captured through pervious pavement infiltration
- Assessment of improvement to water quality after stormwater infiltrated through a pervious pavement
- Assessment of the effectiveness of the pavement for infiltration and water quality improvement variation with time; and
- Calibration of an existing computer software package to simulate hydraulic behavior and stormwater quality improvement

A pervious pavement experimental rig built at the RMIT laboratory to test for infiltration characteristics was used to check improvements to stormwater quality by studying the impact

on Total Suspended Solids (TSS), Total Nitrogen (TN), Total Phosphorous (TP), Oil and Greases, heavy metals (Lead [Pb], Copper [Cu], Cadmium [Cd] and Zinc [Zn])), and reduction in infiltration rate due to sediments entrapped by the pavement. The effective lifetime of pervious pavement was determined as a result of this phase of the study.

A full scale experimental car park was built with two types of pavements with pervious surfaces (C&M Ecotrihex pavers and Atlantis Turf Cells) and an impervious asphalt pavement surface as the control. All three pavements were automated to collect stormwater samples and flow measurements using flow meters and automatically triggered water quality samplers. Flow data were used to quantify the captured water as well as to calibrate the PCSWMMPP hydraulic model. The stormwater samples were analyzed for the same parameters as used in the laboratory study. The results were used to test the existing water quality transfer functions in the MUSIC model and to introduce new transfer functions applicable to pervious pavements with concrete block and turf surfaces.

The water quantity results obtained from C&M Ecotrihex and Atlantis Turf Cell surfaces showed a reduction in runoff volume by 50% and 60% respectively and the reduction in peak discharge by 45% and 55% respectively when compared with the surface runoff peak discharge and volume obtained from the asphalt pavement. The average ratio of total runoff to total rainfall (runoff coefficient) obtained from the C&M Ecotrihex pavement was 0.4 and that of Atlantis Turf Cell pavement was 0.3.

The efficiency of stormwater pollutant removal by the C&M Ecotrihex pavement when compared to the conventional asphalt pavement showed a reduction of TSS, Zn and Oil by 90%. Similarly the pollutants passing through the Atlantis Turf Cell showed 91%, 88% and 95% reductions respectively. The removal efficiencies obtained for TN and TP were 40% each from the Atlantis Turf Cell pavement and 50% and 60% for the C&M Ecotrihex pavement. However, both pervious pavements showed lower reductions in nutrients due to the decomposition of the granular material used within the pavement structure. This factor requires further investigation.

Clogging has been identified as a major concern in the application of pervious pavements. The results obtained from the laboratory test rig reveal that the reduction in hydraulic conductivity over 17 years of continuous simulation of the C&M Ecotrihex pavement was only 10% of its “as constructed” value. Even after 17 simulated years, the pavement showed better removal efficiencies from the C&M Ecotrihex pavement. When compared to the environmental benefits, remediation after about 35 years is not considered a barrier to the use of pervious pavements in practice.

The field experimental results were used to calibrate the PCSWMMPP model and to develop water flow and quality improvement transfer functions of the MUSIC model for concrete block and turf cell pavements.

The research reported herein has demonstrated that pervious pavements can be introduced as a sustainable stormwater management initiative and as a key Water Sensitive Urban Design feature to deliver numerous benefits to the environment. The outcomes from the study will be useful in designing environmentally friendly car parks, pedestrian paths, light traffic drive ways, sporting grounds and public areas in the future. Land developers and local government authorities will be major beneficiaries of the study which has increased the understanding of the use of pervious pavements and explored a number of issues that previously inhibited the wider use of pervious pavements in practice.

1 INTRODUCTION

1.1 Background of stormwater management

Urbanisation causes significant changes to the natural water cycle. Recently, in urban areas flooding and drought have increased in severity due to climate change coupled with urbanisation. Australia has been suffering from severe droughts (since 1998 in Victoria) and extreme floods (South East Queensland floods 2008) and authorities have come to recognise the need for improved stormwater management as an alternative solution to droughts and urban flooding. Due to severe drought, the water levels in major storage reservoirs have been drastically reduced in Melbourne to 34 percent of their full capacity at the time of writing (www.melbournewater.com.au, 2007). Water authorities throughout Australia have introduced water restrictions to their customers as a means of managing water shortages.

The most apparent effect of urbanisation on catchment hydrology is the increase in the magnitude of stormwater flow into natural waterways which causes flooding, river degradation and soil erosion and affects public safety. The precipitated water flows over impervious surfaces polluting receiving waters and exacerbating floods. Impervious surfaces directly reduce the water-retaining function of the soil in the urban landscape. This loss may be absolute, because water that previously recharged groundwater, now flows rapidly across the land surface and arrives at the stream, possibly causing floods. Water is also lost by evaporation from impervious surfaces.

The increasing public consciousness of environmental issues in recent times has led to raised awareness of the importance of better managing urban stormwater. According to results documented by researchers (Fletcher et al., 2003), urban stormwater quality is worse than the runoff from a rural catchment. Poor stormwater quality together with hydrologic impacts associated with increasing peak flow, cause degradation of the environment, affecting the aquatic ecosystems in the urban environment.

The prime objective of stormwater management is to minimise the downstream impacts of urbanisation through the implementation of appropriate policy (Victorian EPA, 1999). Newton (2005) defined design objectives for effective urban stormwater management as the control of peak discharges to minimize flooding causing public inconvenience and promote stable stream morphology, control of water quality to protect receiving waters, and control of runoff volume and flow duration for smaller events to protect stream morphology and hence riparian habitat.

The urban stormwater best practices, Environmental Management Guidelines; (Victorian Stormwater Committee, 1999) require a 45% reduction in nitrogen, a 45% reduction in phosphorous and an 80% reduction in suspended solids concentrations in stormwater.

The department of Environment and Heritage, Australia reported urban stormwater pollutant concentrations for Australia in the State of the Environment Report 2001 (Newton, 2001). According to this author, the Australian urban stormwater pollutant concentrations are well above the regional water quality standards recommended by EPA Victoria. Therefore, treating stormwaters before they divert to receiving waters is of vital importance. Most Water Sensitive Urban Design (WSUD) techniques treat the stormwater at the source to reduce the pollutant levels to acceptable concentration levels. Combinations of different types of treatment techniques (Treatment trains) will give better results than a single treatment device.

WSUD is the integration of water cycle management into urban planning and design. The key principles of Water Sensitive Urban Design as stated in Urban Stormwater – Best Practice Environmental Management Guidelines (Victorian Stormwater Committee, 1999) are to protect natural systems, integrate stormwater treatment into the landscape, protect water quality, reduce runoff and peak flow and add value while minimising development costs. The introduction of a pervious pavement addresses all five principles listed above in WSUD.

Consistent water quality performance standards have been observed from pervious pavements, with reductions in TSS, TP and TN of around 70% to 100%, 40% to 80% and 60% to 80% respectively (Fletcher et al., 2003; Berbee et al., 1999; Bond et al., 1999; Pagotto et al., 2000; Pratt, 1999). Hydrocarbon and metal reductions are commonly around 85% and 75% respectively. These results reveal that pervious pavement itself has an ability to meet the water quality standards recommended by EPA Victoria. Reduction in water quantity (through infiltration), together with its ability to filter pollutants through the structure, render pervious pavement an effective WSUD technique. If the infiltrated water could be harvested, it could be productively reused with the appropriate level of treatment.

1.2 Pervious pavements

A pervious pavement is a structure that allows water to permeate through its structure while being capable of bearing dynamic loads. It overlies a reservoir storage layer. The water holding capacity of the sub-base is of vital importance to reduce peak runoff. The main difference between a pervious and a conventional pavement is the permeability of the surface and the water holding capacity of the sub-base. Pervious pavements reduce the flood peaks and improve the quality of stormwater at source before it is transported to receiving waters as they entrap pollutants. The water first infiltrates through the pavement to a sub-base reservoir from where it infiltrates slowly to the sub-grade soil and/or to drains or to storage for re-use. By reducing peak flow rates and volumes in downstream receiving waters, pervious pavements decrease overland flows and recharge groundwater. This phenomenon can help return the urban water cycle close to its natural condition increasing groundwater recharge and decreasing the pressure on new and existing urban infrastructure. Pervious pavements have an ability to reduce pollutants in stormwater runoff at source before pollutants are transported to receiving waters.

Improvement to receiving water quality benefits the health of the eco-system and protects recreational interests. Jayasuriya et al (2006a) concluded that the poor quality of stormwater is one of the factors limiting the use of stormwater for fit-for-purpose productive use. Pervious pavements have the potential to reduce pollutants in stormwater and improve its reusability. Research reveals that the best way to filter out pollutants from stormwater is to filter it through the ground while recharge the aquifer (www.perviouspavement.com). Pervious pavement permits this to occur freely and naturally without having to incorporate expensive water diversion and treatment systems.

Pervious pavements promote the penitration of stormwater into neighbouring soils. Therefore, the performance of pervious pavement is highly dependent on surrounding soil characteristics. Pervious pavements can be designed in two different ways depending upon the diversion method of captured water. One way of designing is to provide an impervious geotextile under the pavement structure and capture the infiltrated water through perforated pipes installed underneath the pervious pavement structure and harvest the collected water. This design is suitable for sites with clay soil. Usually, sandy soil with deep groundwater is best suited for pervious pavements that are designed to recharge groundwater. They reduce runoff and provide pollutant retention on site. In general, these pavements are perfectly suited to highly permeable soils, so that water can infiltrate at an appropriate rate. Areas with lower permeability soils can still be suitable, but greater depth of the reservoir storage layer for infiltration and detention storage volumes are required. Pervious pavements also require sufficient set-back distances from structures to avoid any structural damage. Distances depend on the local soil structure.

Pervious pavements can be categorised as porous pavements or permeable pavements. Even if the benefits of both are the same, they vary significantly in the way they operate and in their appearance. The basic operating principle behind pervious pavement is permeability. Permeability is a measure of the ease with which a fluid can flow through a porous medium. Permeability depends on the physical properties of the medium, for example grain size, porosity and pore shape and/or 'slotting'.

Porous pavements (Figure 1.1) can be defined as specifically designed and constructed pavement structure that encourage rapid infiltration and percolation of rainfall and stormwater through the entire pavement cross-section, and maintain this function over many decades, while directly supporting traffic loads.

Permeable pavements (Figure 1.2) are constructed from pre-cast blocks that are impervious, assembled in such a way that there are gaps (voids) between interconnected blocks. The block paved surface allows the passage of water through voids between the paving blocks to the underlying reservoir structure.

Depending on the type of pervious surface, use is limited to pedestrian areas, drive ways and private or shopping centre car parks. Therefore, the performances of such systems are diverse and include technical aspects as well as environmental, economic and social aspects.

Research into managing stormwater using pervious pavements is in its infancy in Australia. Groundwater contamination, pavement clogging and durability are some current issues in pervious pavements. These issues need to be addressed before accepting pervious pavements as a suitable means for managing stormwater and incorporating into WSUD. An extensive literature review suggests properly designed pavements could effectively entrap a majority of sediments, nutrients and heavy metals in stormwater and functions well in the urban environment. Some maintenance would be required from time to time to remove clogging.

Figure 1.1 An example of a Porous Pavement

Figure 1.2 An example of a Permeable Pavement

(http://www.highwaysmaintenance.com)

1.3 Objectives of the Investigation

The key objective of the study is to establish relationships between rainfall and pervious pavement runoff and quantify improvements to stormwater quality infiltrated through the pervious pavement. The experiments were carried out on a pavement rig built in the RMIT laboratory as well as at an upscaled pervious pavement site in the field, where a traditional car park was converted to test two types of pervious pavement types manufactured commercially. Stormwater infiltrated through the pavements was captured via a properly designed drainage system and compared with the surface runoff quantity and quality of the water flowing over a conventional asphalt surface (the basecase.)

The main objectives of the study:

- Quantifying the amount of stormwater captured through pervious pavement infiltration;
- Assessing improvements to water quality after stormwater infiltrated through a pervious pavement;
- Assessing the effectiveness of the pavement for infiltration and water quality improvement with time (clogging potential);
- Calibrating an existing computer software package to simulate hydraulic behaviour as well as stormwater quality improvement when passing through a pervious pavement to facilitate design.

1.4 Outline of Thesis

The laboratory and field investigations undertaken to achieve the above objectives of the thesis are detailed in the following five chapters.

Chapter 2 provides a review of the literature in relation to pervious pavements in the context of urban stormwater management. The stormwater quantity reductions through pervious pavements are discussed, followed by stormwater quality improvement by infiltration through pervious pavements. Researh on limitations and maintenance required of pervious pavements is also reviewed in this chapter.

A laboratory-scale pervious pavement rig was used to investigate water quality improvement and quantity reduction by infiltrating through pervious pavements. Chapter 3 provides an overview of the experimental setup in the laboratory and presents results obtained from the study. The experimental procedures and analysis of data carried out to obtain the effective life of the pervious pavement surface (before clogging) are also presented in the chapter.

The study examines two types of pervious pavement surfaces. Chapter 4 presents the site description, experimental setup, instruments used and the data collected in the field. The analysis of water quality and quantity data together with the comparison of results from the asphalt surface (base case) are also presented in the Chapter.

The field data were used to calibrate the PCSWMMPP hydraulic model parameters and to improve the water quality transfer functions of the MUSIC model. Chapter 5, describes the application procedure of the above two computer models, the calibration procedure and the testing of sensitive parameters.

Chapter 6 presents a summary of the research conducted and the conclusions drawn from the thesis. Recommendations for future work, based on the findings of this research project, are also presented in Chapter 6.

2 PREVIOUS APPLICATIONS ON PERVIOUS PAVEMENTS

The necessity of managing stormwater runoff from urban areas was recognised by some of the earliest civilisations (Webster 1962). The introduction of impervious areas has been identified as the major cause of urban stormwater problem. Increased industrialisation and growth in the use of motor vehicles have introduced a runoff quality problem. As reported in the earlier chapter, the use of pervious pavements in light traffic areas such as car parks and driveways can improve stormwater management. Pervious pavements have been in use in Europe, USA and Japan for about two decades. A significant amount of research has been carried out to investigate the ability of pervious pavements to reduce stormwater runoff and improve quality (Booth, 2003; James and Thompson, 1995; Legret et al., 1996).

Booth (2003), James and Thomson (1995) and Legret et al. (1996) examined the reduction in water quantity and contaminants in runoff from different pervious pavements such as Uni Eco-stone, concrete brick and porous asphalt surfaces due to infiltration of surface runoff.

The research carried out on different types of pervious pavements is reviewed in this chapter. Most of the research has been carried out on:

- Reduction in surface water quantity flowing into receiving waters;
- Improvements to water quality;
- Asset maintenance required; and
- Limitations of pervious pavements.

The review will be carried out under the above headings. The literature review will cover:

I. reduction in stormwater quantity and rainfall and runoff relationships due to infiltration through pervious pavements;
II. the reduction in infiltration rate with time due to clogging of the pavement;
III. improvements to stormwater quality and the deposition of pollutants with infiltrated depth;
IV. maintanance requirements and the limitations of pervious pavements.

2.1 Hydraulic performance of pervious pavements

2.1.1 Reduction in surface water quantity flowing into receiving waters

Urbanisation drastically reduces pervious areas. The ultimate result of an increase in impervious areas is the null capability of absorbing water into the soil surface. This will totally end the natural filtration of pervious areas. The aftermath of the increase in impervious areas could result in sudden floods, even for small rain events.

A number of researchers (Pratt et al., 1995; Smith, 1984; Abbott et al., 2000) have carried out laboratory and field experiments to investigate the reduction of flows (peak and volume) due to the introduction of pervious pavements in lieu of impermeable concrete or asphalt surfaces in urban areas. All noted a significant reduction in flows and improvements to water quality by using pervious pavements instead of conventional pavements.

Hogland et al. (1987, 1990) and Larson (1990) in Sweden reported the use of pervious pavements (Porous Concrete Asphalt) as early as the 1980s for car parking areas and for roads and driveways in residential developments. The infiltrated water was drained from the sub-base into the stormwater drainage system. These pavements were also designed to increase the groundwater recharge and to reduce the pressure on the drainage infrastructure. The construction of these pervious pavements successfully reduced the volume of stormwater discharged by about 40% compared to the total discharge from an impervious surface.

In Nottingham a permeable concrete block car park was monitored for stormwater discharges (Mantle, 1993; Pratt et al., 1989; 1990 and 1995). Being completely enclosed within an impermeable membrane, outflow was limited to flows from the sub-base drains and to evaporation from the surface. On average there was a 40% reduction of the volume of stormwater discharged as compared with the performance of traditional impermeable surfaces, which discharge close to 100% runoff to the drainage system within the storm duration. The amount of water discharged depends on the sub-base material. The above authors also observed that the reduction in runoff varied by 34% and 47% when sub-bases were blast furnace slag and granite respectively. This is due to the water storage capacity in the pavement structure due to surface wetting and absorption. According to the reserchers, during some storms, the start of discharge from the sub-base drain was several hours after the commencement of the rainfall event. As a result they observed that the outflow hydrograph of the pervious pavement car park was markedly different from that of a traditional, impermeable one. A full description of the study carried out in Nottingham will be described under water quality improvement in Section 2.2.

Smith (1984) carried out a study on comparison of runoff reductions from two different surfaces in the City of Dayton, Ohio. One car park was surfaced with grass-concrete and the second was surfaced with impermeable asphalt. The observations showed that runoff volume from the grass-concrete pervious car park into the drain ranged from 0% to 35% of the runoff from the asphalt surface. The storm for which the highest percentage of runoff was monitored from the pervious surface was not the largest storm, but one which followed immediately wet day, from which there had been no runoff. This is an indication that antecedent moisture conditions are important, and the number of dry days between storms determines the effectiveness of the pavement to absorb stormwater.

Abbott et al. (2000) provided similar observations at the Wheatley Motorway Service Area, Oxford shire in England from a porous concrete block-surfaced car park. The car park area monitored was 6250m^2 and surfaced with porous concrete blocks. The amount of water drained from the sub-base during events varied from 4% to 47% of the rainfall volume, with an average value of 22.5%. Some events took as long as 2 to 3 days for flow to cease. The peak outflow was markedly reduced (at Wheatley, a peak rainfall intensity of 12mm/h was reduced to 0.4mm/h at the outflow); the duration of discharge was extended, (sometimes considerably); and there was a significant lag between start of rainfall and start of outflow (at the Bank of Scotland car park this varied from some 40 to140 minutes). If a subsequent event occurred before runoff had eased, the flow was superimposed on the previous event discharge. This introduced the phenomenon of a ‘base flow’ release from the sub-base.

Smith (1984) and Abbott et al. (2000) further revealed that the hydrographs obtained were strongly affected by the antecedent conditions. In some instances, base flow from previous storms existed for several days, and subsequent rainfall events ugmented flow.

According to Day et al. (1981), the mean percentage surface runoff from two large elemental permeable block surfaces was almost zero compared to 78% from a concrete paved surface. Their results showed that pervious pavements could absorb almost all the runoff generated through voids in them.

Table 2.1 summarises the reduction in runoff volume from different types of pervious surfaces based on earlier research. Based on case studies, all types of surfaces (eg. porous and permeable) have reduced runoff volume up to 47% compared to runoff from an impermeable surface.

Table 2.1 Summary results: the reduction of runoff volume from different pervious surfaces based on literature

Pavement type	Reduction in volume (%)	Study reference
Porous concrete asphalt	40	Hogland et al. (1987; 1990), Larson (1990)
Permeable concrete block surface (Blast furnace slag sub-base)	34	Mantle, (1993); Pratt et al., (1989; 1990;1995)
Permeable concrete block surface (Granite sub-base)	47	
Permeable grass concrete	0 to 35	Smith (1984)
Porous concrete block surface	4 to 47 (Average 22.5)	Abbott et al. (2000)

2.1.2 Reduction in the infiltration rate with time

The surface infiltration rate depends on the pervious surface, bedding and sub-base materials. Infiltration rates for porous concrete asphalt surfaces have been measured as high as 40,000-60,000mm/h, but values are typically far lower and change with time as debris accumulates in pores in the surface or in inlets (Pratt et al., 1995).

Borgwardt (1994) from the Institute for Planning Green Spaces and Landscape Architecture has conducted a research on UNI ECO-STONE permeable paving. It was said that high permeability is guaranteed when it is constructed with gravel 2-5 mm chips in the drainage openings. The permeability was 10^{-2} m/sec 'as laid'; this number decreased over time. After 5 years, permeability was 10^{-3} m/sec. Borgwardt's study showed that the permeability of the pavement was reduced with usage.

Abbott et al. (2000) reported results from tests conducted at a new car park, surfaced with small element concrete blocks. The infiltrations through the block surface itself and through the gaps between blocks were 550mm/h and 27,000mm/h respectively. At a similar car park, but after some years of use, it was noted that the presence of dirt and oil spillage on the pavement significantly reduced the infiltration rates from both the blocks and the gaps between them. The surface infiltration rate of the porous blocks was assessed, both through the blocks themselves and via the gaps between blocks. There was a large variation in the block infiltration rate (250 to 14,000mm/h), which was also the case with the tests on the gaps, but here the infiltration rates were 50 times higher (11,000 to 229,000mm/h). The infiltration tests were repeated after a 10 month interval, and revealed that the blocks in some cases had become largely impermeable due to clogging, although the gaps still performed well.

The same permeable concrete blocks as used at Nottingham (Pratt et al., 1989) were used at Shire Hall in England for the surfacing of infiltration trenches along one side of a 6500m^2 block-paved car park. The car park, constructed in 1986, was graded to fall to one side, where a one meter wide infiltration surface intercepted the runoff. At installation, the infiltration rate of the concrete block surface, which contained a regular pattern of 50mm diameter, gravel-filled holes for inflow was 4,500mm/h. After six years use, the infiltration rate of the surface was 2,600mm/h, which was still sufficient to ensure full interception of runoff, equivalent to a rainfall intensity on the whole car park of 60mm/h (Pratt et al., 1989).

Australian researchers, Suarman et al. (1999) carried out a laboratory study applied to four potential permeable substructures or permeable surfaces conducted over a period of 24 simulated years. The simulation study used a sediment concentration inflow (80 mg/L), comparable to those which could be expected in the substructures beneath permeable car parks in stable and fully established Adelaide suburbs. Failure of the construction was said to be when hydraulic conductivity of the primary filter systems (upper 50 mm of substructure) falls to 1/3 of the ‘as constructed’ value. To achieve this condition 25 years (or longer) of sediment input was required for the four beds tested.

Valkman (1999) performed a laboratory study on the substructure of permeable pavings. 30 years of sediment loading was simulated via accelerated loading techniques. A sediment load of 200 mg/L was applied. Four different substructures were tested, two substructures for “Grasspave” and two substructures for “Formpave” (type of concrete block pavement). It was found that after simulating 5 years of sediment loading, the hydraulic conductivity dropped to 10% of its initial value. The hydraulic conductivity decreased until it reached equilibrium after 20 years in 3 laboratory pavements. The hydraulic conductivity 20 years after construction was approximately 2% of its “as constructed” conductivity value. For the substructure with 5 mm and 20 mm crushed rock the reduction in conductivity reached equilibrium after 40 years at approximately 8% of its “as constructed” conductivity value.

The Urban Water Resources Centre (2002a), at the University of South Australia has tested a laboratory model which consists of four test beds (Two test beds from BORAL Formpave, ROCLA Ecoloc and Grasspave). Two test beds containing BORAL Formpave blocks were installed in the rig, one of which was subjected to daily (equivalent to yearly) surface cleaning with stiff brush and vacuum to simulate a field street sweeping device. The second test bed was not cleaned. The results revealed that the hydraulic conductivity through the BORAL Formpave test beds was predictably high at the commencement of the test. Hydraulic conductivity declined throughout the 35 years from 4.8×10^{-2}m/s to 1.9×10^{-2}m/s (average of both test beds), an average reduction of 59%. Hydraulic conductivity of the ROCLA Ecoloc was similar to the BORAL Formpave test beds, though slightly lower throughout. Grasspave exhibited a hydraulic conductivity an order of magnitude lower again than the other three pavements under test. This was due to the propagating sand content in the base material and within the Grasspave mat. Sediment input equivalent to 35 years was simulated and sprayed over permeable surfaces over a period of 420 months. Over the 35 year simulation test ROCLA Ecoloc and Grasspave experienced declines in hydraulic conductivity of 68% and 75% respectively.

The University of South Australia used four existing permeable pavement sites in Adelaide to carry out their research on field studies. They are Kirkaldy Avenue (BORAL Formpave), Victoria Road car park (BORAL Formpave), Fletcher Lane (ROCLA Ecoloc) and St. Elizabeth’s Anglican Church (Grasspave). At all four sites hydraulic conductivity tests were carried out and the results showed that clogging occurred at a rapid rate at locations where runoff flowing onto the pavement was concentrated. It also revealed that the hydraulic conductivity was very high in locations where permeable pavements are subjected to rainfall only.

Based on the studies reported above, Table 2.2 summarises the reduction in infiltration rates or hydraulic conductivity with time due to clogging in different types of pervious surfaces. In some of the reported studies the infiltration and the hydraulic conductivity reduced considerably (as high as 75% - 90%). Furthermore, in the results reported by Borgwardt (1994) the permeability dropped by 90% within 5 years. Valkman (1999) has observed that the hydraulic conductivity varied with the size of the subbase aggregates.

It is important to maintain the surfaces with regular cleaning programs in order to retain a high infiltration rate. It is also important to minimise the pollutants coming from the surrounding area on to the surface. This could be achieved by integrating other WSUD features before the pervious pavement. For example the construction of a swale around the pervious pavement car park before the stormwater is washed off on to the surface would greatly assist the longevity of the pavement.

Table 2.2 Summary of reduction in hydraulic conductivity and infiltration rate

Pavement type	Performance	Reference
Permeable Concrete Block Porous asphalt concrete	After 6 years of usage, reduction in infiltration 42%	Pratt et al. (1989) Pratt et al. (1995)
Permeable Concrete Block (BORAL Formpave) Permeable Concrete Block (ROCLA Ecoloc) Permeable Grasspave	After 35 years reduction in infiltration 59% 68% 75%	University of South Australia (2002a)
Four Permeable car parks	After 25 years, Ks dropped by 33%	Suarman et al. (1999)
Permeable Concrete Block (UNI ECO-STONE)	After 5 years, permeability dropped by 90%	Borgwardt (1994)
Permeable (concrete block)	Infiltration dropped by 54.5% (through blocks) and 48.2% (through gaps)	Abbott et al.(2000)
Permeable Grasspave Permeable Concrete Block (Tested for 2 different subbases)	Depending on the subbase 20 to 40 year for equilibrium Ks dropped to 2% to 8% of as built condition	Valkman (1999)

2.1.3 Rainfall and runoff relationships from pervious pavements

In the Nottingham study, Pratt et al. (1995) revealed that the initial wetting loss before drain discharged from the pavement was 2.4 to 3.2mm, dependent upon the stone type used for the sub-base. These authors also found that the concrete surfacing blocks could absorb as much as 4 to 5mm of rainfall with a runoff coefficient (ratio of runoff to rainfall) varying between 0.7

and 0.8. In the same study, Mantle (1993) reported a loss rate from a specimen area of the concrete block paved car park structure of 0.2 to 5.5mm/day. This would amount to a considerable effective depth over time when compared with the total rainfall.

Hunt et al. (2002) describe the early results from three types of permeable pavements constructed in North Carolina, USA, as full-scale research facilities from which to determine the impact of reduction in surface runoff. At one site in Kingston, the pavement had a portion surfaced with a grass-concrete block system ($634m^2$) and a second with a grass-plastic grid system ($244m^2$). Monitoring began in June 1999 and data were restricted to events with at least 12.7mm of rainfall. Fifty such storms have been recorded, of which only 12 produced any measured surface runoff. Based on the results obtained for the study, a rational runoff coefficient ranges from 0.20 to 0.50. This compares with the 0.9 for an asphalt surface.

The surface runoff infiltrated from a porous concrete block-surfaced car park at the Bank of Scotland, South Gyle, Edinburgh has been monitored for both quantity and quality parameters (Schluter and Jefferies, 2001). The discharge volume was just under 50% of rainfall, with the initial wetting loss before outflow began being of the order of 1.65mm and heavily influenced by the antecedent conditions observed by other researchers ((Pratt et al., 1995; Hunt et al., 2002).

Kellagher et al. (2003) discussed hydraulic design criteria for WSUD systems and observed that pervious pavements mimic greenfield site characteristics without the need for throttling devices to be installed, allowing outflows to be restricted to 1 or 2 L/s/ha. They review the current modelling capability for pervious pavements and note the difficulties which remain in estimating key parameters, such as ‘initial loss’ and seasonally variable factors such as ‘evaporation’.

Table 2.3 presents the initial loss values and runoff coefficients obtained from different types of pavements carried out by other researchers (Pratt et al, 1995; Hunt et al., 2002; etc.)

The summary of the studies of rainfall and runoff relationships from different pervious surfaces indicates that both porous and permeable pavements achieved high runoff coefficients and loss rates that are very similar to natural permeable grasslands. Therefore, the application of pervious pavements can be considered as key to sustainable stormwater management practice.

Table 2.3 Rainfall and runoff relationships from different pavement types

Pavement surface type	Parameter	Reference
Concrete block (Permeable)	Runoff coefficient 0.7- 0.8	Pratt et al. (1995)
Grass concrete (Permeable) Grass plastic (porous)	Runoff coefficient 0.2- 0.5	Hunt et al. (2002)
Concrete block (Permeable)	Initial wetting loss 2.4 – 3.2 mm	Pratt et al. (1995)
Concrete block (Permeable)	Loss rate 0.2 – 5.5 mm/day	Mantle (1993)
Concrete block (Permeable)	Initial wetting loss 1.65mm Runoff coefficient 0.5	Schluter and Jefferies (2001)

2.1.4 Modelling of flows from pervious pavements

James et al. (2003) developed the StormWater Management Model for Permeable Pavements (PCSWMMPP), a computational model to predict the hydraulic performance and assist the design of the drainage system for pervious pavements especially permeable pavements. The model uses Manning's equation to calculate the surface runoff volume, the Green and Ampt infiltration equation (Mein and Farrel, 1974) to calculate the infiltration rate through the bedding layer, and Darcy's Law (James et al., 2003) to calculate the percolation rate through the sub-base layer.

Jayasuriya et al. (2006b) reported that algorithms in the PCSWMMPP model can be successfully used in hydraulics calculations when designing permeable pavements. Zhang et al. (2006) successfully estimated all parameters of the Green and Ampt infiltration algorithm and Darcy's equation in the laboratory from physical properties of the aggregates.

Shackel et al. (2003) used PCSWMMPP to design the drainage of the permeable pavement and Lockpave-Pro2001 to design the pavement structure at Smith Street, NSW, Australia. According to the Lockpave-Pro2001 and PCSWMMPP models the thickness of the sub-base layer was 200mm for the maximum design rainfall. The researchers were satisfied with the performance of the constructed permeable pavement with the results obtained from LOCKPAVE-Pro2001 and PCSWMMPP models.

2.2 Stormwater Quality Improvement Through Pervious Pavements

Wash off material from impervious surfaces is an overland flow phenomenon, and appears to be associated most strongly with rainfall intensity (Duncan, 1999). Rapid urbanisation converts pervious surfaces into impervious surfaces. Duncan (1999) has carried out an extensive review of urban stormwater quality processes. According to Duncan's study, build-up of contaminants on impervious surfaces is one of the major processes that contribute to urban stormwater contamination. Newton (2001) and Duncan (1999) reported that on average, the level of stormwater contamination observed in Australia exceeds the national stormwater quality guidelines.

Newton (2001) stated that stormwater quality varies greatly between locations, although the values quoted in Table 2.4 provide a guide to the typical range in contaminant concentration observed in urban areas across Australia. These above authors also presented stormwater parameter values reported in urban areas worldwide for comparison. On average, the level of stormwater contamination observed in Australia is greater than that recorded in other parts of the world and exceeds the stormwater quality guidelines recommended by the Victorian State Environment Protection Policy (SEPP) (Government of Victoria 1988).

Table 2.4 Comparison of urban stormwater contaminant concentrations from Australia with world data (Newton, 2001)

Pollutant	Guidelines for Australian urban waterways (mg/L)	Australian data set (mg/L)		World data set (mg/L)	
		Mean	Range	Mean	Range
Suspended solids	50 (90)	141	42-478	148	45-490
Total nitrogen	0.9	2.63	1.29-5.37	2.51	1.12-5.62
Total phosphorus	0.1	0.24	0.08-0.72	0.32	0.12-0.82
Lead	0.005	0.1	0.01-0.74	0.12	0.03-0.5
Zinc	0.05	0.63	0.23-1.7	0.25	0.08-0.78
Cadmium	0.002	0.007	0.003-0.018	0.003	0.0007-0.01
Chromium	0.01	0.03	0.01-0.11	0.02	0.005-0.08
Copper	0.005	0.06	0.012-0.18	0.05	0.02-0.17
Nickel	0.15	0.02	0.01-0.04	0.03	0.02-0.07

As mentioned in the introductory chapter, pervious pavements have an ability to trap the sediments as well as other pollutants such as total nitrogen, total phosphorous, heavy metals, greases and oil in the infiltrated water and improve the water quality that will otherwise flow to receiving waters.

2.2.1 Improvements in trapping pollutant parameters

A number of researchers (Hogland et al., 1990; Schluter and Jefferies, 2001; Dierkes et al., 2002; Thompson and James , 1995; James and Shahin, 1997; McDonald and Jefferies, 2001; Pratt et al., 1995) have carried out research to investigate the amount of pollutants that could be removed by infiltrating the surface water through different types of pervious pavement surfaces (ROCLA ecoloc, BORAL Formpave, Grasspave and Porus asphalt). Results obtained from all the studies are consistent. The pollutant levels from conventional asphalt surfaces were always higher than from different types of pervious pavements. All studies reported that pervious pavements reduced surface runoff contaminant loads.

James and Shahin (1997) and Hogland et al. (1990) completed laboratory studies on leachate from pervious pavements. Runoff collected from a laboratory pervious pavement showed very low concentrations of water quality parameters such as TSS, hydrocarbons (oil and greases, phenols) heavy metals (Cr, Al, Cd, Cu, Zn, Pb, Ni) and bacteria. James and Shahin (1997) reported that percolation through the pervious pavement structure increases the detention time through its slow water flow which allowed more time for oxidation and reaction of chemicals. It was also reported that the pavement structure was able to filter suspended solids and some contaminants such as sodium and sulphate. An increase in concentration was found for nitrite/nitrate, ammonia and chlorides in Hogland et al. (1990) study, and these authors concluded that it was due to the use of deicing agents. Pagotto et al. (2000) reported that the retention of fine particulates within the porous surface was identified as significant in producing the reduction in hydrocarbon and metals discharge.

Legret et al. (1996) compared the quality of infiltrated water from a porous asphalt pavement (PAP) installation located at Rezé near Nantes (Loire-Atlantique, France). Results showed that pH values were close to neutrality for both the PAP site and a reference catchment (conventional asphalt pavement). The chemical oxygen demand (COD) for both sites was similar. Suspended solid loads were 64% and 44% lower in the PAP site when compared to the asphalt paver. The rates of removal of heavy metal loads and hydrocarbons were consistent with the previously reported studies.

Booth et al. (2003) examined the long-term effectiveness of a pervious pavement as an alternative to traditional impervious asphalt pavement in a parking area. Commercially available pervious pavement systems (UNI Eco-Stone, Grasspave2, & Gravelpave2) were evaluated after six years of daily parking usage for quality of infiltrated water. All pervious pavement systems showed no major signs of wear. Virtually all rainwater infiltrated through the pervious pavements, with almost no surface runoff. The infiltrated water had significantly lower levels of copper and zinc than the direct surface runoff from the asphalt area. In all cases, the asphalt samples had measurable concentrations of copper and zinc. In addition, all samples from asphalt runoff exceeded the Washington State surface water-quality standards for copper at both acute and chronic toxicity levels (Washington State Department of Ecology, 1997). In contrast, 72% (copper) and 22% (zinc) of the infiltrated water samples from the permeable systems were below the minimum detection limit. Motor oil was detected in 89% of samples from the asphalt runoff but not in any water sample infiltrated through the permeable pavement. Neither lead nor diesel fuel were detected in any sample (Booth et al., 2003).

The surface runoff infiltrated from a porous concrete block-surfaced car park at the Bank of Scotland, South Gyle, Edinburgh has been monitored for both quantity and quality parameters (Schluter and Jefferies, 2001). Water quality analyses show mean heavy metal concentrations (µg/L) for Cd less than 0.068, 1.8 for Pb, 5.2 for Cu, 1.7 for Ni and 22.2 for Zn. Hydrocarbon concentrations were up to 3.5mg/L for the event producing the highest rate of outflow at 2.9 L/s, although for spot samples and smaller events the results were much lower and sometimes below detection.

Water Sensitive Urban Design (WSUD) Engineering Procedures (stormwater) provides investigations of the performance of pervious pavements for water quality and flow effects based on research. Fletcher et al. (2003) carried out a review study of the water quality performance of pervious pavements which clearly showed that pervious pavements have an ability to remove 80% (70-100) of Total Suspended Solids(TSS), 65% (60-80) of Total Nitrogen (TN), 60% (40-80) of Total Phosphorous (TP) , 85% (80-99) of Oils and Greases, 75% (40-90) of Heavy Metals (Zn, Cu, Cd, Pb and Ni).

Day et al. (1981) conducted laboratory experiments to investigate runoff, retention and throughflow of pollutants from four different surfaces. The surfaces were a traditional concrete pavement, two large element permeable block surfaces (grass-concrete types) and a continuous-laid permeable concrete surface. The pollutant concentrations in runoff from the continuous-laid permeable surface were greater than the corresponding concentrations for the concrete slab, except for organic phosphorus and heavy metals. However, the pollutant load being discharged in the surface runoff was much less for the continuous-laid surface than for the concrete slab, because of the significant differences in the runoff volumes. In the case of lead in the runoff, the mass from the concrete slab was found to be 350 times greater than from the permeable surface. Samples of the percolating waters were obtained from near the top of the subsoil layer (sub grade) below the permeable surfaces. Some of the pollutants were retained in the soil. The retention of TP, ortho phosphate and organic phosphate was better than 75%. Organic Nitrogen was retained 70% to 80%. Heavy metals (Pb, Zn and Cr) were retained in each of the three permeable pavements between 94% to 98% and 90% to 97% respectively, and chromium 45%, 81% and 94%. The results for chromium indicate the difficulty of reproducibility in laboratory rigs. Samples taken towards the base of the subsoil layer showed that phosphorus removal, particularly ortho phosphorus, increased with depth. Over 80% of organic nitrogen was removed at or before this level in the pavement. The effluent samples showed nitrate/nitrite was being leached from pavement structures. Ammonia and TOC were not well treated with percentage removals on a mass basis of 26% to 78% and 5% to 76%, respectively.

The pavement type and the amount of pollutants removed from each study are reported in Table 2.5, which indicates that both porous and permeable pavements show a similar reduction in water quality parameters. Almost all the parameters could be removed at least by 60%. Therefore it could be safely concluded that the application of pervious surfaces improves surface water quality. If the water is collected through a properly designed drainage system, water could be used for fit- for purpose reuse or recharge groundwater.

Table 2.5 Reduction in stormwater quality parameters through pervious pavements.

Reference	Pavement type	Pollutant removal (%)				
		TN	TP	Other	TSS	Oil
Fletcher et al. (2003)	Porous and permeable	60-80	40-80	(Pb, Cu, Cd, Ni and Zn) 40-90	70-100	80-99
Pagotto et al. (2000)	Porous asphalt	60	60	(Pb, Cu, Cd and Zn) - 60, COD - 60	60	N/A
Lagret et al. (1996)	Porous asphalt	N/A	N/A	Pb – 44 CoD – No reduction	64	N/A
Macdonald & Jefferies (2001)	Porous concrete	N/A	N/A	Hydrocarbon -70	N/A	N/A
Booth et al. (2003)	Uni Eco stone (Permeable) Grasspave 2 Gravelpave 2	N/A	N/A	Cu - 72 of samples BDL Zn – 22 of samples BDL	N/A	100 BDL
Dierkes et al. (2002)	Porous concrete asphalt	N/A	N/A	(Pb, Cu, Cd and Zn) – 72 to 98	N/A	N/A
Day et al. (1981)	Three permeable block	70-80	75	Pb – 94 to 98 Zn – 90 to 97 Cr - 45, 81, 94		
Schluter and Jefferies (2001)	Permeable concrete block	N/A	N/A	Output pollutant concentrations Cd <0.068mg/L Pb<1.8mg/L Ni<1.7mg/L Zn<22.2mg/L	N/A	3.5mg/L

BDL –Below Detectable level

2.2.2 Removal of pollutants with time

Raimbault et al. (1999) examined samples of porous asphalt concrete pavements to identify the location of pollutants deposited within the pavement. They found that most of the heavy metals were deposited in the porous surface after 8 years of usage, with little migration of particulate pollution within the structure. They also found that 14%-40% of the particles deposited were less than 100µm. Only a small quantity of clay size particles adversely affected the permeability of the surface.

Legret and Colandini (1998) built a porous pavement over a 700m section of residential road where traffic usage was about 1600 vehicles per day. The weathered clay subgrade was placed over a woven geotextile on which the construction materials were placed. The surface comprised a 60mm layer of 14mm porous concrete asphalt over two 100mm layers of porous bituminous-bound, graded aggregates, above a 300mm layer of 10-80mm crushed stone. Stormwater percolating through the construction either infiltrated through the sub-grade or was intercepted by a perforated sub-base drainage pipe. After 8 years of usage, soil samples (200mm immediately beneath the construction) from the car park were analyzed for heavy metals and the results compared with the French Agricultural Soil Threshold Standard (ASTS). Pb, Cu, Cd and Zn amounts in one kilogram of soil were 39, 11, 0.08 and 111 milligrams respectively and the ASTS values were 100, 100, 2 and 300. Further laboratory-based investigations suggested that lead and, to a lesser degree, copper and zinc concentrations decrease rapidly with depth of soil, being generally nil below 350mm. Cadmium on the other hand was not retained well and could migrate to 700mm, or beyond, in favorable soil conditions. As a result, Legret et al. (1998) above authors stated that it is not advisable to install pervious pavements close to the groundwater table if the infiltration process is the only means to drain off stormwater.

Water quality sampling was undertaken at a small elemental, permeable block-surfaced car park in Nottingham Trent University during its first three years of operation (Pratt et al., 1989). The four different sub-base stones (limestone, granite, gravel and blast furnace slag) produced a different range of values in water quality parameters, although any one parameter was remarkably consistent, storm event by event. For an example, the pH and alkalinity of the effluent were lower for the blast furnace slag sub-base discharges as compared with those from the limestone sub-base. Similarly, hardness and lead were lower in discharges from the limestone sub-base. The highest removal efficiency of hardness and lead was recorded for the limestone sub-base, granite, gravel and blast furnace slag surfaces.

Pratt (2001) reported that over two years of monitoring, the water quality parameters for the four pervious pavement sections showed small, slow variations with time. Blast furnace slag effluent showed a gradual decrease in hardness, whilst both granite and blast furnace slag exhibited slow decreases in conductivity. The variation of suspended solids concentration over the period was limited to a range from near zero to 50mg/L, after an initial period of sediment flushing due to material brought to the site on the construction materials. This range of SS concentrations is considerably less than is typical for discharges from impermeable surfaces, where fluctuations of 30 to 300mg/L occur frequently during storm events, and peak concentrations of some 1000s mg/L are not uncommon. The consistency of concentration of suspended solids in the effluent is in marked contrast to the variability occurring with impermeable surfaces between consecutive events, where antecedent conditions and the storm characteristics determine solids wash-off. A limited number of determinations of hydrocarbon concentration in the effluent were attempted but, in all cases they were below the level of detection.

The studies initiated at the car park at Nottingham Trent University in the late 1980s were extended through the 1990s in laboratory experiments examining not only the retention but also the degradation of oil within the permeable construction. The previous study had failed to identify hydrocarbons in the effluent from the permeable structure, despite visual evidence of surface contamination through car sump leakage.

A laboratory model of the permeable construction at the Nottingham car park, 610mm by 610mm in surface area, was built and supplied with artificial rainfall and clean mineral oil regularly each week over a period which extended to four years (Bond, 1999). The research aimed to determine whether the retained oil could be degraded through microbial action that is whether the free-draining structure could act as an aerobic digester. Accordingly, the model was seeded with a commercially available bacterial inoculum and nutrients. Both liquid and granular forms of nutrient were tried, with the latter giving better degradation results, and the levels of nutrient concentrations in the effluent were low.

The model drained through its base and samples of effluent were analysed for oil and grease, total nitrogen, phosphate phosphorus and potassium. Results reported by Bond et al. (1999) showed that 98.7% of the applied oil was retained or degraded over the period and that, with an input oil concentration of 1800mg/L, the effluent oil concentration was only in the range 3.8-39.5mg/L. The fact that degradation was occurring was established by the measurement of elevated levels of carbon dioxide within the pavement and by the use of a second model, which allowed a mass balance for oil to be calculated. The measured oil degradation rate using granular nutrients was equivalent to 356g/m^2/year and it was estimated that the mean residence time of the oil in the structure was 7 months.

Examination of the component materials within the permeable structure showed that around 60-90% oil was retained on the geotextile, from where it would be slowly released and degraded. The long term capacity of the structure to retain oils was investigated by immersing samples of the component materials in an oil bath for 15 minutes and then allowing them to drain for 25 days before weighing. These tests showed that 9.5kg of oil could be retained in total per square metre surface area, with the concrete surfacing blocks, gravel bedding layer, geotextile and granite sub-base each retaining 12%, 29%, 5% and 54 %, respectively, of this total within the as-built structure. The actual oil retention capacity per unit weight of each component was approximately 17, 36, 3190 and 7g oil/kg material, respectively, for the materials in the same list order.

Using the above results, a hypothetical car park design was assessed for its potential to become saturated with oil (Pratt, 1999). The car park was assumed to have 4690m^2 impermeable surface area, all of which drained to a permeable surface side strip of 310m^2. Using the same oil input concentration, 1800mg/L, which is 100 times the concentrations identified in the literature as likely in highway runoff, the permeable strip was estimated to have a 44-year life before saturation. If the total area of the car park was constructed as a permeable structure, the time to saturation was estimated to exceed 100 years. This appears to suggest that oil saturation may not be a major problem where supply is evenly spread over time at this high level.

The Urban Water Resources Centre at the University of South Australia (Urban Water Resources Centre, 2002a) conducted laboratory testing of permeable pavements with four test beds (Two test beds from BORAL Formpave, ROCLA Ecoloc and Grasspave). Each test rig was supplied with a known quantity of pollutants equivalent to 35 years of stormwater input. The pollutant levels of output water were tested. The average outflow concentrations of suspended solids from the BORAL Formpave, ROCLA Ecoloc, and Grasspave test rigs were13.0, 22.8 and 6.2 mg/L respectively. A total of 1110 grams of sediment was added to each of the BORAL Formpave test beds, whilst only 70 grams passed through with the outflow water. The average sediment retention efficiency of this permeable pavement over the 35 year simulation was therefore 94%. ROCLA Ecoloc and Grasspave test beds had retention efficiencies of 89% and 97% respectively.

The removal efficiencies of the pervious pavement after several years of usage show that it would take more than 25 years (on average) to reach an equilibrium condition requiring remediation. When environmental benefits are considered, it is more worthwhile to remediate the pervious pavement than construct impervious pavements.

Table 2.6 summarises the removal efficiencies of stormwater pollutants in urban stormwater through different types of pervious pavements.

Table 2.6 Summary of pollutant removal with time

Reference	Pavement/sub-base type	Usage (years)	Removal efficiencies (%)
University of South Australia (2002a)	BORAL Formpave ROCLA Ecoloc Grasspave	35	94 – TSS 89 – TSS 97 – TSS
Dierkes et al. (2002)	Gravel sub-base Basalt sub-base Limestone sub-base Sand sub-base	15	98-Pb, 98-Cd, 96-Cu, 97-Zn 98-Pb, 98-Cd, 96-Cu, 98-Zn 98-Pb, 88-Cd, 94-Cu, 88-Zn 89-Pb, 74-Cd, 89-Cu, 72-Zn
Bond et al. (1999)	Concrete block	4	98.7 – Oil
Raimbault et al. (1999)	Porous asphalt	8	14-40% - TSS less than 1000µm

2.2.3 Deposition of pollutants with depth

A laboratory study was reported by Hogland et al. (1990) relating to pollutant transport and retention on porous concrete asphalt surface. This Swedish construction consisted of a 40mm surfacing layer with 15% to 24% voids overlaying two layers of free-draining aggregate. A 40 mm deep upper layer with 4 to 25mm stones acted as a leveling course, below which a layer consisted of 30-70mm aggregate with a 300-700mm deep sub-base layer. The pavement was separated by a geotextile layer from the sub-grade, which is typically boulder clay and effectively impermeable.

Artificial rainfall was simulated using highway runoff to twelve test samples of the porous pavement over various periods to simulate the pollutant retention of the pavement in service for a period between 1.5 to 30 years. The laboratory constructions had a 500mm sub-base layer over 500mm boulder clay. After the simulated time span for the experiment, the pavement was dismantled and the pollutant concentrations at various depths within the construction (sub-base structures) were determined. The concentrations varied with depth, with the highest for all pollutants analyzed being at the geotextile on the base of the construction, except for chloride and nitrite/nitrate, the latter being highest in the porous concrete asphalt. Sediment accumulated on top of the geotextile, much of it organic in nature, which would adsorb heavy metals, accounted for their elevated levels at that depth in the pavement. Nitrite/nitrate and ammonia concentrations were also higher at the geotextile interface than within the sub-base generally. In the soil below the geotextile, sulphur showed an eleven-fold increase on the initial value in the soil; ammonia, zinc and total phosphorus up to a four-fold increase; otherwise other pollutants displayed lower values. Analyses conducted on samples obtained from an operational pavement during its reconstruction showed total phosphorus, total solids, copper and cadmium at their highest concentration in the boulder clay below the geotextile, whereas other pollutants were at the highest levels at the geotextile interface. The lowest concentrations were at the mid-depth in the sub-base stone, suggesting that pollutants were either trapped in the porous surface, or transported to the base of the construction, where they might be retained or discharged from the sub-base drain, located just above the geotextile.

2.3 Limitations of Pervious Pavements

The design and application of pervious pavements is site specific. Therefore these pavements are not suitable for all subsoil and site conditions. In addition, the use of pervious pavements is restricted to gentle slopes. As these surfaces are porous there is a higher risk of abrasion and damage than for solid block paved surface. However, gravel-filled sub-structure can be isolated from highly reactive local soils by appropriate lining. Some manufacturers (Formpave, UK) refer to this as "tanked", providing opportunities for haevesting/re-use.

Durability of pervious pavement structure, clogging due to stormwater infiltrating through the pavement, groundwater contamination, traffic load capacity and maintenance of the pavement are limitations when using pervious pavements. The relationship between the hydrological (storage) requirements of the sub-structure and the structural requrements is discussed on p107 of Argue, Ed (2004).

The EPA (1999) recommended that the site, traffic conditions, design storm storage volume, drainage time for design storm, construction, pavement placement and pre-treatment be evaluated before constructing pervious pavements. The correct choice of materials and components is critical to the success of a pervious pavement system at installation and throughout its operational life. It is generally accepted that a large percentage of pervious pavement failures is a direct result of poor quality workmanship at installation and incorrect design (Jayasuriya et al., 2006a).

Application of pervious pavements should be limited to residential carriageways with low traffic volumes, axle loads and speeds (less than 30 Km/h limit), car parking areas and other lightly trafficked or non-trafficked areas. Pervious surfaces are currently not considered suitable for roads with high traffic due to the risks associated with failure on high speed roads, the safety implications of ponding, and disruption arising from reconstruction (California stormwater BMP handbook, 2003)

When using un-lined infiltration systems such as pervious pavements, there is some risk of contaminating groundwater, depending on soil conditions and aquifer susceptibility. However, this risk is likely to be small because the areas drained tend to have naturally low pollutant loadings (California stormwater BMP handbook, 2003). The California stormwater BMP handbook states that pervious pavements can easily clog if improperly installed or maintained. However, this is countered simply by focusing on small areas where paving can be cleaned or replaced when blocked or damaged.

A field study of the infiltration capacity of permeable paving showed that the permeability of the pore system of the filling of the drainage openings (or joints) increases with the use of coarser mineral mixes, and that infiltration decreases with increasing age. After five years, the infiltration was observed to decrease by 50% (Borgwardt, 1997).

As mentioned in Section 2.2.1, pollutant removal is one major advantage of pervious pavements. However it is advisable to study the long-term effect of retaining pollutants in the pavements and their effect on groundwater. Legret et al. (1998) concluded that the installation of the reservoir structure should be well above the groundwater table. Legret et al. (1998) showed that there is a risk of ground water contamination for sites with higher water tables.

Dierkes et al. (2002) extended their study to investigate the pollutant build-up on a 15 year old permeable pavement car park subject to high usage. After determining the surface infiltration rate, the surface was lifted and the underlying materials were excavated in one bay. They found that the heavy metals and hydrocarbons after 15 years of operation were very low. Even the highest concentrations did not reach the permissible German limits on disposal to ground. In the underlying soil a slight increase of hydrocarbons was observed, but Dierkes showed that this did not endanger soil and groundwater.

2.4 Maintenance

Maintenance of a pervious pavement depends on the pavement type and the environment in which it is constructed. Proper maintenance is essential to its operation, but is similar to that required for traditional pavements.

The problem of surface clogging on pervious surfaces remains a concern. Kobayashi (1999) has presented useful details on Japanese experience in the use of manual and automatic washing/suction techniques on both porous asphalt and permeable surfaces. It has been possible to raise the infiltration rate from around 0.4mm/h to 400mm/h, the best performance being achieved with the higher jetting pressures combined with suction.

A study at a car park in Tampa, Florida, USA is reported by Rushton (2002). Eight sub-catchments were established with four different types of drainage system, two of each permeable paving, concrete pavement and asphalt surfacing each with a swale collector for excess surface runoff and asphalt surfacing without a swale, but with a lined, surface channel for excess runoff. All eight sub-catchments had garden areas onto which waters could flow from either a swale or from a channel. Over two years of data were collected of rainfall, runoff, water quality parameters and sediment/soil contaminants. Over the two years, the permeable pavement with swale had the lowest percentage runoff, being on average for the two locations 10% to 17%, while the other systems were in the order of twice or three times these figures.

Dierkes et al. (2002) reported the results of similar laboratory tests on different surfacing blocks. Four types were investigated: concrete blocks with large joints between blocks, porous blocks with close joints, and two styles of grass-concrete blocks with soil infill. Most pollutants of the four heavy metals tested were retained by the grass-concrete block systems and least by the blocks with large joints. They suggest that the joints should be filled with suitable material to limit the movement of heavy metals into the pavement, but this would probably adversely affect the infiltration capacity of the surface. The authors identified clogging as a major concern with applying pervious pavements in practice. They conducted some tests with surface cleansing machines. A newly developed cleansing machine raised the infiltration capacity of a ‘blocked’ surface from 0.4mm/h to 540mm/h, a value said to meet then German regulations.

As reported earlier, clogging is a major concern with adopting pervious pavements (Dierkes et al., 2002; Kobayashi, 1999; Rommel et al. 2001). Therefore researchers have carried out studies to minimise clogging. Manual and automatic washing/suction techniques have been tested by several researchers (Kobayashi, 1999; Rommel et al. 2001)

Field and laboratory studies carried out by Berry (1995) found that increase of void filling in the top 50mm of the pavement structure with sediment 2% to 3% have a big impact on the rate of infiltration. Davies et al. (2002) report on laboratory research into joint blockage and the effect of pavement surface slope on surface water interception efficiency. Pratt (1997) mentioned that the effects on the performance of the pervious pavements of poor selection and poor maintenance far exceed the effect of a miss-selection of design rainfall on the design.

Bond (1999) has done a full-size model of the permeable construction at the Nottingham car park, 610mm by 610mm surface area. The model was built and supplied with artificial rainfall and cleaned mineral oil regularly each week over a period which extended to four years. The research aimed to determine whether the retained oil could be degraded through microbial action. The degradation occurring was established by the measurement of elevated levels of carbon dioxide within the pavement and by the use of a second model, which allowed a mass balance for oil to be calculated. The measured oil degradation rate using granular nutrients was equivalent to $356g/m^2/year$ and it was estimated that the mean residence time of the oil in the structure was 7 months. Bond et al. (1999) revealed that pervious pavement has its own ability to degrade oil without any treatments such as vacuuming or sweeping.

The University of South Australia extended their research to field studies with four existing permeable pavement sites in Adelaide. They are Kirkaldy Avenue (BORAL Formpave), Victoria Road car park (BORAL Formpave), Fletcher lane (ROCLA Ecoloc) and St. Elizabeth’s Anglican Church (Grasspave). All four sites underwent hydraulic conductivity test and the results showed that clogging occurred at a rapid rate at locations where runoff flowing onto the pavement was concentrated. Tests revealed that the hydraulic conductivity was very high in locations where permeable pavements are subjected to rainfall only. However, for effective long term usage of pervious pavements, it is necessary to prevent the runoff coming from surrounding catchments by constructing drainage channels, preferably swales.

Pervious pavements should be vacuumed rather than swept. Vacuuming removes sediment and debris which block the percolation of runoff. Frequency of vacuuming depends on the amount of sediments carried by wind, vehicles or pedestrians etc. into the pervious pavement from neighbouring areas.

The EPA (1999) recommended sweeping the pavement at least four times a year and hosing the top layer with high pressure water to remove clogging of the pavement.

When considering grass (Atlantis Turf Cell, Grasspave and Grasscrete) surface, the major concern is keeping vegetation alive in drought periods. If the grass is not kept alive optimum performance from this surface cannot be expected.

2.5 Summary of the current research on pervious pavements

The traditional approach to stormwater management is based on the development of urban drainage networks to convey stormwater away from developed areas to receiving water effectively and efficiently. The increase in impermeable areas due to rapid urban development causes the quantity of runoff to significantly increase at times stretching the capabilities of the stormwater infrastructure. Pollutants carried by stormwater to receiving waters are also a major concern. It is best to tackle some of these problems at source rather than at receiving waters.

Water Sensitive Urban Design is the integration of water cycle management into urban planning and design. Key principles of Water Sensitive Urban Design listed in Urban Stormwater Best Practices Environmental Management Guidelines (Victorian Stormwater Committee, 1999) are to protect natural systems; integrate stormwater treatment into the landscape; protect water quality; reduce runoff and peak flow and add value while minimising development costs.

The introduction of pervious pavements addresses all five principles listed above in Water Sensitive Urban Design. Except for pervious pavements, WSUD techniques such as ponds, bioretention swales and basins and sand filters are not suitable for roads and car parks as they always carry moving traffic. As a result, engineers and environmentalists have been in favour of pervious pavements that have water infiltration capacity, traping pollutants and have load bearing capacity. According to Melbourne Water's statistical data, 22% of the urban area is covered by roads and car parks (Shackle and Pearson, 2004). Therefore, pervious pavements have the potential to contribute more to managing stormwater than all the other WSUD techniques mentioned above. Pervious pavements do not have a history of more than two decades of application in the world. The only study reported from Australia is by the Urban

Water Research Centre in Adelaide. Further research addressing some of the core issues is needed before pervious pavements are widely adopted as a WSUD feature in Australia.

The literature survey clearly shows that properly designed and maintained pervious pavements have the ability to contribute to managing stormwater in a sustainable manner. Several types of pervious pavements have been studied to investigate different aspects such as water quality improvements, water quantity reduction and structural performance (ROCLA Ecoloc, BORAL Formpave, Atlantis Turf Cell and Permapave). The design and the performance of the pervious pavements are very site-specific. Pervious pavements have proved their ability to effectively increase the hydraulic performance of car parks. The runoff volume has reduced by 0% to 50% (Hogland et al., 1987; Larson, 1990; Pratt et al., 1989). The literature suggests some limitations of pervious pavements, especially the clogging effect of the pervious pavement surface due to trapping of pollutants on the structure of the pervious pavements.

The findings from the literature search indicate that the concept of pervious pavement is feasible for lightly loaded pavement structures. It is clear that the effectiveness of properly designed pervious pavements depends on the site and the sub-base material. It is also clear that pervious pavements have not been commonly used as a WSUD feature in Australia. More laboratory and field tests are needed to address some of the related issues before pervious pavements will be widely accepted by practising engineers, land developers, regulators and local government authorities as a viable alternative to conventional designs.

Prior to ready acceptance of the technology by the stakeholders, development of a design framework is required to address the following areas:

1. Optimum pavement design for the required load bearing capacity and maximum infiltration;
2. Most efficient design for long term performance of pervious pavements; and
3. Methods of ensuring sustained improvements to the quality of water infiltrating through the pervious pavement.

To address the above issues, the current research will concentrate on laboratory and field studies to determine the applicability of pervious pavements in Australia. It is planned to identify the rainfall-runoff relationships and water quality improvements due to water infiltrating through pervious pavements. Laboratory studies will be carried out to investigate the long-term behaviour of infiltration rates, pollutant retention and water quantity improvements of pervious pavements due to clogging of pavements.

ater quantity and quality modelling softwares (PCSWMMPP and MUSIC) could be developed and calibrated using the results obtained from the proposed experimental studies. Improved pervious pavement algorithms in these models will ultimately be available for use in Australia.

3 MODEL STUDY

The experience of the application of pervious pavements in Australia and overseas indicates that a well-designed pervious pavement is capable of contributing to the effective management of urban stormwater. The literature survey reported in Chapter 2 referred to several studies (Suarman et al 1999; Valkman, 1999; Urban Water Resource Center, University of Adelaide, 2002a) employing laboratory model experiments to study the behavior of pervious pavements. According to Suarman et al. (1999), research into water quality improvement using pervious pavements in Australia has been carried out only since 1999. These authors also reported that hydraulic conductivity fell to 1/3 of ‘as constructed’ value within 25 years due to sediment clogging inside the pores of the pavement structure. Few research studies have been carried out in Australia to study water quality improvements when stormwater infiltrates through pervious pavements.

Zhang (2006) constructed an experimental pavement rig in the hydraulics laboratory at RMIT University. The pervious pavement was designed and constructed in accordance with the recommendations by Shakel et al. (1996). Different rainfall intensities were simulated and the water infiltrated was collected underneath the experimental base. Zhang (2006) tested the pervious pavement rig for its hydraulic performance using a rainfall simulator with potable water without any pollutants. The primary objective of Zhang’s (2006) study was to investigate the infiltration through the pavement structure. The author concluded that infiltration through pervious pavement could be estimated using the Green and Ampt infiltration model.

The current study used the pavement rig designed by Zhang (2006) to investigate improvements to water quality when stormwater infiltrates through the pavement. As discussed in the previous chapter, clogging has been identified as one of the factors limiting wider use of pervious pavements in actual practice. The current study will also investigate the effect on infiltration and water quality improvement of clogging of the pavement structure.

This chapter will initially summarise the work carried out by Zhang (2006) using the pervious pavement experimental rig to identify the infiltration (hydraulic) characteristics of the pervious pavement. This will be followed by the methodology used to investigate improvements to water quality by permitting stormwater with pre-determined pollutants to infiltrate through the pavement. The chapter will conclude by presenting the results on water quality improvements and the effect on infiltration and water quality improvement due to pollutants entrapped within the pavement structure.

3.1 Previous work carried out by Zhang et al (2006) at RMIT University

3.1.1 Experimental setup

An experimental rig designed by Zhang (2006) was used to construct a pervious pavement in the laboratory. The pervious pavement (Figure 3.1) was constructed in a 1.5mx1.5mx0.3m steel box which was set up with holes in the bottom plate for water to pass through. According to the researcher, the holes were drilled in an area of 1mx1m to minimise errors due to the boundary effect. A rainfall simulator with 25 evenly spaced sprays was set up above the pavement surface to cover the surface area of the pervious pavement (Figure 3.2). Rainfall intensities applied were controlled by a flow meter (Figure 3.3). The water flowing through the pavement was collected from underneath the pavement via a funnel connected to the 1m x 1m area to avoid boundary effects influencing hydraulic flow within the steel box (Figure 3.4). The flat surface at the top of the funnel was screwed on to the bottom plate. These four flat surfaces of the funnel were attached to the bottom plate of the pavement with an adhesive. This was done to prevent the infiltrated water leaking through joints. There were 10,000 infiltrated holes in the center of the bottom steel plate. The diameter of the holes was set to 4 mm and the distance between the middle of two holes was 10 mm. In the boundary (outside the 1m x 1m area), 25 drainage holes were drilled on each side of the bottom plate to drain the water that fell on the area outside the central 1m x 1m. The pavement was designed at a slope of 3% to drain any surface runoff generated from the pavement surface during the heavy rainfall intensity simulations.

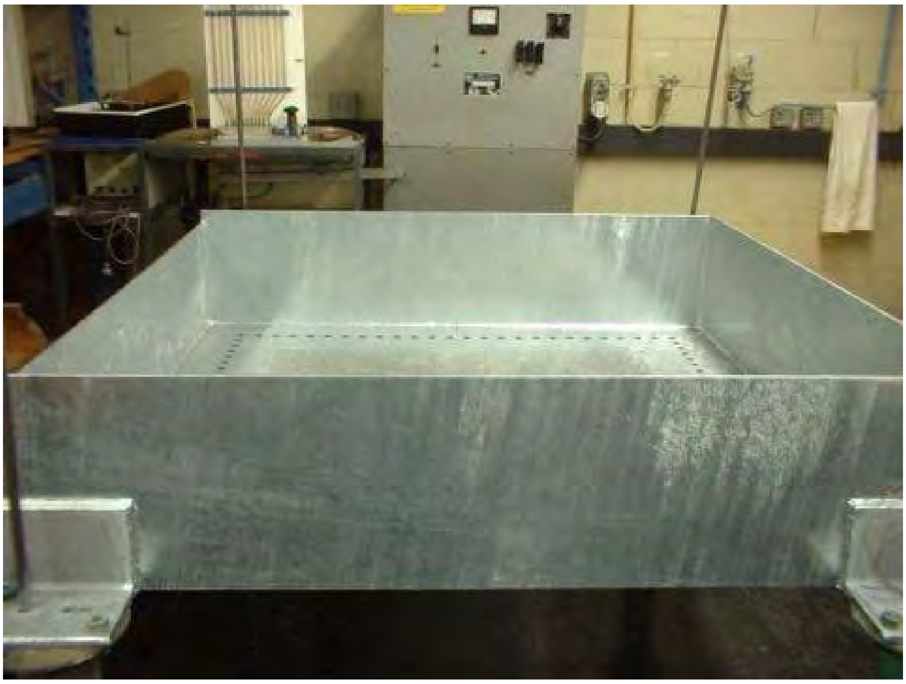


Figure 3.1 The steel box with holes in its bottom plate (Zhang, 2006)

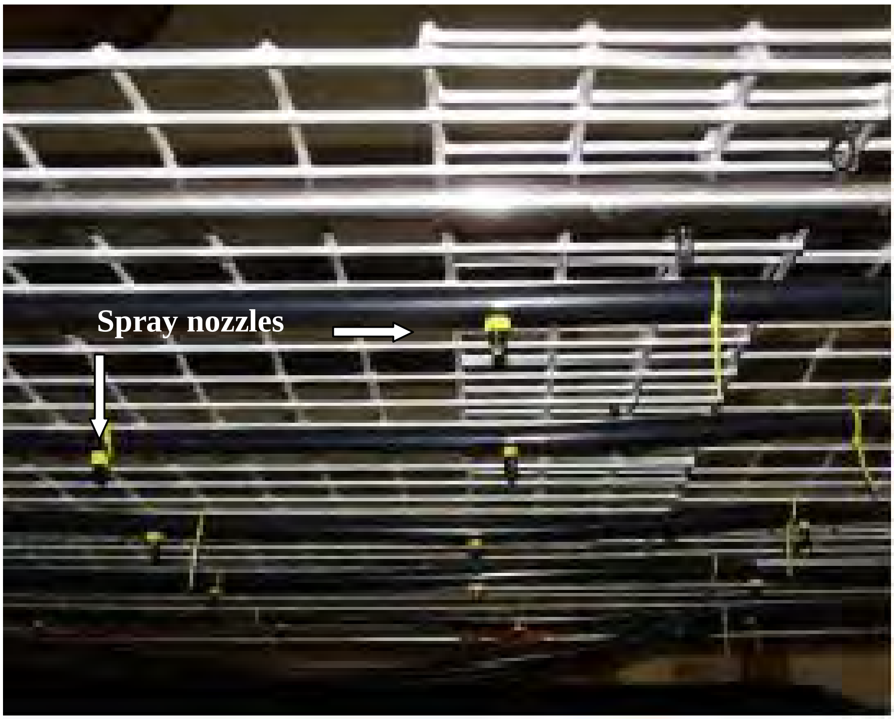


Figure 3.2 The rainfall simulator with evenly spaced sprayers (Zhang, 2006)

Figure 3.3 The flow controlling device attached to the model (Zhang, 2006)

Figure 3.4 The funnel attached to collect the infiltrated water (Zhang, 2006)

3.1.2 Design Aspects

As stated above, the pavement rig was designed and constructed by Zhang (2006) based on recommendations by Shakel et al. (1996). The thickness of the pavement layers and aggregate sizes are given in Figure 3.5.

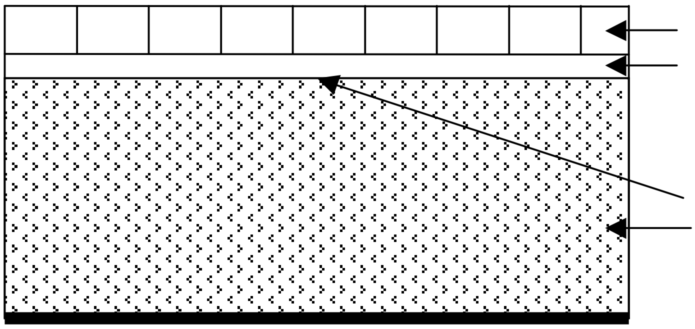


Figure 3.5 Cross section of the laboratory Pavement model

Prior to constructing the pavement in the experimental steel box, Zhang (2006) performed laboratory tests to obtain relevant physical properties of the bedding and sub-base aggregates according to published Australian Standards. They were as follows: particle size distribution of aggregate materials, relationship between moisture content and density, specific gravity and saturated hydraulic conductivity. These properties were used by Zhang (2006) to estimate the parameters of the Green and Ampt infiltration model (Mein, 1980).

As physical properties of the aggregates play a key role in the construction and performance of the pervious pavements, all the properties (specific gravity, dry density, porosity of bedding and sub-base) were tested by Zhang (2006) to obtain the correct compaction when constructing the pavement.

3.1.3 Details on aggregates

The soil laboratories at the School of Civil, Environmental and Chemical Engineering at the RMIT University were used to carryout tests to obtain the physical properties of the aggregates. The results presented in the following sections were obtained by Zhang (2006).

Particle size distribution

Zhang (2006) carried out a sieve analysis for 2 to 5 mm (Figure 3.6) bedding material and 5 to 20 mm (Figure 3.7) sub-base material. Based on the grading curves, only 14.3 % of bedding material was passed through the 2 mm sieve and was classified as sand. 85.7% of the bedding material and 100 % of the sub-base material was gravel.

Optimum moisture content and maximum density of aggregates

Tests were carried out by Zhang (2006) to obtain the density and moisture content of oven dried, surface dried and 24 hours saturated material. According to the test results, the optimum moisture content of the bedding material was 2.3% when the maximum density was 1.766g/cm^3. The optimum moisture content of the sub-base material was 8.7% when the maximum density was 1.744g/cm^3.

Specific gravity and porosity

The specific gravity, dry density and porosity of the bedding and sub-base aggregates were evaluated by Zhang (2006). The specific gravity and dry density of the bedding were 2.94 and 1.765g/cm^3 respectively. These properties of the sub-base material were 2.73 and 1.720g/cm^3. The calculated porosity (Whitlow, 1995) of the bedding and sub-base materials was 40% and 37.1% respectively. From the void ratio, the calculated total volume of pores within the constructed steel box was 0.194m^3.

Saturated hydraulic conductivity

A constant head permeability rate test was carried out by Zhang (2006) with both types of aggregates to obtain the saturated hydraulic conductivity of the materials. The results indicate that the permeability rate of the bedding material was 4.45x10^{-2} mm/s at a hydraulic gradient of 1. Under the same experimental conditions, the permeability rate of the sub-base material was 6.35x10^{-2}mm/s.

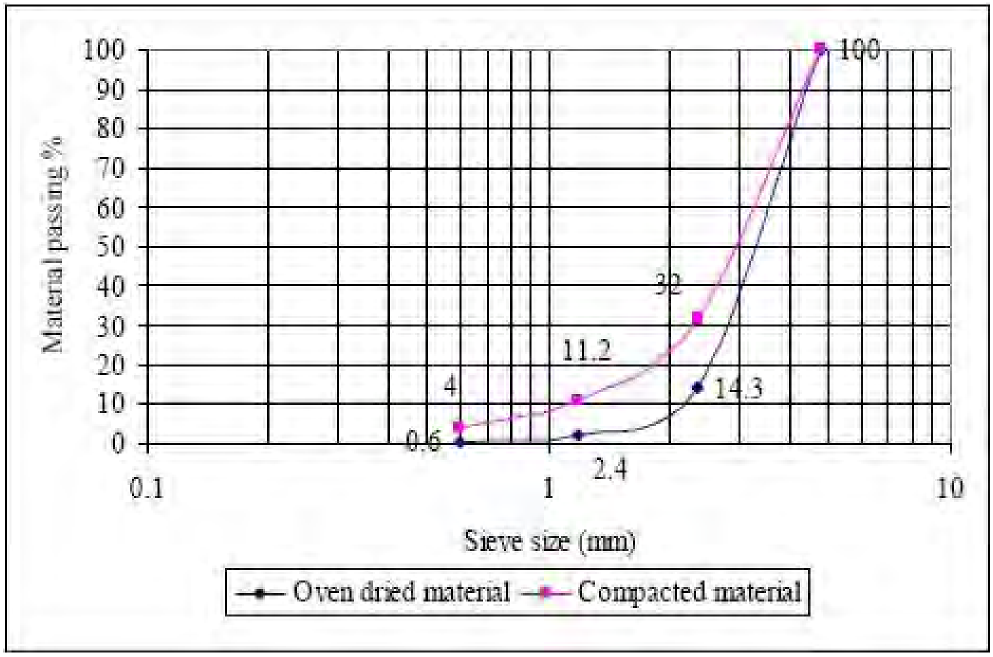


Figure 3.6 Grading curve for bedding material (Zhang, 2006)

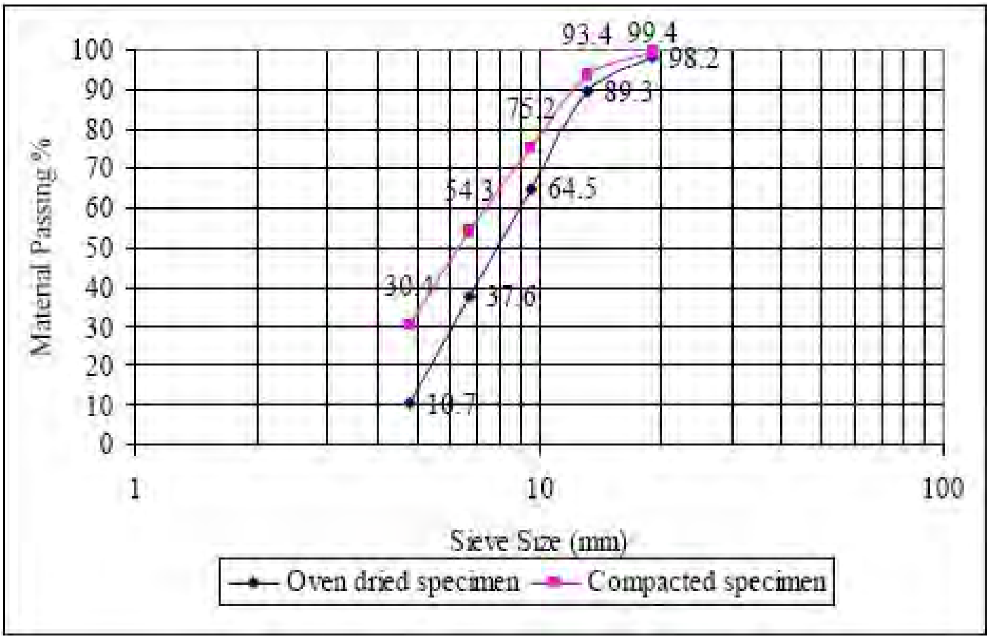


Figure 3.7 Grading curve for sub-base material (Zhang 2006)

3.1.4 Hydraulic properties of the pavement

Zhang carried out an extensive investigation of the hydraulic properties of the pavement. Details of the experimental procedure are given below. Seven different rainfall events of uniform intensities were simulated to test the infiltration rate. The flow rates through the simulator were varied between 1.4 L/min to 7.4 L/min. The nozzles of the rainfall simulator were placed directly above the central 1m x 1m experimental area. The funnel underneath the pavement was also placed within the 1m x 1m area. This was done to reduce the boundary effects from the solid surface. To obtain the infiltration characteristics through the bedding layer and flow through the whole pavement structure for each rainfall event, the water flow through the bottom of the pavement was measured at 1 minute intervals until the flow rate was almost constant. There was no surface runoff generated from the pavement surface for the storms simulated in the laboratory due to the high permeability of bedding and sub-base material and the non-placement of sub-grade soil underneath the sub-base layer.

Using the parameters obtained in Section 3.1.3, Zhang (2006) revealed that the infiltration through pervious pavements satisfied the Green and Ampt infiltration model (Equations 3.1 to 3.4)

If $I <= K_s$ $\quad f = I; \quad F \leq F_s$ (3.1)

If $I > K_s$; $\quad F_s = M*S_{av}/[(I/K_s)-1]$ (3.2)

If $I > K_s$; $\quad f = f_p = K_s(1+M*S_{av}/F; \quad F > F_s$ (3.3)

$$K_s(t-t_s) = F-(M*S_{av})\log_e(F+M*S_{av})-F_s+(M*S_{av})\log_e(F_s+M*S_a \quad (3.4)$$

where,

f = infiltration rate (mm/h)

f_p = potential infiltration rate or infiltration capacity (mm/h)

F = Volume of water infiltrated (mm)

F_s = volume of infiltration at moment of surface saturation (mm)

S_{av} = average suction at wetting front

I = rainfall intensity (mm/h)

K_s = saturated hydraulic conductivity (mm/h)

M = initial moisture deficit (vol/vol)

Except for storm intensities (80mm/hr or 1.4 L/min and 444mm/hr or 7.4 L/min) less than the hydraulic conductivity (228mm/hr or 3.8 L/min) of the bedding material, for all other storms output reached equilibrium within 20 and 30 minutes.

3.2 Investigation of Water Quality Parameters

3.2.1 Critical stormwater quality parameters

The current study used an experimental rig to investigate water quality improvements and reductions in infiltration rates over a longer period whilst stormwater was infiltrating through the pavement. When considering water quality improvements, the identification of key water quality parameters is of vital importance. As shown in Chapter 2, the study conducted by University of South Australia (2002a) tested the effect of Total Suspended Solids (TSS) on a laboratory pervious pavement. Dierkes et al (2002) conducted a laboratory test on full scale pervious pavement under artificial rain which was highly contaminated with heavy metals such as Lead (Pb), Copper (Cu), Zinc (Zn) and Cadmium (Cd). Newton (2001) identified the major pollutants in urban stormwater as Total Nitrogen (TN), Total Phosphorous (TP), Total Suspended Solids (TSS) and heavy metals (Cu, Zn, Pb, Cd, Chromium (Cr) and Nickel (Ni)) as presented in Table 2.2. Vehicles are one of the major contributors to pollutants in the urban environment. Pb comes as a result of fuel combustion, whereas Cd, Cu and Zn come from tyre waste due to friction. Considering the literature and the field of interest, TN, TP, TSS, Heavy metals (Cu, Zn, Pb and Cd) and oil have been selected as the most relevant and important pollutants to study in the current research.

3.2.2 Preparation of the artificial stormwater sample

Following Hsieh and Davis (2005), a synthetic stormwater sample was prepared in the laboratory and sprayed over the pavement rig before rainfall was simulated. The input stormwater quality sample applied to the surface was prepared from the values reported by Newton (2001) study (Table 2.1). A trial simulation was carried out with normal tap water to confirm the water quality parameters in infiltrated water. The rainfall was simulated at the rate of 90 mm/hour for 1 hour. It was found that there was some Zn, TN, and TP in the infiltrated water (Table 3.1). Five samples were taken at different time intervals to better understand the variation in pollutant levels. The reason for the presence of Zn in the infiltrate is the decay of the test rig that was made out of Zinc coated iron. The presence of TN and TP may be due to leaching of nutrients in the soil used for the bedding and sub-base and the decomposition of granular material into nutrients.

Table 3.1 Pollutants in outflow from the rig with clean tap water

Sample	Pollutants (mg/L)		
	TN	TP	Zn
1	0.20	0.00	2.55
2	0.30	0.00	2.95
3	0.20	0.01	2.54
4	0.30	0.02	0.74
5	0.20	0.02	0.43
Average	0.25	0.02	1.84

In their laboratory studies Sansalone and Buchberger (1997), Sharply et al. (1981); Usitalo et al. (2000) and Hsieh and Davis (2005) prepared synthetic stormwater samples. For the present study the stormwater quality sample was prepared according to the recommendations of Hsieh and Davis (2005). The current study used the typical Australian stormwater quality values reported by Newton (2001) when preparing the synthetic stormwater quality samples (Table 2.4). It was assumed that the annual rainfall in Melbourne is 675mm when preparing the water quality sample.

Equivalent annual rainfall volume that will fall in 1 year over the rig

$$= 0.675\text{m} * 1\text{m}^2 = 675\text{L}$$

Therefore the equivalent amount of TSS in the synthetic stormwater sample which represents 1 year of loading = 141mg/L (TSS concentration) * 675L (annual rainfall volume)

= 95.18g.

The required weights of pollutants were calculated as shown in the above specimen calculation and weighed by selecting appropriate sources of pollutants as shown in Table 3.2.

First three simulations were carried out each with one year equivalent pollutant loads and a rainfall equivalent to 90 mm/hour for a duration of 1 hour. The rest of the test runs were simulated with two years equivalent pollutant loads at a time in order to reduce the number of simulations. The simulated rainfall duration was also extended to 1.5 hours.

The objective of the laboratory study was to investigate the improvements to stormwater quality parameters in the source water over time due to clogging of the pavement. Therefore the quality of the input stormwater and the infiltrated water through the pervious pavement were measured in the study. Calculated quantities of pollutants (eg. 95.18g of TSS) were dissolved in 1L of potable water. The synthetic stormwater sample was sprayed uniformly over the surface of the laboratory pavement and rainfall was simulated over the permeable pavement. The rainfall was simulated at a constant rate of 90 L/hour (1.5L/min) for the durations given above. The outflow was collected from the bottom of the pavement and analysed for pollutant concentrations.

Table 3.2 Constituents of the synthetic urban stormwater sample

Parameter	Concentration (mg/L)	Source of pollutant
TSS	141	Local soil sieved through 0.5mm
TP	0.24	Na2HPO4
TN	2.63	NaNO3 , NH4Cl
Lead (Pb)	0.1	PbCl2
Copper (Cu)	0.06	CuCl2
Zinc (Zn)	0.63	ZnCl2
Cadmium (Cd)	0.007	CdCl2
Oil and Greases	20	Used oil from a motor vehicle repair garage

3.2.3 Method of analysis of stormwater quality parameters

Analysis of stormwater samples was carried out by the author at the RMIT University Chemical Engineering laboratories. As the accuracy of data depended entirely on the results obtained from sample analysis, all the tests were carried out in accordance with the American Society of Testing Materials (ASTM) standard operating procedures. Sample collection, storage, and preservation, and standard methods to analyse stormwater parameters were carried out as described below. As stated above, TSS, TN, TP, Oil and Greases, Zn, Cu, Cd and Pb were selected as the stormwater quality parameters for laboratory testing.

Sample collection, storage and preservation

Preservation of water quality was carried out in accordance with ASTM standard operating procedures. Samples were collected in plastic bottles that had been acid washed with 1:1

Hydrochloric Acid Solution (Cat. No. 884-49) and rinsed with deionised water. It was necessary to analyse the samples as soon as they were collected to ensure accurate results. Some samples were preserved for up to 28 days by adjusting the pH to 2 or lower by acidifying with sulphuric (H_2SO_4) acid or nitric (HNO_3) acid. The sample that was preserved using H_2SO_4 was used to analyse for TN and TP. The other sample (preserved with HNO_3) was used to analyse for heavy metals (Cd, Cu, Zn and Pb). The refrigerated (4 °C) unacidified samples were used to obtain TSS. All preserved samples were stored at 4 °C. Before analysis, samples were warmed to room temperature and neutralized with 5.0 N Sodium Hydroxide (Cat. No. 2450-53). It is important to note that a correction was carried out for the addition of extra volume of chemicals to the solution.

Standard methods to analyse storm water parameters

According to ASTM international (2006), there are several ways to analyse stormwater samples for water quality parameters. Based on the laboratory facilities available, the methods used in this research are reported in Appendix A, Section A.1.

3.3 Analysis of results

3.3.1 Reduction in infiltration rate and water quality improvements due to pollutant trapping on the pervious surface

The current research also studied the reduction in infiltration and hydraulic conductivity due to pollutants trapped on the pervious surface by applying synthetic stormwater. A synthetic stormwater sample was prepared using the constituents shown in Table 3.2, and the prepared synthetic stormwater sample was sprayed over the rig. The pollutant load of the sample was equivalent to one year of pollutants generated as reported by Newton (2001). The input pollutant loads for each sample are given in Table 3.4. Then the rainfall was simulated using the rainfall simulator set above the test rig (Figure 3.2). The rainfall was sprayed at a rate of 90mm/hr (1.5L/min) to ensure that it was less than the saturated hydraulic conductivity of the aggregate in the bedding and sub-base. The infiltrated water was collected underneath the funnel and the time taken to collect every 0.5L of water was recorded from the start of the simulation until there was no flow. For water quality analysis, the first three samples were taken at 15 minute intervals and thereafter samples were taken every 30 minutes until the outflow stopped. This was undertaken to improve the accuracy of the pollutograph. A pollutograph was drawn for each pollutant under study from each storm. Table 3.3 gives the discharges and the concentrations of TN during each sampling period for the 4th simulation (5 years equivalent pollutant loads were sprayed).

Table 3.3 The discharge and TN concentration data when 5 years equivalent pollutants were sprayed on the test rig

Time (min)	Discharge,Q (L/s)	Concentration,C (mg/L)	QC (mg)
15	0.86	30	25.8
30	1.05	22	23.1
45	1.11	23	25.53
75	1.18	15	17.7
105	1.18	14.5	17.11
135	1.18	15	17.7

After all the water from the pavement rig had drained, the surface of the rig was again sprayed with an artificial stormwater sample with pollutant loads equivalent to 1 year of pollutants generated as reported by Newton (2001). Similar to the earlier simulated rainfall event, the rainfall was simulated at the rate of 1.5 L/min (90mm/hr) and the infiltrated water was collected at the bottom of the rig (Figure 3.8). Water quality was also analysed to obtain pollutographs.

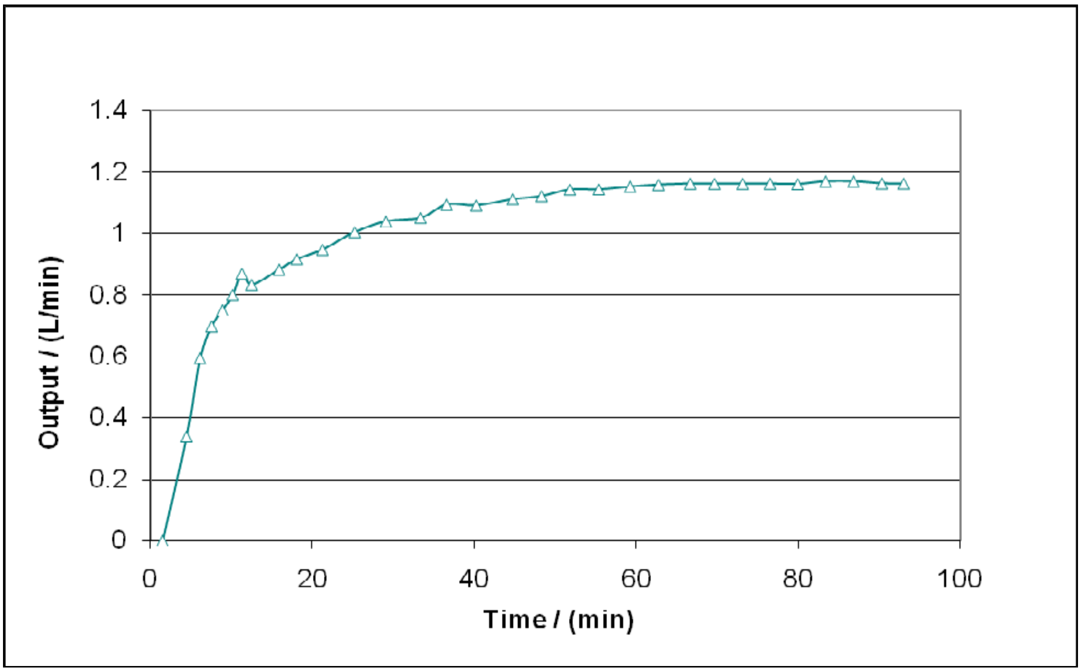


Figure 3.8 The variation of output flow with time (single simulation)

There was no noticeable reduction in the infiltration rate as well as the reduction in water quality parameters (Table 3.5) after pollutant load equivalent to 3 years was applied. As a result, the pollutant loads were doubled to make the simulated stormwater sample equal to 2 years of pollutants. Simulation runs were repeated until stormwater pollutants equivalent to 17 years were sprayed on to the pavement. A constant rainfall intensity of 90 mm/hr (1.5L/min) was used for all the simulated rain events.

Figure 3.8 shows the output flow rates with time after 5 years of equivalent pollutants were sprayed on the pavement surface. The rate of outflow was constant after 60 minutes of simulation. Similar results were obtained from all simulation runs. The final outflow rate was slightly lower than the simulated rainfall intensity of 1.5L/min. This is due to the lateral flow from the centre (1m x 1m) of the rig to the outer periphery (1.5m x 1.5m) of the rig. During the first three trial runs the rainfall simulations were carried out for durations of 60 minutes. Therefore the data from the first three tests were not considered when calculating the reduction in infiltration rates as they did not reach a constant outflow rate.

As the laboratory pavement was prepared in a steel rig, there was no surface runoff. Therefore the constant outflow rate (after 90 minutes of rainfall simulation) was considered as equivalent to the infiltration rate (note: as mentioned earlier there was a small lateral flow from centre 1m x 1m to 1.5m x 1.5m periphery). Figure 3.9 shows the change in infiltration rate with time due to sediments accumulating on the pavement surface. It shows that the infiltration rate declines with the accumulation of sediments.

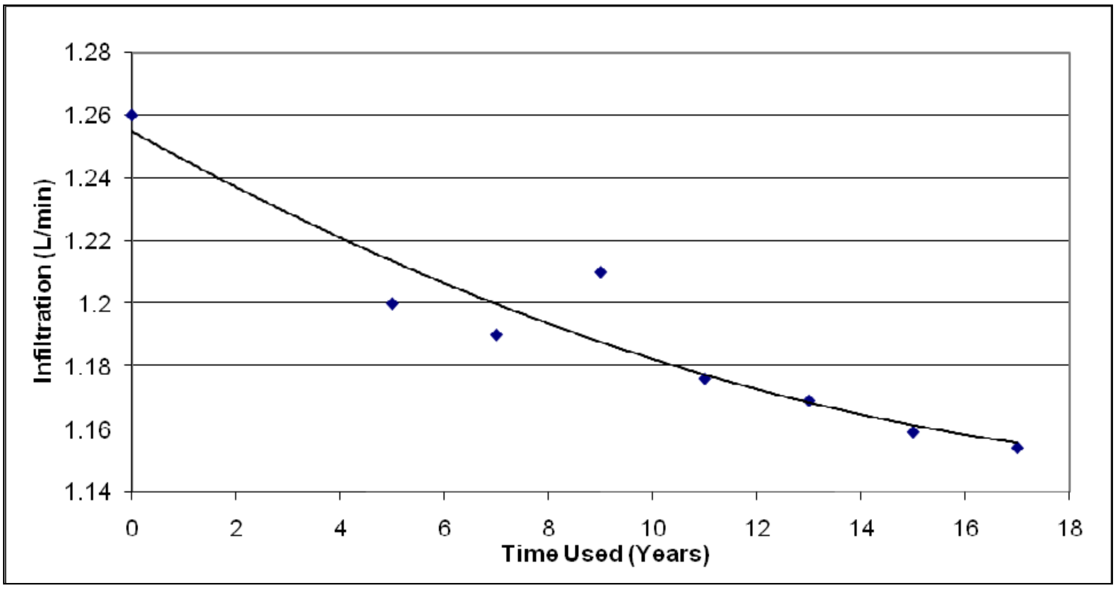


Figure 3.9 The change of infiltration rate with accumulation of sediments on the pavement rig

Figure 3.10 shows the change of cumulative outflow volume of water with time for different simulation runs. According to Figure 3.10, the cumulative outflow volume collected within 150 minutes is equal to 109L after 5 years of equivalent pollutants were sprayed on to the surface. However, after 17 years of sediment addition to the test rig the collected cumulative outflow within 150 minutes reduced to 98L. This clearly indicates that the clogging of pores due to sediment entrapping has reduced the hydraulic conductivity of the pavement structure.

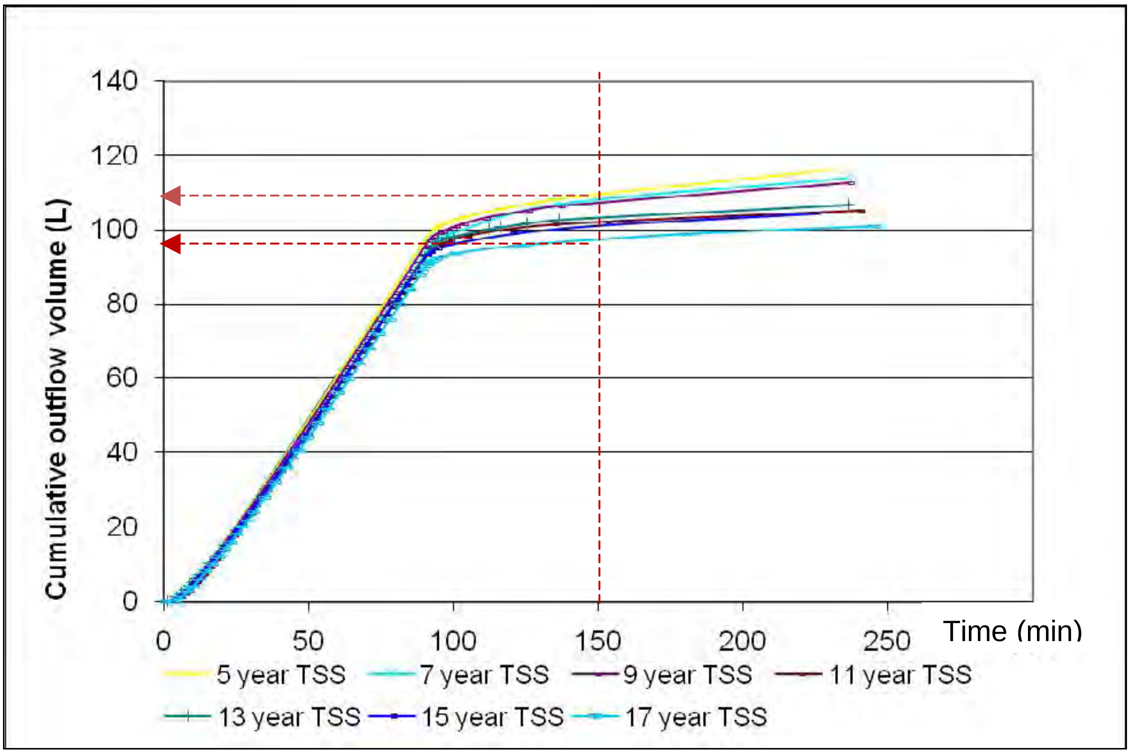


Figure 3.10 The relationship of cumulative outflow from different simulated stormwater samples vs. time

3.3.2 Improvements to water quality parameters

Figures 3.11 to 3.16 show the pollutographs drawn for the 4th simulation which was equal to the sum of five year stormwater pollutants. Ten rainfall events were simulated and the pollutographs for other storms are presented in Appendix A, Figures A.10 to A.63.

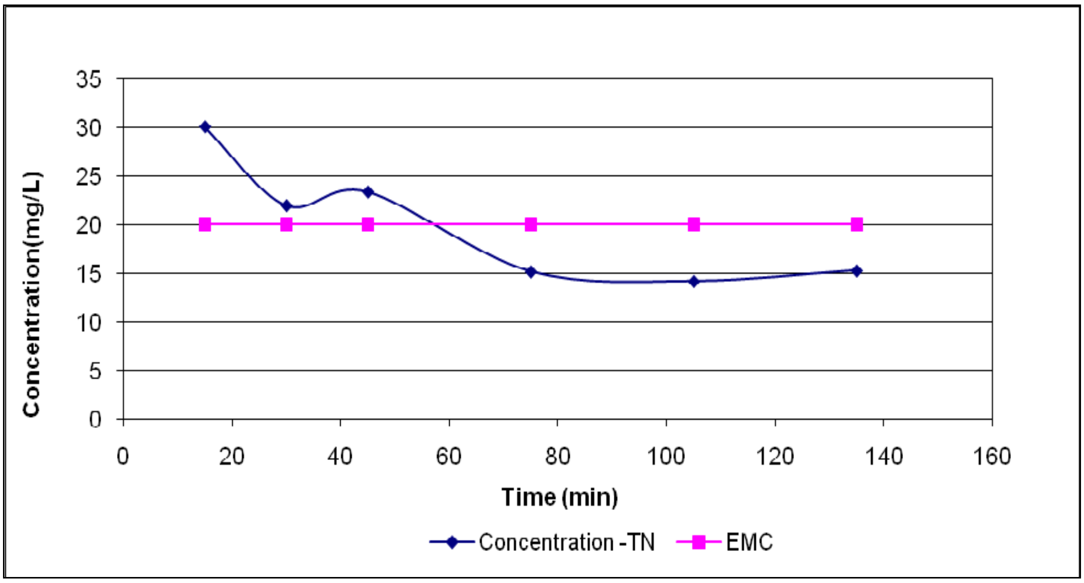


Figure 3.11 Pollutograph of Total Nitrogen output from the rig

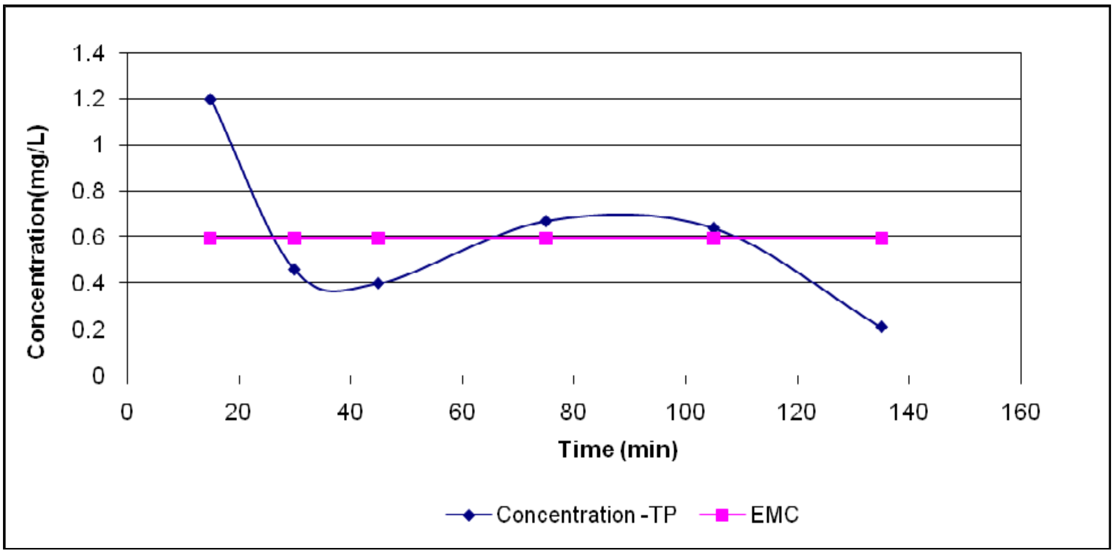


Figure 3.12 Pollutograph of Total Phosphorous output from the rig

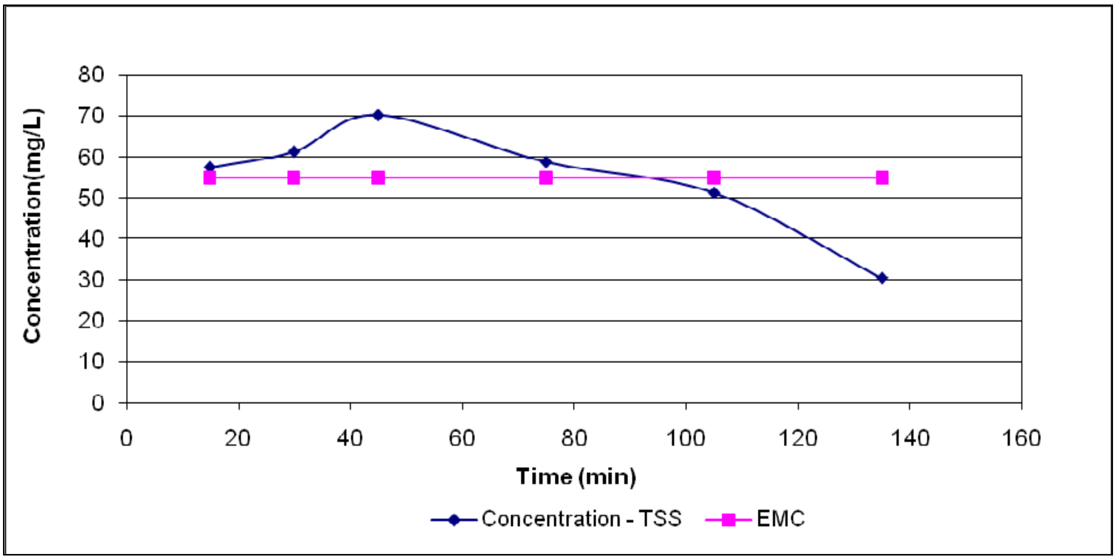


Figure 3.13 Pollutograph of Total Suspended Solids output from the rig

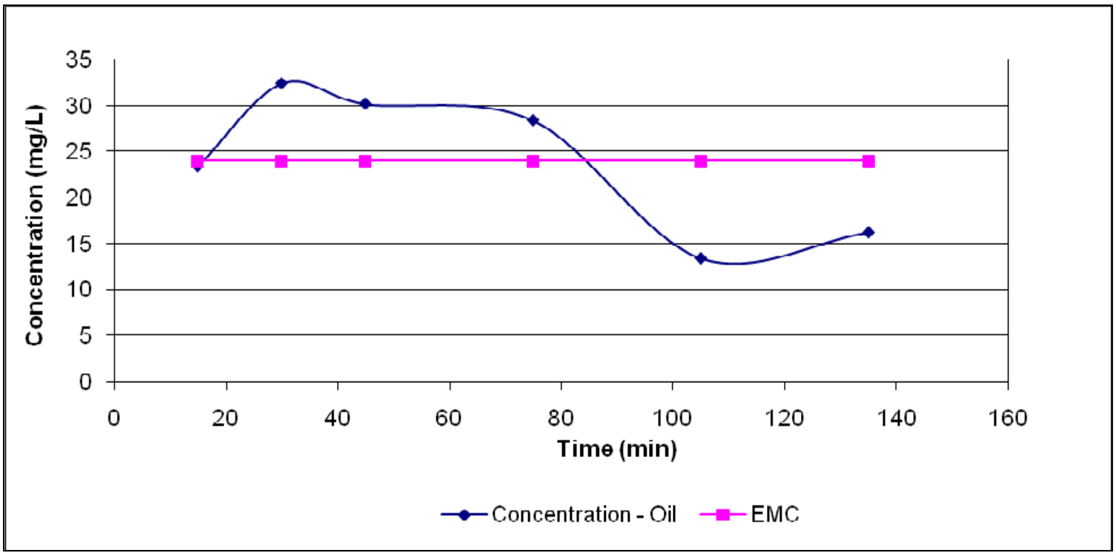


Figure 3.14 Pollutograph of Oil output from the rig

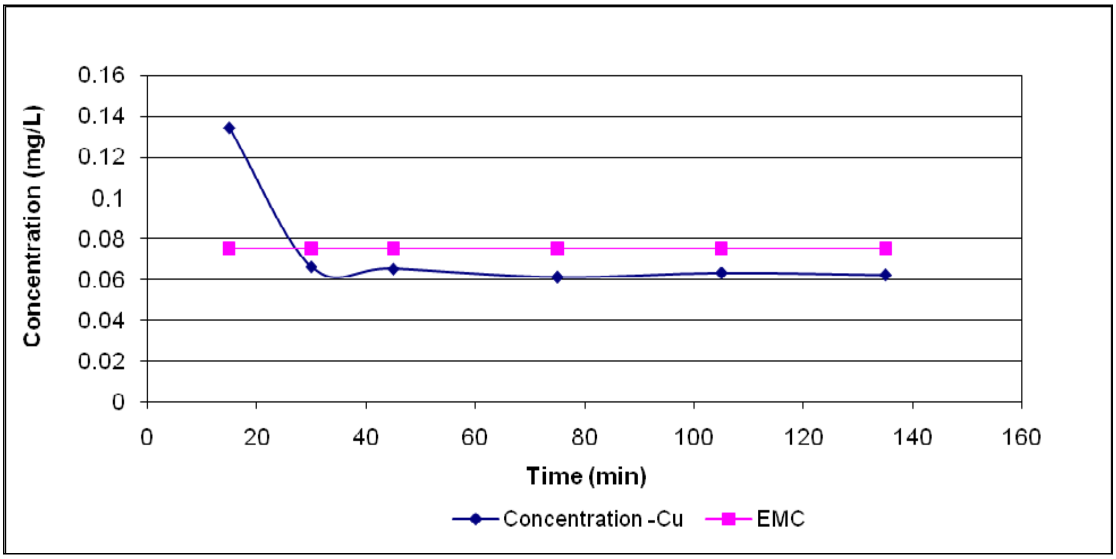


Figure 3.15 Pollutograph of Copper output from the rig

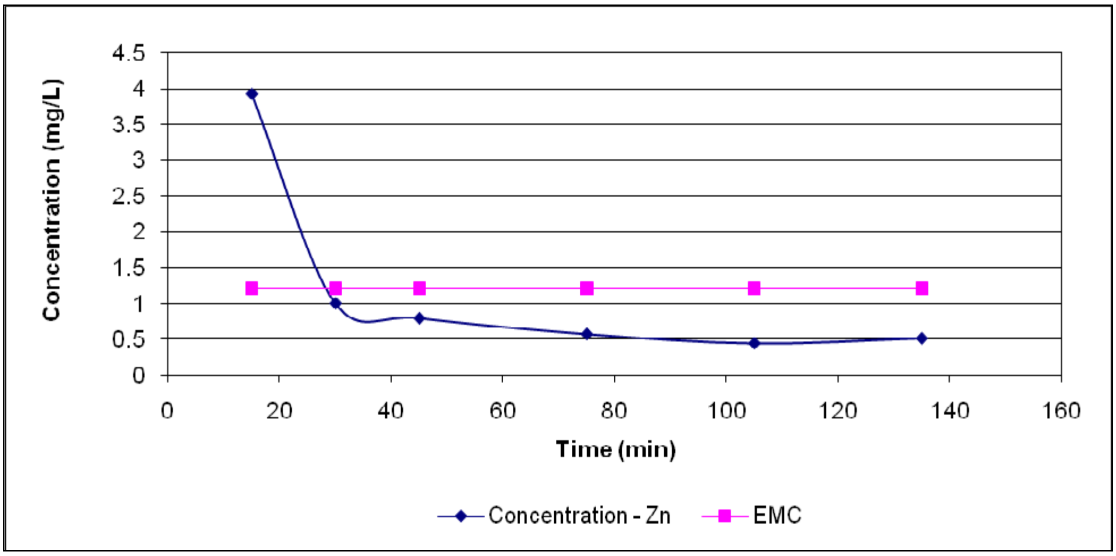


Figure 3.16 Pollutograph of Zinc output from the rig

Cd and Pb were below detectable levels and as a result there are no pollutographs for these two parameters.

Event Mean Concentrations (EMC) were calculated using Equation 3.5.

$$EMC = \frac{\sum_{t=0}^{T} Q_t C_t}{\sum_{t=0}^{T} Q_t} \qquad (3.5)$$

where,

EMC = Event mean concentration of a particular water quality parameter (mg/L)

Q_t = Discharge at a given time t (L/s)

C_t = Concentration of the water quality parameter at time t (mg/L)

T = Time base of the hydrographs

The EMC for the above simulation is

$$EMC_{TN} = \frac{25.8 + 23.1 + 25.53 + 17.7 + 17.11 + 17.7}{0.86 + 1.05 + 1.11 + 1.18 + 1.18 + 1.18} = 19.4 \text{ mg/L}$$

The total output pollutant load (Table 3.6) which is equal to 2572.2mg was calculated by multiplying the EMC with total infiltrated volume of water collected (132.6L) from underneath the test rig (Equation 3.6).

Total pollutant Load = EMC*(Total infiltrated volume of water) (3.6)

The removal efficiency of the each pollutant is calculated using Equation 3.7. Table 3.5 shows the removal efficiencies of water quality parameters obtained in this research project.

Removal efficiency = (∑ Input -∑ Output) /(∑ Input) (3.7)

As a specimen calculation, the removal efficiency of TSS after 5 years simulation

={(5*95180)–(5271.3+5871.7+6095+7046)}/(5*95180)

= 0.949*100 = 94.9 %

Table 3.4 The weight of pollutants of the synthetic stormwater sample sprayed over the pavement to represent equivalent pollutants over a time period

Time (Years)	Input Pollutant load (mg)							
	TN	TP	Zn	Cu	Cd	Pb	TSS	Oil
1	1775.2	162	67.5	40.5	4.73	67.5	95180	13500
2	1775.2	162	67.5	40.5	4.73	67.5	95180	13500
3	1775.2	162	67.5	40.5	4.73	67.5	95180	13500
5	3550.5	324	135.0	81.0	9.45	135.0	190360	27000
7	3550.5	324	135.0	81.0	9.45	135.0	190360	27000
9	3550.5	324	135.0	81.0	9.45	135.0	190360	27000
11	3550.5	324	135.0	81.0	9.45	135.0	190360	27000
13	3550.5	324	135.0	81.0	9.45	135.0	190360	27000
15	3550.5	324	135.0	81.0	9.45	135.0	190360	27000
17	3550.5	324	135.0	81.0	9.45	135.0	190360	27000

Table 3.5 Pollutant loads in output flow from the rig

Years of simulation	Output pollutant load (mg)					
	TN	TP	Zn	Cu	TSS	Oil
1	657.9	76.2	98.4	2.5	5271.3	1940.4
2	764.0	37.6	23.2	3.1	5871.7	2028.7
3	796.7	43.7	54.4	2.4	6095.0	2585.4
5	2572.2	76.7	155.4	2.1	7046.0	3081.6
7	4079.9	333.6	143.7	13.2	6104.9	3364.3
9	3473.0	275.2	190.0	2.5	7822.9	3512.5
11	3761.3	363.4	186.2	2.1	8287.5	3725.8
13	4331.6	343.6	12.9	2.3	9740.8	4016.6
15	3389.9	280.5	0.0	1.5	12105.2	4480.3
17	2726.3	307.6	0.0	0.0	14261.7	4935.7

Table 3.6 Removal efficiencies of pollutant load

Equivalent Pollutant addition in years	Total Pollutant Removal Efficiency/ (%)					
	TN	TP	TSS	Oil	Zn	Cu
1	62.94	52.96	94.46	85.63	-45.82	93.72
2	59.95	64.89	94.15	92.49	9.87	95.77
3	58.34	67.6	93.96	93.62	13.07	96.47
5	46.03	71.1	94.9	95.43	1.81	96.85
7	28.62	49.94	95.44	96.44	-0.55	94.41
9	22.74	42.19	95.54	97.11	-9.47	94.97
11	17.53	32.31	95.56	97.49	-14.64	95.41
13	11.45	26.41	95.45	97.71	1.53	95.71
15	10.52	24.68	95.21	97.79	14.66	96.03
17	12.02	22.37	94.89	97.85	24.7	96.45

The removal efficiencies for TSS and Cu are around 95% and that of Oil varies between 85% and 97%. However the removal efficiencies obtained for TN and TP are very low. This could be due to the presence of leachate of organic matter in the soil. The decomposition of granular material can also cause leaching of TN and TP.

The removal efficiencies of Zn show negative values indicating a gain in Zn. This is mainly due to the oxidation of the galvanized iron test rig.

Rommel et al. (2001) reported that the ultimate decrease of permeability is likely to be 80% of the initial as constructed infiltration rate after 35 years of use. That is, effective long term permeability is 20% of the new product value. The time taken to reach this level of permeability depends on the nature and rate of sediment contamination at the site. Rommel et al. (2001) showed that for a pervious pavement with a ratio of paved area to permeable area of 1.0, the “lifespan” is likely to be around 40 years. As summarised in Table 2.2, Valkman, (1999), Pratt et al. (1989), Rommel et al. (2001), Borgwardt, (1994) and Abbott (2000) reported the performance of pervious pavements with usage. These authors revealed that pervious pavements can be used for at least 20 years without remediation. However, a properly designed maintenance program could extend the useful life of the pavement.

The current research further confirmed the above results. With 17 years of simulated pollutants, the infiltration rate had reduced only by 9%. Furthermore, laboratory results showed that after 17 years of usage, the removal efficiencies of pollutants TSS (95%), Oil (98%) and Cu (96%) were as from a new pervious pavement (Table 3.5). Rommel et al. (2001) have suggested that with a routine maintenance programme (cleaning and vacuuming), the clogging of the pavement could be reduced. Furthermore, by introducing swales (Rushton, 2002) upstream to the pervious pavement, the washing of pollutants on to the pavement surface could possibly be controlled.

3.4 Summary and conclusion

Previous research suggests that pervious pavements reduce the pollutant loads in stormwater while infiltrating the water through the surface. Based on the existing limited research, it was decided to examine the retention of TN, TP, TSS, Oil and heavy metals (Pb, Cu, Cd and Zn) on the pervious pavements when stormwater is infiltrated through its structure. Synthetic stormwater samples were prepared in the laboratory and sprayed on the pavement rig. The rainfall was simulated on top of the pavement and the infiltrated water was collected from the bottom of the experimental rig.

The laboratory results clearly show that the removal efficiencies of TSS, oil and Cu vary between 80% and 98% after spraying equivalent to 17 years of pollutants on to the pavement rig. In some circumstances, the output load of Zn was greater than input. This unusual behaviour is due to decay of the steel frame in which the pavement was built. This was confirmed while carrying out the trial simulation using only tap water without any pollutants. Removal rates of TN and TP were low compared to other pollutants. This is due to the leaching of TN and TP in the granular material in the sub-base and the decomposition of aggregate used for the pavement structure.

At the end of the 17 simulated years, the reduction in infiltration rate was calculated using initial and final infiltration rates. The results show that the reduction in infiltration rate due to entrapping of sediments was 9% of its initial infiltration rate. Therefore clogging is not a major concern, and pervious pavements can therefore be used for more than 20 years without remediation. The application of pervious pavements can result in long term environmental benefits such as reduction in runoff volumes and improvements in water quality parameters entering receiving waters. However, an appropriate maintenance program must be planned before the construction of the pervious pavement. Regular maintenance such as vacuuming or the use of high pressure water jets will help to reduce the clogging of the pavement.

The initial results obtained from the laboratory pavement rig were useful when planning and implementing the field scale experimental car park. The results obtained clearly show that pervious pavements effectively reduce the volume of water and peak discharge and reduce the pressure on urban drainage infrastructure. Furthermore, pervious pavements are capable of removing pollutants that are present in urban stormwater.

4 FIELD STUDY

Over the last few years a number of urban developments in Australia have constructed pervious pavements as a WSUD feature. The Olympic Boulevard at the Homebush Olympic site in Sydney, constructed in 1999 is an example. Furthermore, there are some roads that have been constructed since 1998. Examples include roads in Kiama and Smith Street in Manly, Sydney. A car park was constructed in July 1999 by the City of Charles Sturt, using BORAL Formpave units at Kirkaldy Avenue, Adelaide. The car park located adjacent to the North Haven Football Clubrooms was constructed by the City of Port Adelaide, Enfield in late 1999 using BORAL Formpave unites. A Grasspave installation was completed in 1997 at the premises of St. Elizabeth's Anglican Church in Adelaide. The use of pervious pavements would increase in Australia if their stormwater improvement features (both quantity and quality) are quantified and design guidelines developed to assist WSUD.

Research has been limited to a few studies carried out to investigate the application of pervious pavements in Australia. Most of the research studies have concentrated on design aspects, structural durability, reduction in volume of surface runoff and peak discharge from pervious pavement. The research carried out on water quality improvements is restricted to a small number of parameters. Pervious pavement as a WSUD measure has not been widely used by water authorities, councils, land developers and builders, mainly due to lack of information as highlighted in Chapter 2. As a result, further research is necessary on water quality and quantity improvements, structural durability and maintenance and design guidelines to promote wider use.

For the purpose of the present study, an experimental car park was built with two types of pervious surfaces namely C&M Ecotrihex pavers and Atlantis Turf Cells. A conventional asphalt (impervious) surface was also built as a control to simulate the base case. The two pervious surfaces were selected to compare the effectiveness and maintenance of pervious pavements so that they could be introduced as sustainable stormwater management elements.

The chapter will initially report on site description followed by design aspects and parameters of C&M Ecotrihex, Atlantis Turf Cell and asphalt pavement. The field set-up will include a description of the instrumentation at the sampling site. The data analysis will include both simulated and natural rain events followed by reduction in water quantity. The chapter will conclude by presenting the results of water quality improvements.

4.1 Site Description

A pervious car park was built at the Centre for Education and Research in Environmental Strategies (CERES) in Brunswick, Melbourne, Australia for the study. CERES is a community environment organisation which aims to foster awareness and action on environmental and social issues affecting urban areas. The site displays functional demonstrations on a range of environmental issues to show just what can be achieved at household, community and local levels. The conventional staff car park located at CERES was been converted to a pervious pavement car park for the study. Figure 4.1 shows the car park before the pervious pavements were constructed.

Figure 4.1 The staff car park at CERES before the pervious pavements were installed

The size of the study area is 200 m^2 (15m * 13m). The study area was separated into 3 experimental areas with different pavement surfaces as shown in Figure 4.2. C&M Ecotrihex pavers and Atlantis Turf Cells were used as pervious pavement surfaces and an impervious Asphalt surface was used as the control site. Each surface type consisted of two car parking spaces of 50.4 m^2 (4.8m * 10.5m). As shown in Figure 4.2, each pavement type was separated with vertical impermeable geotextile to avoid water flowing between experimental sites. Agricultural (Agi) pipes were installed around the experimental car park to avoid water entering from surrounding areas (Figure 4.3) and to ensure the site was a closed catchment for experimental purposes.

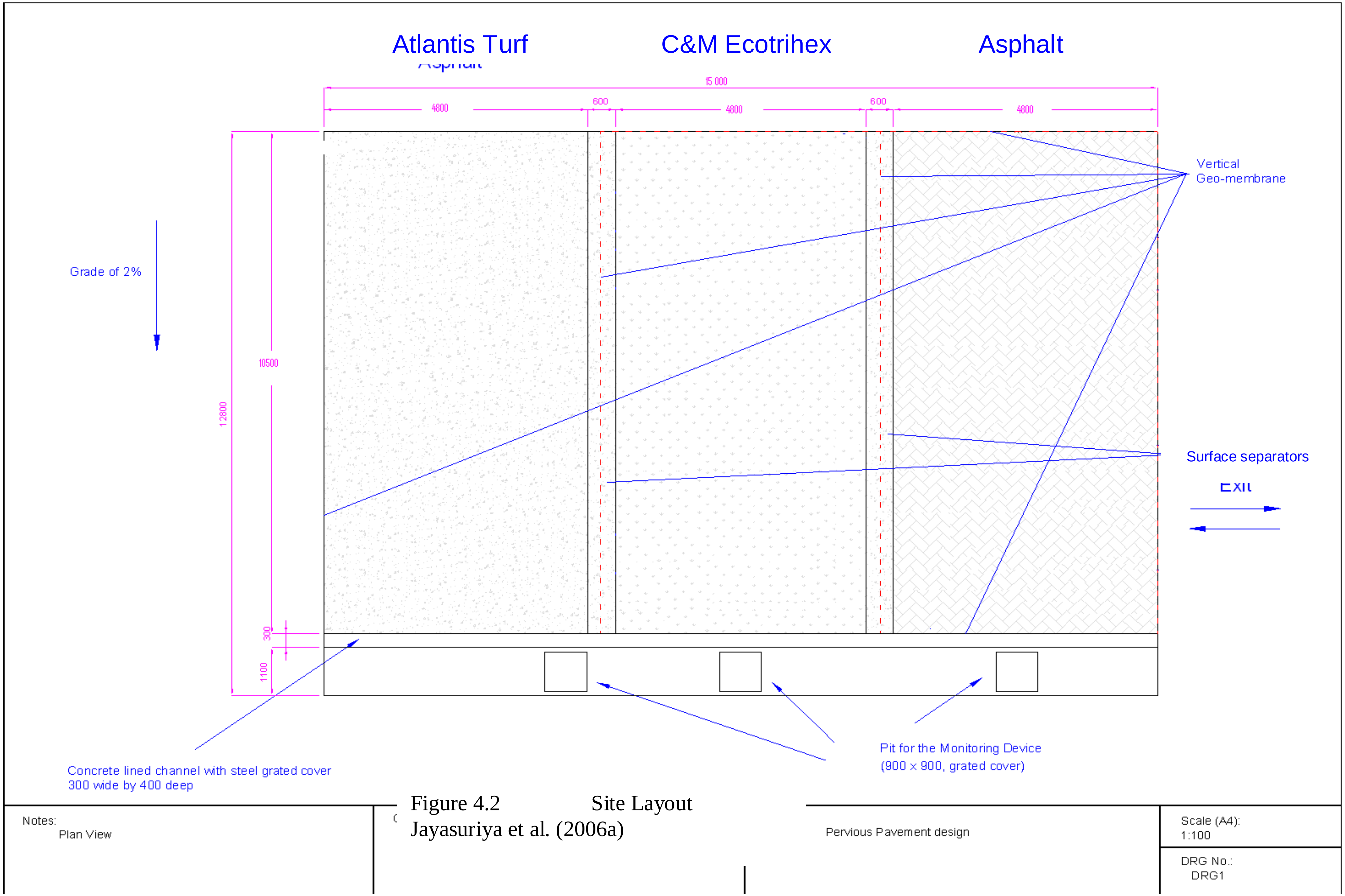


Figure 4.2 Site Layout
Jayasuriya et al. (2006a)

Figure 4.3 Agricultural pipes installed around the car park

4.2 Design of Pervious Pavements

Proper design of pervious pavement plays a role of vital importance to its performance in reduction of water quantity and improvement to infiltrated water quality. As mentioned in Chapter 2, Shackel (1993) used the PCSWMMPP model (James et al., 1992) and LOCKPAVE V15.2 to design the drainage arrangement and structure of the pervious pavement in Smith Street, Sydney. Shackel et al. (1996) carried out a number of tests before recommending the thicknesses of the bedding and the base layers of the pavement depending on the conditions of the sub-grade. The authors also considered at the load-bearing capacities based on the amount of traffic movement on the pavement. The pervious pavements used in the current research were designed based on the recommendations by Shackel et al. (1996).

Figure 4.4 is a schematic diagram of a pervious pavement used to infiltrate stormwater with the potential for reuse. The drainage design of pervious pavements can be carried out in two different ways, according to the sub-grade soil type at the site. If the sub-grade soil is highly impermeable such as silty clay, the drainage pipe is laid close to the bottom of the bedding layer. The drainage from the pavement will depend on the sub-grade material. Sandy soil with deep groundwater best suits pervious pavements designed to recharge groundwater (Jayasuriya et al, 2006a). The information given in Table 4.1 on sub-grade soil was obtained from tests conducted at RMIT laboratories.

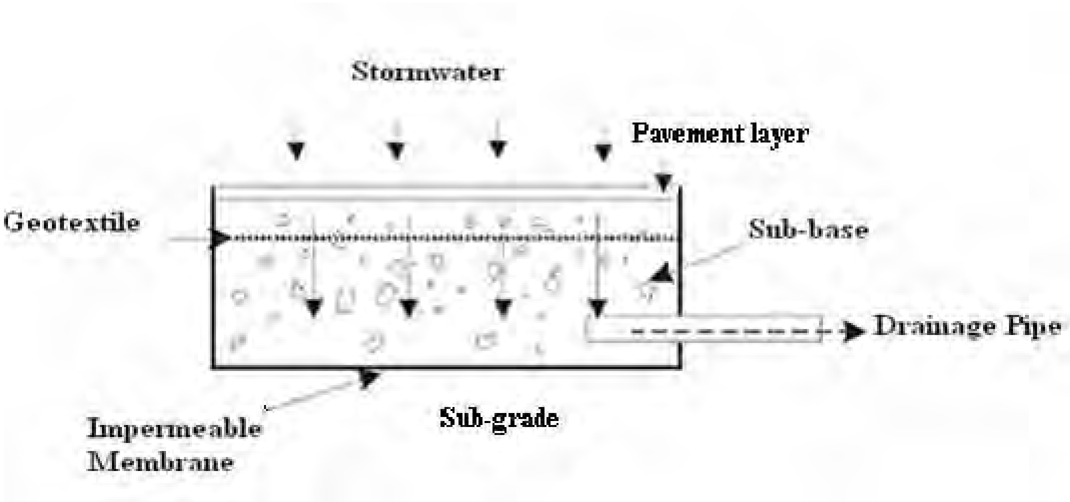


Figure 4.4 Schematic diagram of a pervious pavement (www.ciria.org)

Table 4.1 Details of sub-grade soil at experimental site

Parameter	Value
Soaked CBR	4
Swell	1/2%
Optimum moisture content	35%
Maximum dry density	1.470 ton/m^3

Based on the soil profile records taken from CERES, the sub-grade soil was classified as Silty Clay. Although the hydraulic conductivity of this type of soil is very low, it was decided to lay an impermeable geotextile between the sub-base and sub-grade in order to capture all the infiltrated water. The physical properties of the sub-grade soil are also needed to achieve the correct compaction when constructing the pavement. The base layer of the pavement should be compacted to achieve an optimum moisture content equal to 98% of maximum dry density (Table 4.1).

4.2.1 C&M Ecotrihex

As mentioned earlier the design of the pervious C&M Ecotrihex pavement structure was based on recommendations of Shackel et al. (2003) and verified using LOCKPAVE Version 15.2. The pavement configuration, thickness of the bedding and sub base, and the aggregate sizes are given in Figure 4.5.

The grading curves of the 2 to 5 mm coarse aggregate and the 5 to 20 mm open graded aggregate bedding material are given in Figure 4.6

The following results give the optimum moisture content equal to 98% of maximum dry density for the bedding and sub base materials with the C&M Ecotrihex pavement.

Bedding material	Optimum moisture content	2.3%
	Maximum dry density	1.766 ton/m3
Sub-base material	Optimum moisture content	3.0%
	Maximum dry density	1.744 ton/m3

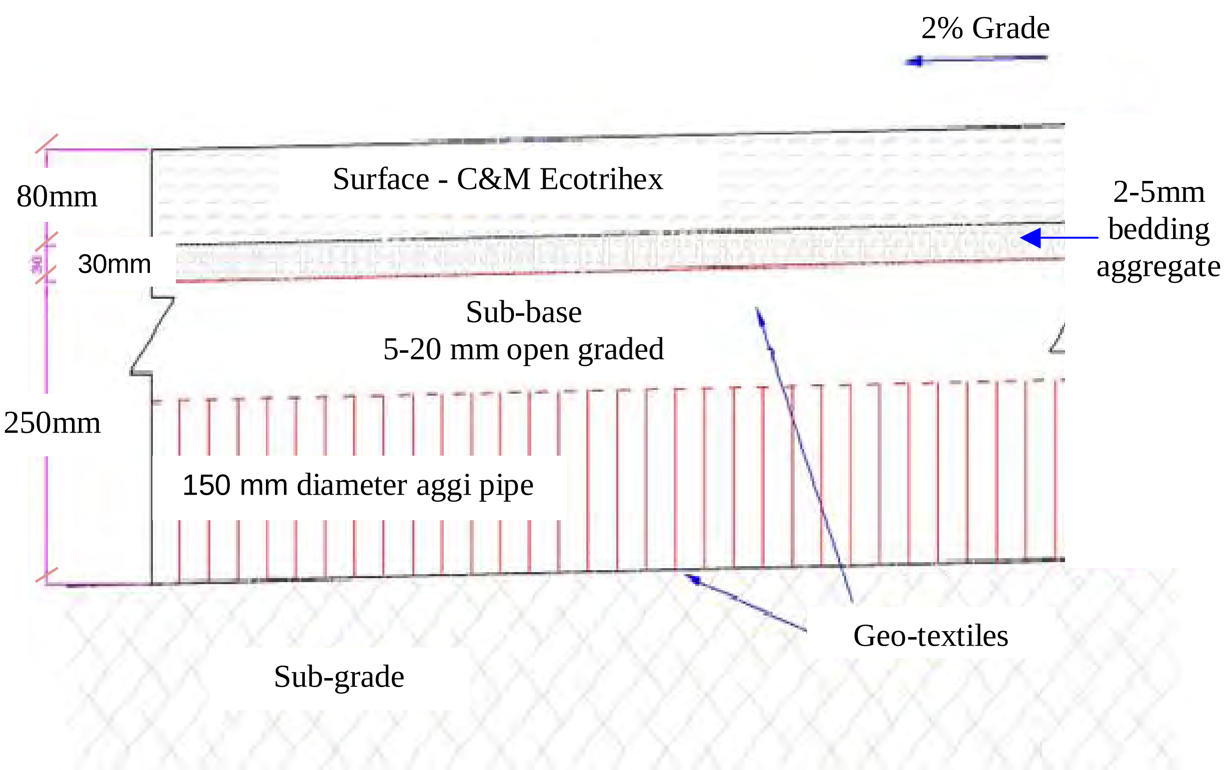


Figure 4.5 Cross section of C&M Ecotrihex pavement

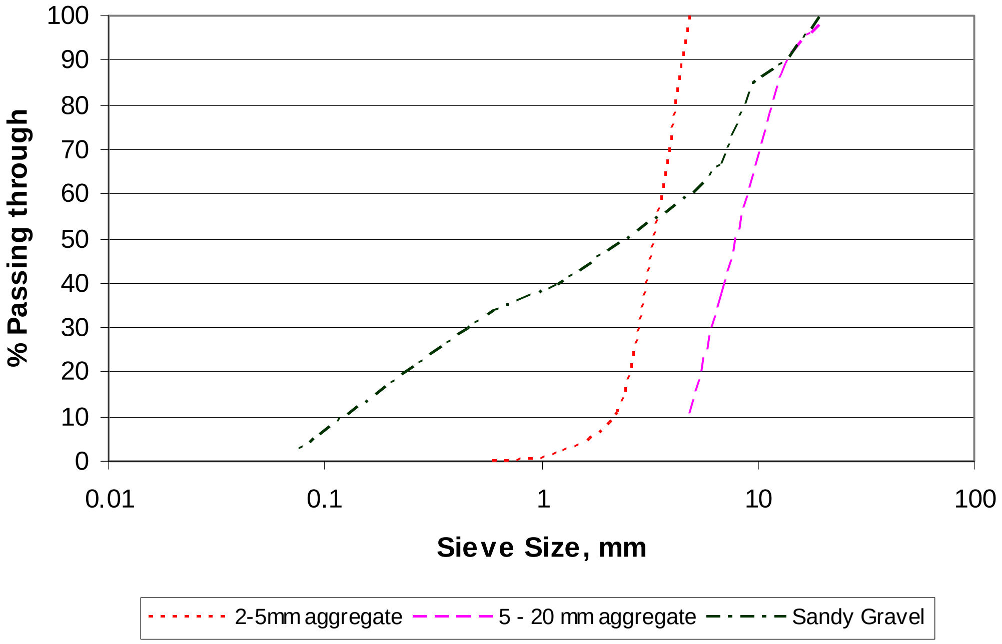


Figure 4.6 Grading curves of the aggregates used for the bedding layer and subbase (Jayasuriya et al, 2006a)

4.2.2 Atlantis Turf Cell

The design of the Atlantis Turf Cell pavement was based on the information provided on www.atlantiscorp.com.au and personal communication with the Atlantis Turf Cell provider, Wayne Alexander and verified using LOCKPAVE Version 15.2. The pavement configuration and design details of the pavement structure are given in Figure 4.7.

The Turf Cell was placed on a permeable geo-textile. It was filled with clean fine sharp sand (washed concrete sand) mixed with a starter fertilizer. It is important that Turf Cells should not be filled with top soil and the grass should be a species resistant to wear by traffic. The subbase material is classified as sandy gravel material. The grading curve is given in Figure 4.6. Alternatively, this mixture could be replaced with 2/3 of 19 mm crushed rock and 1/3 river sand.

It was decided to use the same subbase material for both the C&M Ecotrihex and the Atlantis Turf Cell pavements. As a result, the optimum moisture content of 3.0 % was maintained at a maximum dry density of 1.744 ton/m^3 for the subbase.

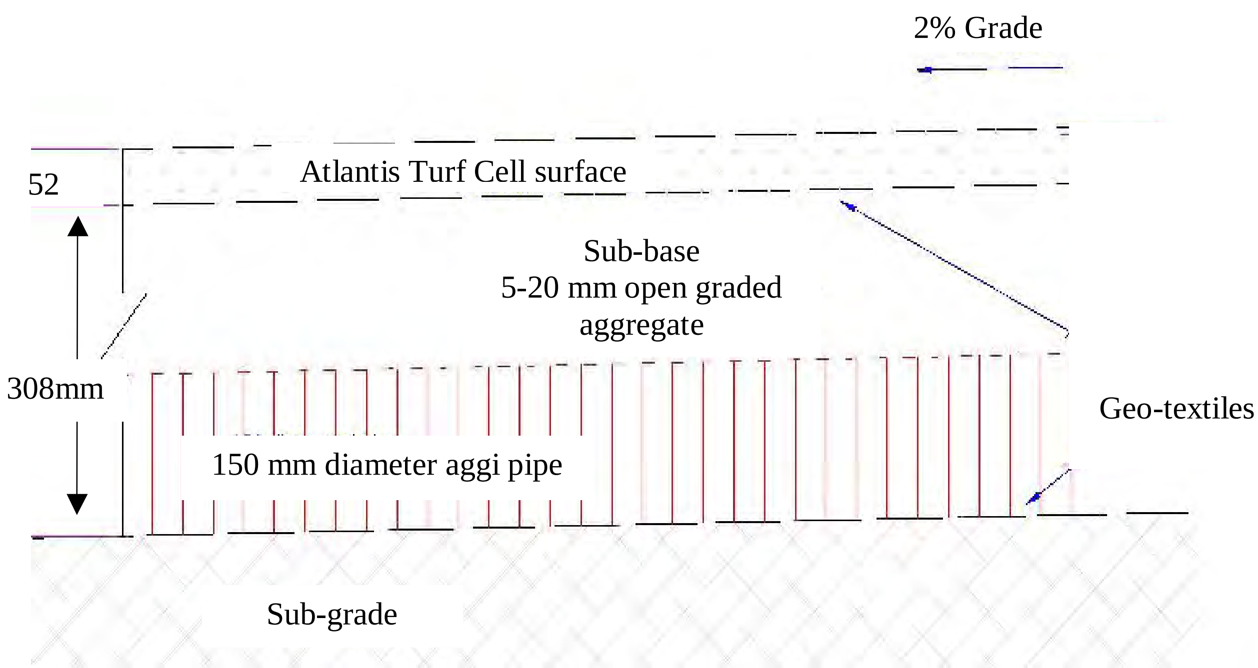


Figure 4.7 Cross section of Atlantis Turf Cell pavement

4.2.3 Asphalt pavement

The asphalt pavement thicknesses and materials were specified according to the Pavement Design guidelines, Austroad manual (Jayasuriya et al, 2006a). The aggregates are according to the appropriate Australian Standard and VicRoads specifications. The cross-sectional details of the Asphalt pavement are provided in Figure 4.8 below.

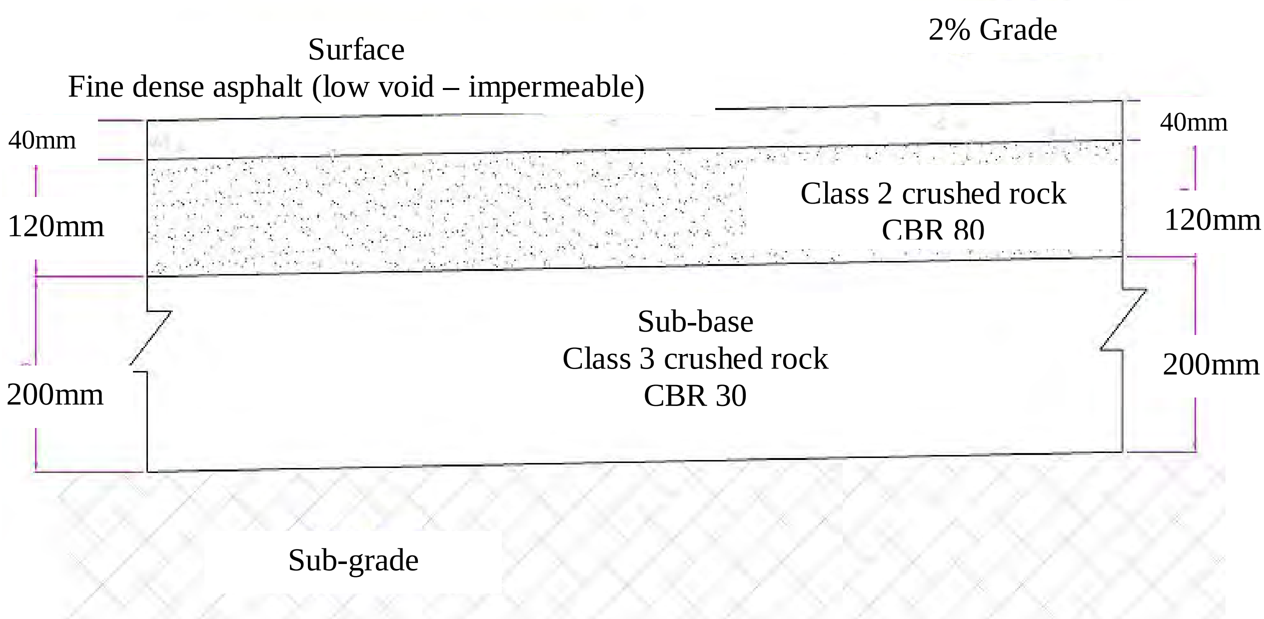


Figure 4.8 Cross section of asphalt pavement

4.2.4 Drainage design

Jayasuriya et al (2006a) used the PCSWMMPP model to design drainage in the two pervious surfaces. This program has been developed for the hydraulic design of eco-pavement and is derived from the well-known US EPA SWMM program (James, 2003). The program uses the Green and Ampt infiltration equation and Darcy's percolation equation for drainage design. The theory behind the hydraulic principle, the input parameters and the application of the PCSWMMPP model will be described in detail in Chapter 5.

The constant head permeability rate test was carried out with both types (bedding and sub-base) of aggregates to obtain the saturated hydraulic conductivity of the materials. Zhang at al (2006) reported the permeability rate of the bedding material to be 4.45×10^{-2} mm/s at hydraulic gradient of 1 and applied pressure of 200 kPa. Under the same experimental conditions, the permeability rate of the sub-base material was 6.35×10^{-2}mm/s.

The aggregate properties were used to calculate the parameters in the Green and Ampt infiltration equation. The Green and Ampt infiltration equation is presented and explained in Chapter 3. Variation of infiltration rate with infiltrated volume for 2 to 5 mm aggregate are given in Figure 4.9.

Zhang et al. (2006) used aggregate properties to calculate parameters for the Green Ampt infiltration equation and Darcy's percolation equation. Jayasuriya et al. (2006b) used parameters recommended by Zhang et al (2006) for the PCSWMMPP computer program to design the drainage system. The drainage infrastructure was designed to capture stormwater infiltrated from a 1 in 100 year storm. Thus the ARI value was selected based on the urban drainage design guidelines (Australian Rainfall and Runoff, 1999). The study showed that 150 mm diameter Agricultural pipes are required at the bottom of the sub-base to capture infiltrated water from the C&M Ecotrihex and Atlantis Turf pavement.

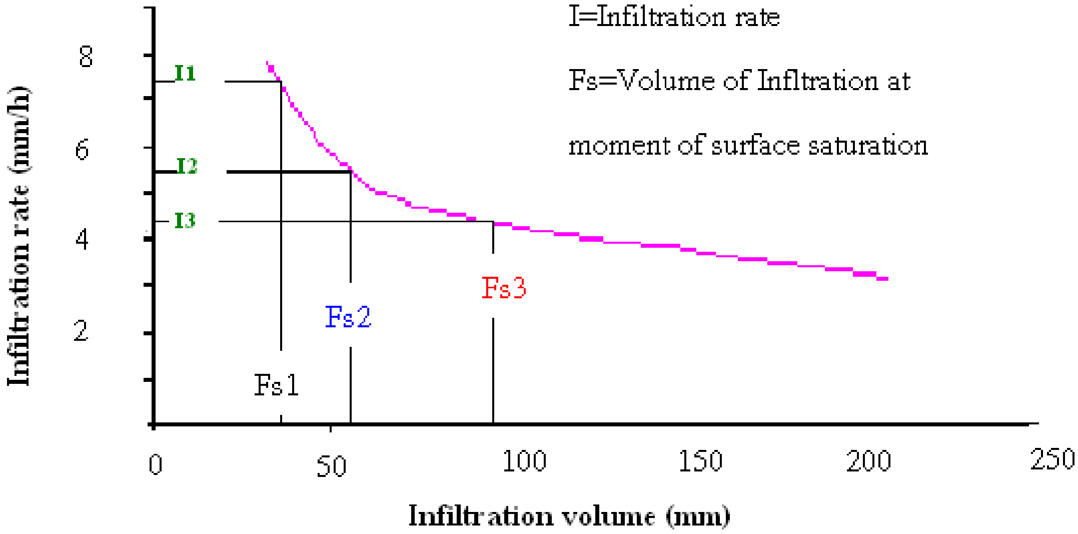


Figure 4.9 Infiltration rate and infiltration volume through the bedding layer for the C&M Ecotrihex pavement (Jayasuriya et al, 2006a)

Infiltrated stormwater was collected in a channel at the end of the car park through a perforated pipe installed at the middle of the pavement (Figure 4.10). Stormwater samples were collected at the sample point shown in Figure 4.11.

Figure 4.10 The pervious car park during construction at the CERES Environment Park in Brunswick, Melbourne

Figure 4.11 Sample Point showing entry of drainage pipe

4.3 Field Setup

Each test surface, namely C&M Ecotrihex, Atlantic Turf Cell and conventional asphalt, contained a flow meter and an autosampler as described below. Figure 4.12 shows the photograph of the field car park.

Three auto samplers were installed in the field to collect event-based water quality samples from the three types of pavements. Auto samplers were placed in special pits. Each pit was covered by a 900mmx900mm grated pit cover (Figure 4.12). One sampler collected surface runoff from the impervious surface (control surface). Stormwater from the control pavement surface flowed to the 300mmx400mm channel. Another two samplers collected the water infiltrated through the Ecotrihex and Atlantis Turf Cells respectively. Samples were collected from the drainage pipes laid on the base layer of each pavement. The stormwater infiltrated through the pervious concrete block and the Turf Cell was captured via a properly designed drainage system. The infiltrated water was diverted to a small onsite dam for productive recycling use in the future. The quality of the infiltrated water in the car park through the pervious material was be monitored and benchmarked against the surface water quality flowing through the conventional car park. The water quality parameters monitored included Total

Suspended Solids (TSS), Total Nitrogen (TN), Total Phosphorus (TP), Oil and Grease, Lead (Pb), Copper (Cu), Zinc (Zn) and Cadmium (Cd). Surface water quantity flowing over the pavement and through the drain after infiltration was also measured. Three flow meters were installed to measure the surface flow from the control surface and infiltrated water from the two pervious surfaces.

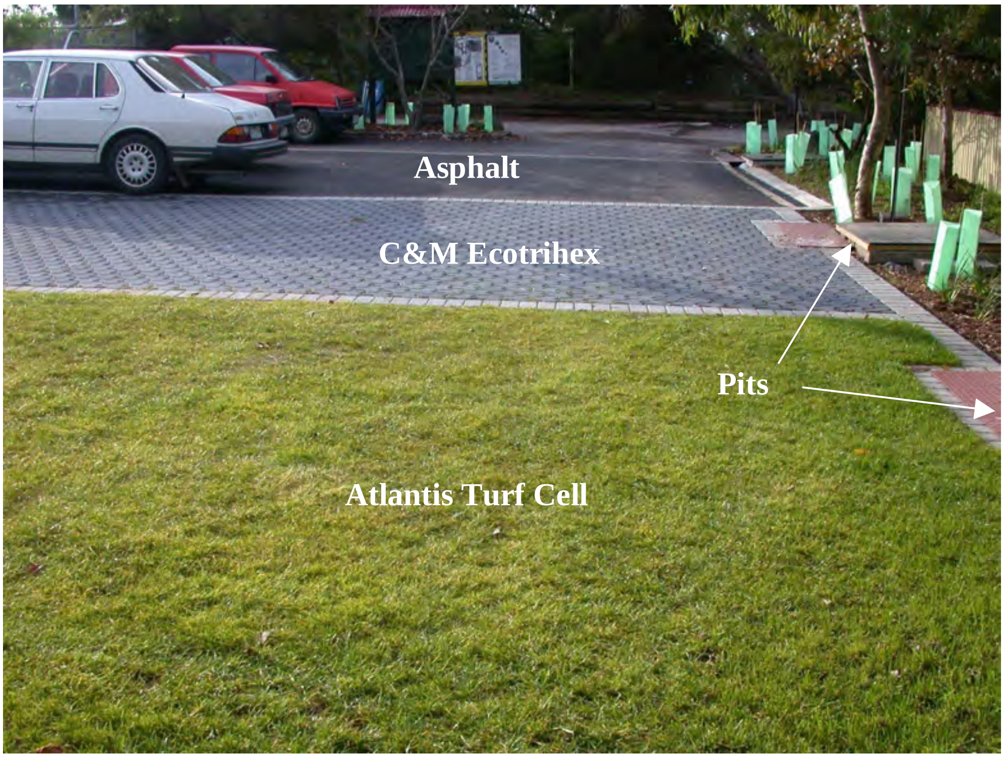


Figure 4.12 Experimental car park at CERES after construction

The traditional method of water quality monitoring involves manually sampling water at remote sites and transporting it to a laboratory for chemical analysis. This approach is non-technical and not easily repeatable. It is also time consuming, leads to inconsistent results, involves high labour costs and does not allow for continuous data collection. Automated instrumentation at the site improved the ability to monitor continuous flow data as well as water sampling in spite of weather and accessibility issues.

As rain events are unpredictable, extremely good instrument set up is necessary to study field scale pervious pavements. Sampling should be carried out simultaneously with flow measurements. Hence the three surfaces that were installed in the field included of three independent flow meters and autosamplers. The flow meters record the flow data whenever they reach a certain amount of flow or water depth. But the autosamplers do not respond to the flow without any initiation such as pressing the start to initiate sampling. Considering all these issues, autosamplers were modified to trigger using flow meters.

As mentioned earlier, three different test surfaces were investigated during the research. To collect the individual flow data and stormwater samples from each surface type it was necessary to have three flow meters and three autosamplers. There were two Sigma 900 autosamplers, one GLI/Manning autosampler, one Sigma 950 flowmeter and two Starflow flow meters. As they are not the same brand, one Starflow meter was modified to work in conjunction with the GLI/Manning autosampler and the combination was installed in the pit opposite to the grass surface as shown in Figure 4.12. As the Sigma 950 flow meter is compatible with the Sigma 900 autosampler, two Sigma 900 autosamplers were connected to the Sigma 950 flow meter using three auxiliary cables. This was able to trigger both the Sigma 900 autosamplers using one Sigma 950 flow meter as shown in figure 4.13.

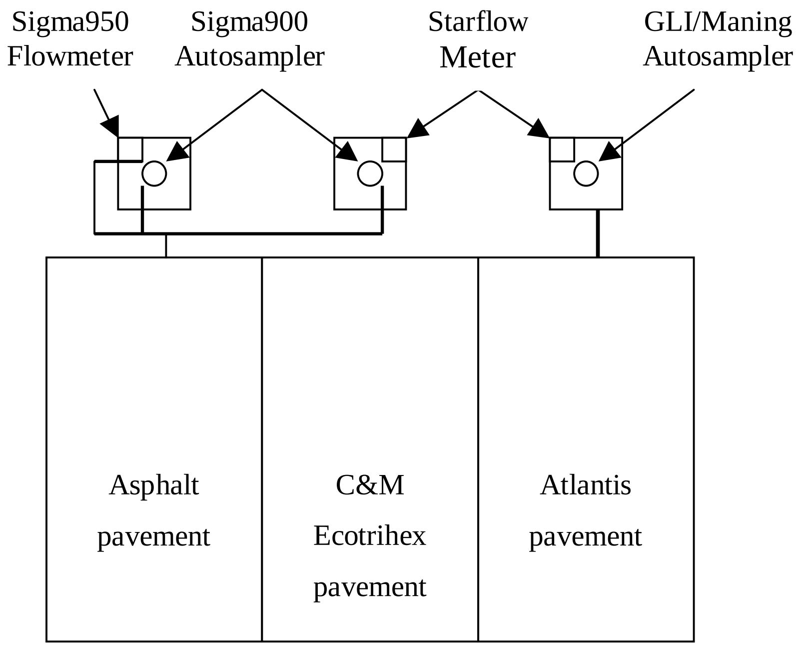


Figure 4.13 Layout of the instrumentation at site

4.3.1 Flow Meters

Accurate flow measurement is very important when calculating infiltration of each permeable surface, especially when using flow-based sampling. There were two types of flow meters at the site. They are the Sigma 950 flow meter (Figure 4.14) and the Starflow flow meter (Figure 4.15). As they are of two different brands, there were some basic differences encountered while programming them for flow measurements. Flow meter sensors were installed inside the drains to measure velocity, flow and depth of water.

Before they were installed in the field, both the Starflow and Sigma 950 flow meters were calibrated in the hydraulics laboratory at the School of Civil Environmental and Chemical Engineering, RMIT University. Calibration was carried out under known flow rate and flow depths. It was found that for smaller flow depths (less than 5mm), the accuracy is less than stated in the company catalogue (2% of the reading). Therefore all the instruments were set up to initiate after flow meters reached more than 5mm of flow depth.

Sigma 950 flow meter

The transducer was installed to calculate the flow, velocity or depth of water that passes through a specific profile. By programming Sigma 950 to “set point sampling”, only the flow meter can be used to trigger the autosampler. The logging interval was set to 1minute as it has a higher data storage capacity. Based on the manual, to achieve higher accuracy, the depth of triggering was specified as 10mm to minimize error.

Figure 4.14 Sigma 950 flow meter

Starflow flow meter (model 6526)

Firstly, the Starflow support software was installed into the computer, then a new scheme was created. At the same time, the scan rate was set to 5 seconds and the logging interval to 2 minutes. Then the scheme was loaded to the installed Starflow flow meter. While installing the transducer inside the drain, extra care was taken to make the surface horizontal to minimise errors. The flow depths, discharges and flow velocities were downloaded after each rainfall event to make sure that no data were lost.

Figure 4.15 Starflow flow meter

4.3.2 Autosamplers

Two different autosamplers were set up in the field, the Sigma 900 (Figure 4.16) and the GLI/Manning (Figure 4.17). As neither are refrigerated autosamplers, sample preservation was carried out according to the Australian Standard Testing Methods (ASTM).

Sigma 900 autosampler

Sigma 900 autosamplers were connected to the flow meter through an auxiliary cable. When the flow depth reached 10mm the flow meter sent a pulse to the autosampler to trigger the sampler. The Sigma 900 autosamplers were programmed to "level control". The sampling interval was set to 15 minutes in the autosamplers. According to the initial rainfall and flow data, it was found that it took take at least one hour to have an outflow from C&M Ecotrihex (concrete block) and Atlantis Turf Cell pavements. Therefore delay time was set to 1 hr. Water samples were taken at 15 minute intervals.

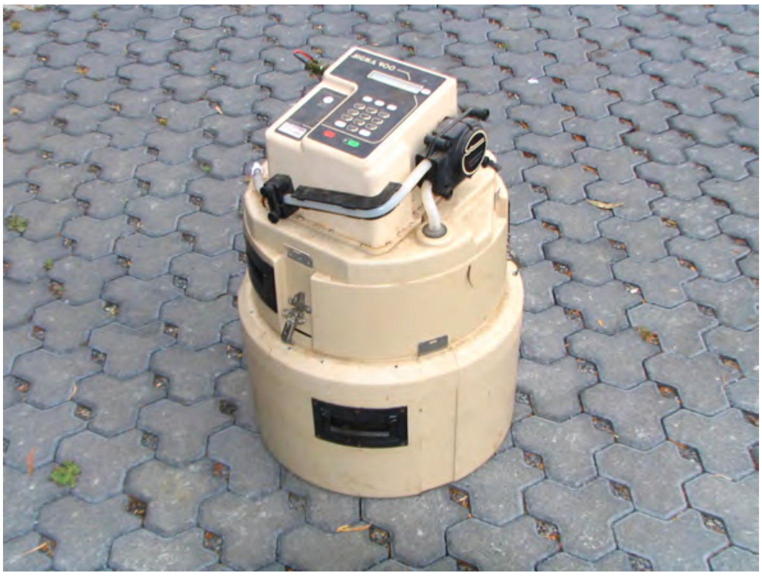


Figure 4.16 Sigma 900 autosampler

GLI/Manning autosampler

The Starflow meter was connected to the autosampler through a cable. The GLI /Manning autosampler was programmed according to flow-based sampling. The sample spacing was set to 15 minutes for the first three samples and then to 30 minutes for the rest. As the combination of both the autosampler and the flow meter are independent of the other instruments, there was no delay in the set up time. When the flow meter reached 10mm of water depth, it sent a signal to the flow meter to start sampling. As a result the sampling is reliable, accurate and independent of time of the rainfall event.

Figure 4.17 GLI/Manning autosampler

4.3.3 Rain gauge

A tipping bucket rain gauge (Figure 4.18) was installed at the field. The rain gauge provided daily rainfall at the site (CERES).

Figure 4.18 Tipping bucket rain gauge (www.scientificsales.com)

4.4 Details of Field Data

The installation of all the flow meters and water quality samplers was completed in September 2006. The data collection began at this site in September 2006 and continued until January 2008. The catchment area considered for natural and simulated rainfall events for each pavement was 50.4 m^2. Since September 2006 there were only 7 natural rain events that produced runoff from the pervious pavements. Table 4.2 shows the dates of rainfall events and the magnitude of the rainfall. The table also contains details of the events and the respective surfaces that produced runoff. The daily rainfalls were recorded from a tipping bucket rain gauge installed at site and were compared with data collected from three surrounding (within 4km) rain gauging stations. The maximum daily rainfall recorded at the site was 20 mm/day. The asphalt surface produced runoff with a minimum total rainfall of 3 mm. The C&M Ecotrihex surface produced runoff from seven storms with 13 mm, 14 mm, 15mm, 18 mm, 20mm, 24mm and 25mm events occurring on 2 November, 2006, 24 March 2007, 18 May 2007, 27 June 2007, 13 July 2007, 04 November 2007 and 21 December 2007 respectively. So far the Atlantis Turf Cell pavement produced runoff only from four actual storm events on 27 June, 12 July 2007, 04 November and 21 December 2007 respectively.

Table 4.2 Dates of rainfall events, the magnitude of the rainfall and surface that produced runoff

Date	R/F/(mm)	Asphalt	C&M	Grass
26/10/2006	1			
27/10/2006	4	*		
02/11/2006	13	*	*	
12/11/2006	3			
15/11/2006	3	*		
16/11/2006	2			
22/12/2006	3	*		
23/12/2006	1			
24/12/2006	1			
25/12/2006	5	*		
26/12/2006	1			
20/01/2007	3	*		
26/01/2007	3	*		
27/01/2007	3	*		
10/02/2007	1			
19/02/2007	3	*		
24/02/2007	7	*		
20/03/2007	1			
24/03/2007	14	*	*	
25/03/2007	8	*		
29/03/2007	10	*		
22/04/2007	10	*		
28/04/2007	3	*		
29/04/2007	1			
1/05/2007	6	*		
3/05/2007	3	*		
4/05/2007	5	*		
16/05/2007	4	*		
18/05/2007	15	*	*	
19/05/2007	3	*		
30/05/2007	6	*		

Date	R/F(mm)	Asphalt	C&M	Grass
11/06/2007	6	*		
12/06/2007	3	*		
20/06/2007	5	*		
21/06/2007	4	*		
26/06/2007	7	*		
27/06/2007	18	*	*	*
28/06/2007	1			
30/06/2007	2			
1/07/2007	3	*		
2/07/2007	1			
4/07/2007	3	*		
5/07/2007	2			
6/07/2007	5	*		
7/07/2007	8	*		
8/07/2007	7	*		
9/07/2007	1			
12/07/2007	20	*	*	*
14/07/2007	2			
15/07/2007	1			
18/07/2007	9	*		
19/07/2007	3	*		
21/07/2007	1			
26/07/2007	2			
28/07/2007	1			
28/07/2007	1			
01/11/2007	4	*		
04/11/2007	24	*	*	*
20/12/2007	5	*		
21/12/2007	25	*	*	*
22/12/2007	7	*		

The lack of rainfall in Melbourne in the past year has been a major factor influencing the progress of the research. Therefore, due to lack of natural rain a decision was taken to install sprinklers to simulate rainfall. It was necessary to obtain permission from Yarra Valley Water (one of the retail water suppliers in Melbourne) to use sprinklers as Melbourne is currently under Level 3A water restrictions. The sprinklers were selected and placed so that the water was uniformly sprayed over each surface. When constructing the pervious pavements aggi (agricultural) pipes (Figure 4.3) were placed around the experimental field to prevent surface water flowing from adjacent areas to the experimental site, thus producing closed conditions. Hence, there was no difference between the stormwater generated from a real storm and a sprinkler-simulated event. The flow rate from the sprinklers was adjusted to simulate different rainfall intensities between 14 mm/hr to 21 mm/hr. The storm durations were varied between 25 mins to 55 mins to cover typical rainfall events in Melbourne.

4.4.1 Estimating hourly rainfalls to develop the storm pattern

Rainfall monitoring continued throughout September 2006 to January 2008. A tipping bucket rain gauge was installed at the site to obtain daily rainfall. It is important to obtain the hourly rainfall patterns to study runoff hydrographs. Data from Flemington, Northcote and Coburg continuous rain-gauging stations maintained by Melbourne Water within a 4km radius of the research site were used to calculate rainfall hyetographs (hourly rainfall) at CERES.

The two accepted methods for calculating average rainfall of an area are the Thiessen polygon method (Figure 4.19) and the Isohyetal method (Figure 4.20). These methods calculate the area-weighted average of the rainfall amounts. Each uses a different technique to delineate the sub-areas for which individual precipitation measurements are assumed to be representative.

Both methods use a weighted average method and calculate the average rainfall over the catchment using Equation 4.1. The Thiessen polygon uses areas based on polygons, whereas the Isohyetal method uses areas based on the isohytal map.

$$\bar{P} = \frac{A_1 P_1 + A_2 P_2 + \dots\dots\dots + A_n P_n}{A_T} \qquad (4.1)$$

where,

A_i = Area of i^{th} catchment

A_T = Total catchment area = $A_1 + A_2 + A_3 + ... + A_n$

P_i = Rainfall intensity of i^{th} catchment

The Isohyetal method needs rainfall data from a larger number of rain gauging stations to locate the rainfall isohytals than the Thiessen Polygon method. As there is limited available data, the Thiessen polygon method was used to calculate the hourly rainfalls for each rain event.

Considering 10 rain gauge stations with known co-ordinates (Melbourne Water), Figure 4.21 was drawn using AutoCAD 2006. The stations were connected (Red) as shown in Figure 4.21 to draw triangles. Perpendicular bisects were drawn to each triangle and rain polygons were located as shown in green lines. Areas of each polygon that include the three selected nearby rain gauging stations to CERES (Flemington, Northcote and Coburg) were calculated and used to calculate the hourly rainfall at CERES. The areas of Polygons 1, 2 and 3 are 14.77, 17.09 and 23.93 km^2 respectively. Table 4.3 shows the data used and hourly rainfall values obtained at CERES for the rain event occurring on the 18th of May 2007.

As given in Equation 4.1, the cross-product of each "n" of the sub-area and its corresponding rainfall amount are summed and then divided by the total area. The results are tabulated in Table 4.3

A specimen calculation of the readings for the first hour in Table 4.3 is as follows.

$$P1 = (0.2*17.09 + 0.6*23.93 + 0.2*14.77)/ (17.09+23.93+14.77)$$

$$= 0.4 \text{ mm/hr}$$

As given in Table 4.3, the total rainfall calculated using the Thiessen polygon method at CERES is 15mm/day for the storm occurring on 18^{th} May 2007. Table 4.4 depicts the total rainfall values obtained from nearby gauges using the Thiessen polygon method and the values recorded at CERES. As the estimated total rainfall values were very close to the observed rainfall values, hourly rainfall hyetographs calculated from the nearby gauges were used for the study.

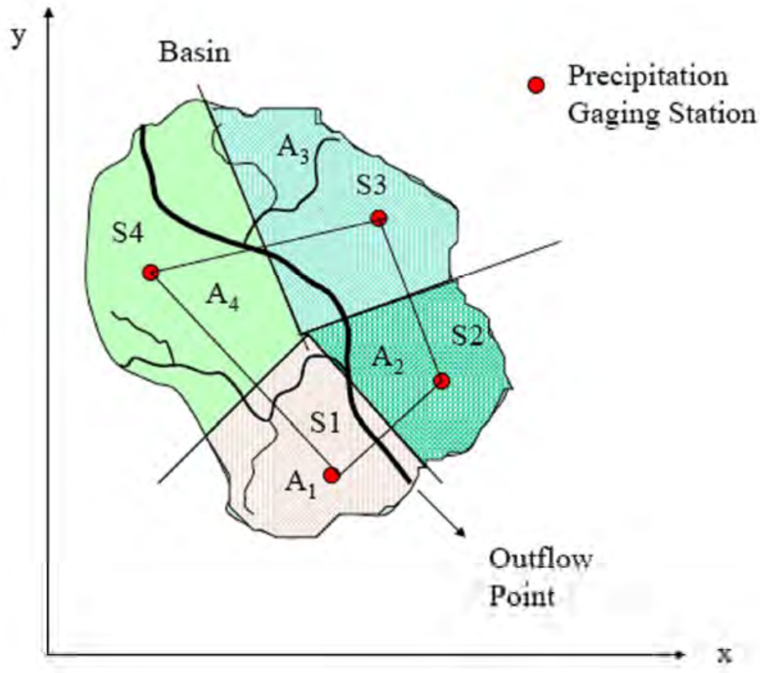


Figure 4.19 Schematic diagram for Thiessen polygon method www.nicholas.duke.edu

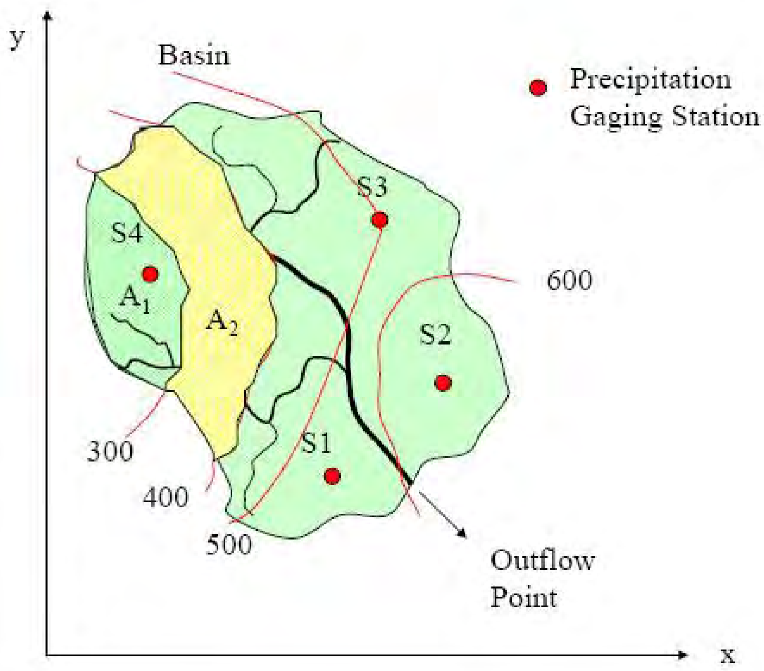


Figure 4.20 Schematic diagram for Isohyetal method (www.nicholas.duke.edu)

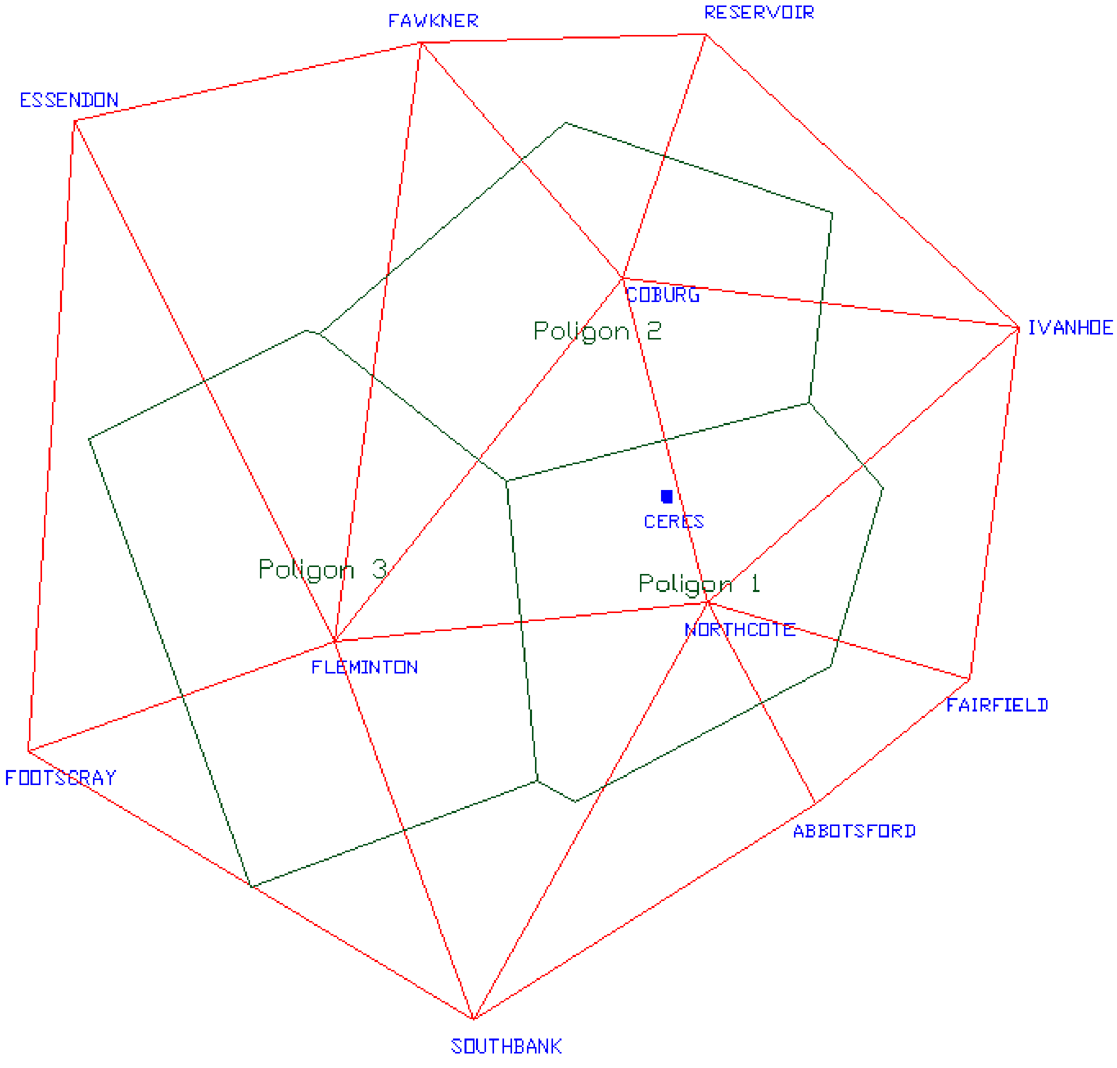


Figure 4.21 Polygons drawn for the Thiessen analysis

Table 4.3 Hourly rainfall values calculated at CERES

Date of Event	Hours	Rainfall (mm/hr)			
		Coburg	Flemington	Northcote	CERES
18/05/2007	1	0.2	0.6	0.2	0.4
	2	0	0	0	0.0
	3	0.2	0	0.2	0.1
	4	1.2	0.8	1.2	0.1
	5	0	0	0	0.0
	6	0	0	1	0.3
	7	0	0.2	3	0.9
	8	0	0	2	0.5
	9	1.2	0.2	1.2	0.8
	10	0.4	0.2	0.4	1.3
	11	5	6.2	6	5.7
	12	1.2	0.8	1.2	1.0
	13	1	0.4	1	0.7
	14	1.2	0.4	1.2	0.9
	15	0.4	0.2	0.4	0.3
	16	0.6	0.2	0.6	0.4
	17	1.4	0.6	1.4	1.1
	18	1	1.4	1.4	0.3
	19	2.4	1.8	2.4	0.2
	20	0.2	0	0.2	0.0
Daily rainfall		14.6	16	21	15.0

Table 4.4 Comparison of total rainfall values obtained from nearby gauges using the Thiessen polygon method with the values recorded at CERES

Date	From nearby gauges (mm)	Recorded at CERES (mm)
02/11/06	12.8	13
24/03/07	14.3	14
18/05/07	15.0	15
27/06/07	16.0	18
13/07/07	19.1	20
04/11/07	23.6	24
21/12/07	23.8	25

4.4.2 Water quantity analysis

Natural storms that produced runoff are presented in Table 4.2. The minimum rainfall required to produce runoff from the C&M Ecotrihex and Atlantis Turf Cell pavements are 13 mm and 18 mm respectively. As expected, the asphalt pavement produced runoff with a minimum rainfall of 3 mm. The runoff hydrographs produced from the above storms are given in Figures 4.22 to 4.28. The area under the hydrograph gives the total runoff produced from each storm.

The total simulated rainfall volume was measured with a flow meter attached to the sprinkler. The total runoff volume was calculated by considering the area under the hydrograph obtained for each event (Figure 4.29). The rainfall intensities were higher and the durations were longer in the simulated storms than during the actual events.

The detailed hydrograph information obtained for natural rain events are shown in Tables 4.5 to 4.11. Table 4.12 gives the percentage reduction in runoff from C&M Ecotrihex pavement and Atlantis Turf Cell pavement when compared to runoff from the asphalt pavement. Tables 4.13 and 4.14 presents the percentage reduction of peaks and total runoff obtained from the two pervious pavements for the simulated storm events.

Peak reduction was calculated for both C&M Ecotrihex and Atlantis Turf Cell pavement with compared to the peak in asphalt pavement. Considering Figure 4.24, a specimen calculation is shown below.

Peak discharge in asphalt	=	0.075L/s
Peak discharge in C&M Ecotrihex surface	=	0.042L/s
% reduction in peak discharge	=	(0.075-0.042)*100/0.075
	=	44%

Table 4.5 Flow data for the storm event on 2nd November 2006

	Asphalt	C&M Ecotrihex
Time for runoff to commence (hr:min)	1:40	6:40
Lag time in commencement of runofft (min)	N/A	300
Time to peak (hr:min:sec)	5:15:00	6:15:00
Lag time to the peak (hr:min)	N/A	1:00
Peak discharge (Qp) (L/s)	0.05	0.025
Difference in Qp compared to asphalt (L/s)	N/A	0.025
Difference in Qp compared to asphalt (%)	N/A	50.00

Table 4.6 Flow data for the storm event on 24 March 2007

	Asphalt	C&M Ecotrihex
Time for runoff to commence (hr:min)	0:03	00:42
Lag in commencement of runoff (min)	N/A	39
Time to peak (hr:min:sec)	00:25:00	00:73:00
Lag time to the peak (hr:min)	N/A	0:48
Peak discharge (Qp) (L/s)	0.128	0.0558
Difference in peak Qp compared to asphalt (L/s)	N/A	0.072
Difference in peak Qp compared to asphalt (%)	N/A	56.25

Table 4.7 Flow data for the storm event on 18 May 2007

	Asphalt	C&M Ecotrihex
Time for runoff to commence (hr:min)	5:45	10:15
Lag time in commencement of runoff (min)	N/A	270
Time to peak (hr:min:sec)	10:45:00	11:00:00
Lag time to the peak (hr:min)	N/A	00:15
Peak discharge (Qp) (L/s)	0.075	0.042
Difference in Qp compared to asphalt (L/s)	N/A	0.033
Difference in Qp compared to asphalt (%)	N/A	44.00

Table 4.8 Flow data for the storm event on 27 June 2007

	Asphalt	C&M Ecotrihex	Atlantis Turf Cell
Time for runoff to commence (hr:min)	2:00	3:30	4:00
Lag time in commencement of runoff (min)	N/A	90	120
Time to peak (hr:min:sec)	3:30:00	4:15:00	4:30:00
Lag time to the peak (hr:min)	N/A	0:75	1:00
Peak discharge (Qp)(L/s)	0.113	0.051	0.046
Difference in Qp compared to asphalt (L/s)	N/A	0.062	0.067
Difference in Qp compared to asphalt (%)	N/A	55%	59%

Table 4.9 Flow data for the storm event on 12 July 2007

	Asphalt	C&M Ecotrihex	Atlantis Turf Cell
Time for runoff to commence (hr:min)	0:45	3:15	3:30
Lag time in commencement of runoff (min)	N/A	150	165
Time to peak (hr:min:sec)	3:00:00	4:15:00	4:15:00
Lag time to the peak (hr:min)	N/A	1:15	1:15
Peak discharge (Qp)(L/s)	0.071	0.045	0.038
Difference in Qp compared to asphalt (L/s)	N/A	0.026	0.033
Difference in Qp compared to asphalt (%)	N/A	37%	46%

Table 4.10 Flow data for the storm event on 4 November 2007

	Asphalt	C&M Ecotrihex	Atlantis Turf Cell
Time for runoff to commence (hr:min)	0:36	3:6	3:24
Lag time in commencement of runoff (min)	N/A	150	168
Time to peak (hr:min:sec)	2:45:00	4:12:00	4:30:00
Lag time to the peak (hr:min)	N/A	1:27	1:45
Peak discharge (Qp) (L/s)	0.19	0.098	0.096
Difference in Qp compared to Asphalt (L/s)	N/A	0.092	0.094
Difference in Qp compared to Asphalt (%)	N/A	48.42	49.47

Table 4.11 Flow data for the storm event on 21 December 2007

	Asphalt	C&M Ecotrihex	Atlantis Turf Cell
Time for runoff to commence (hr:min)	0:15	3:45	4:15
Lag time in commencement of runoff (min)	N/A	210	240
Time to peak (hr:min:sec)	5:30:00	8:15:00	8:30:15
Lag time to the peak (hr:min)	N/A	2:45	3:0
Peak discharge (Qp) (L/s)	0.24	0.14	0.13
Difference in Qp compared to Asphalt (L/s)	N/A	0.1	0.11
Difference in Qp compared to Asphalt (%)	N/A	41.67	45.83

Table 4.12 Summary of percentage reduction of volume for natural rain events

Date	Total rainfall (mm)	Runoff volume (L)				
		Asphalt (L)	C&M Ecotrihex (L)	Reduction (%)	Atlantis Turf Cell (L)	Reduction (%)
2/11/2006	13	647.2	317.1	51.0	0	NA
24/3/2007	14	698.5	405.1	42.0	0	NA
18/5/2007	15	732.7	411.3	43.9	0	NA
27/6/2007	18	867.8	461.8	46.8	391.4	54.9
13/7/2007	20	903.4	501.3	44.5	428.6	52.6
4/11/2007	24	1200.3	559.5	53.4	485	59.6
21/12/2007	25	1256.4	675.3	46.3	525	58.2

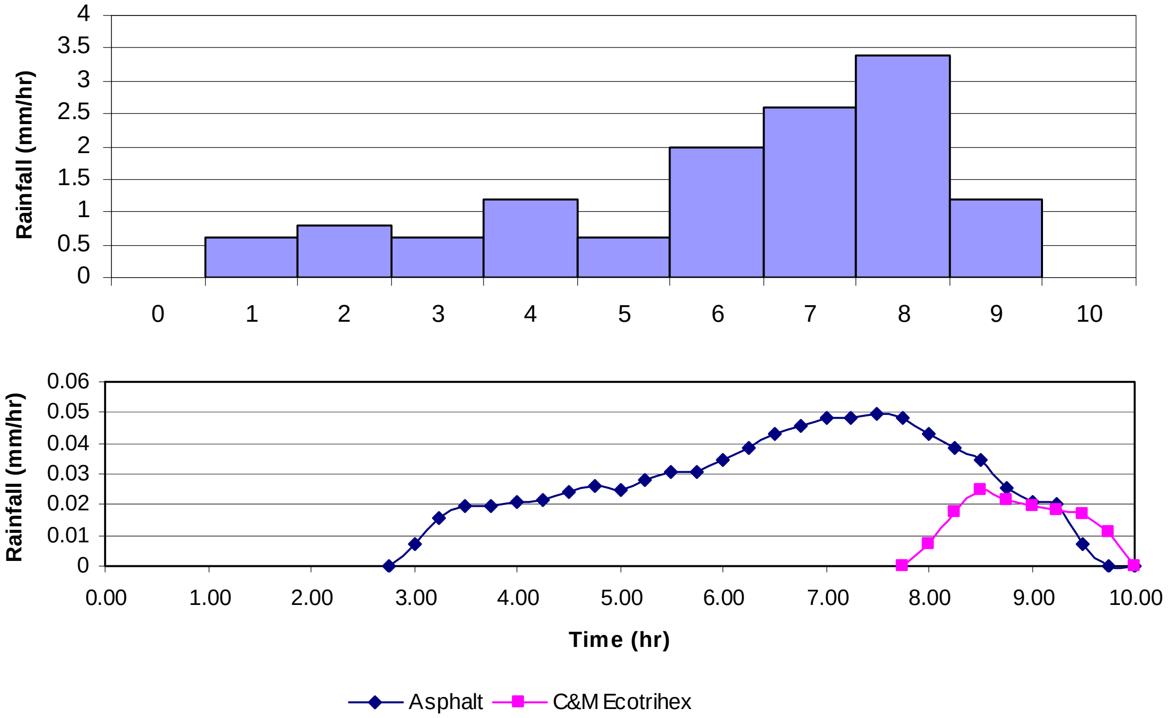


Figure 4.22 Runoff hydrographs produced by the asphalt and C&M Ecotrihex pavements from 02nd November 2006 storm event (Note: no runoff produced from Atlantis Turf Cell surface)

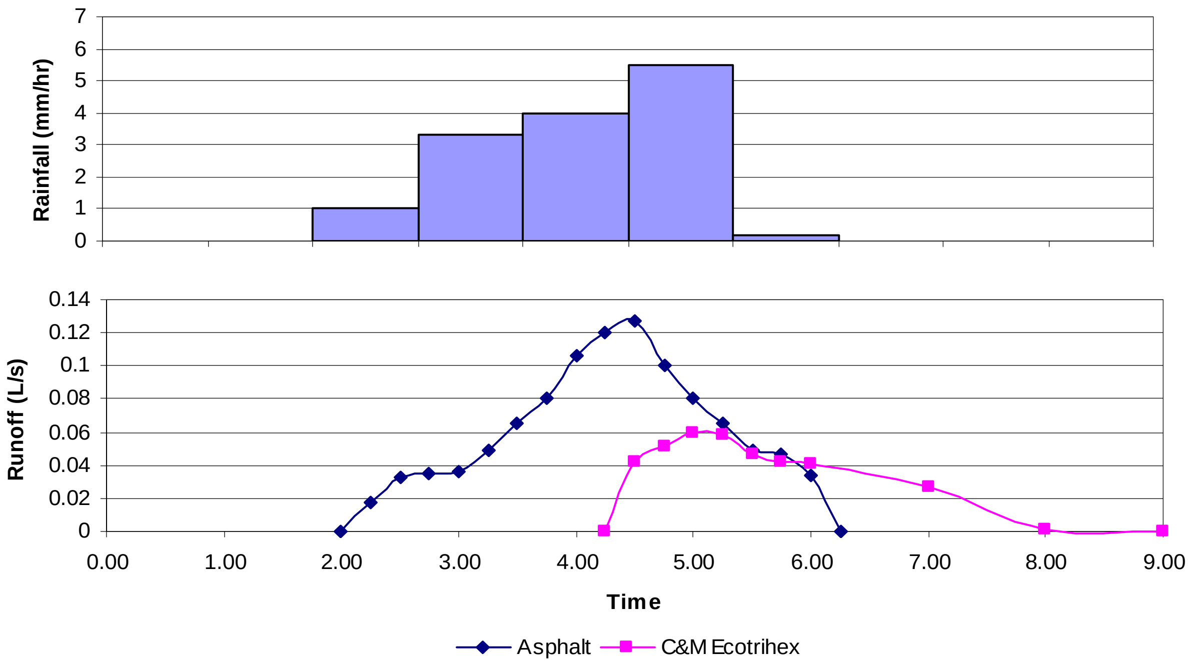


Figure 4.23 Runoff hydrographs produced by the asphalt and C&M Ecotrihex pavements from 24th March 2007 storm event (Note: no runoff produced from Atlantis Turf cellsurface)

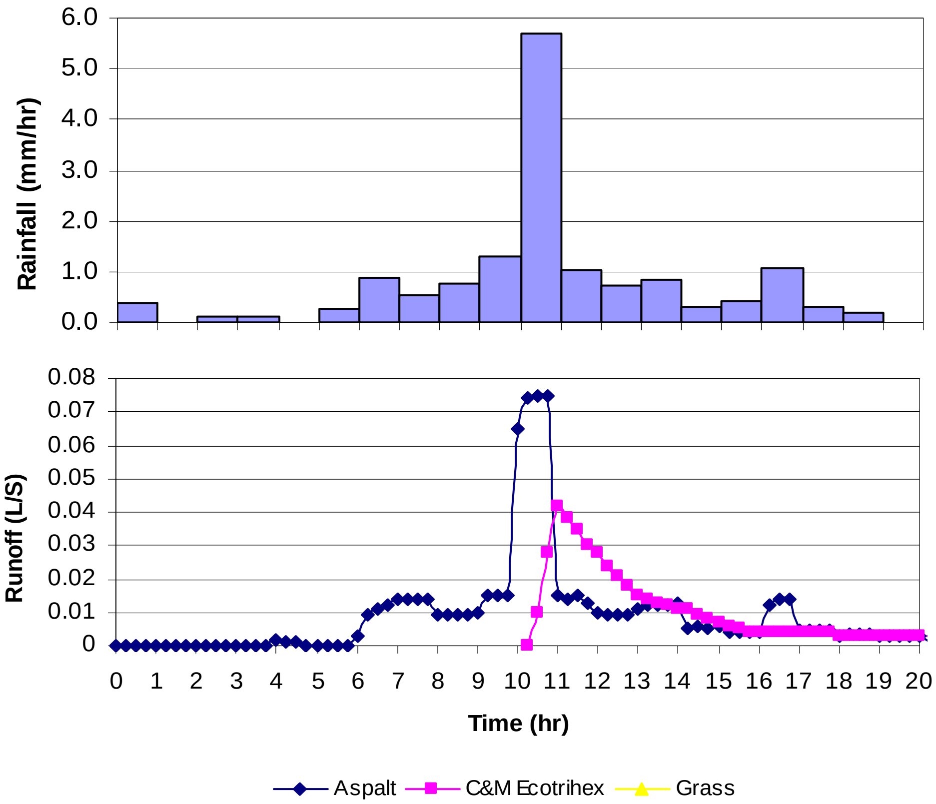


Figure 4.24 Runoff hydrographs produced by the asphalt and C&M Ecotrihex pavements from 18th May 2007 storm event (Note: no runoff produced from Atlantis Turf Cell surface)

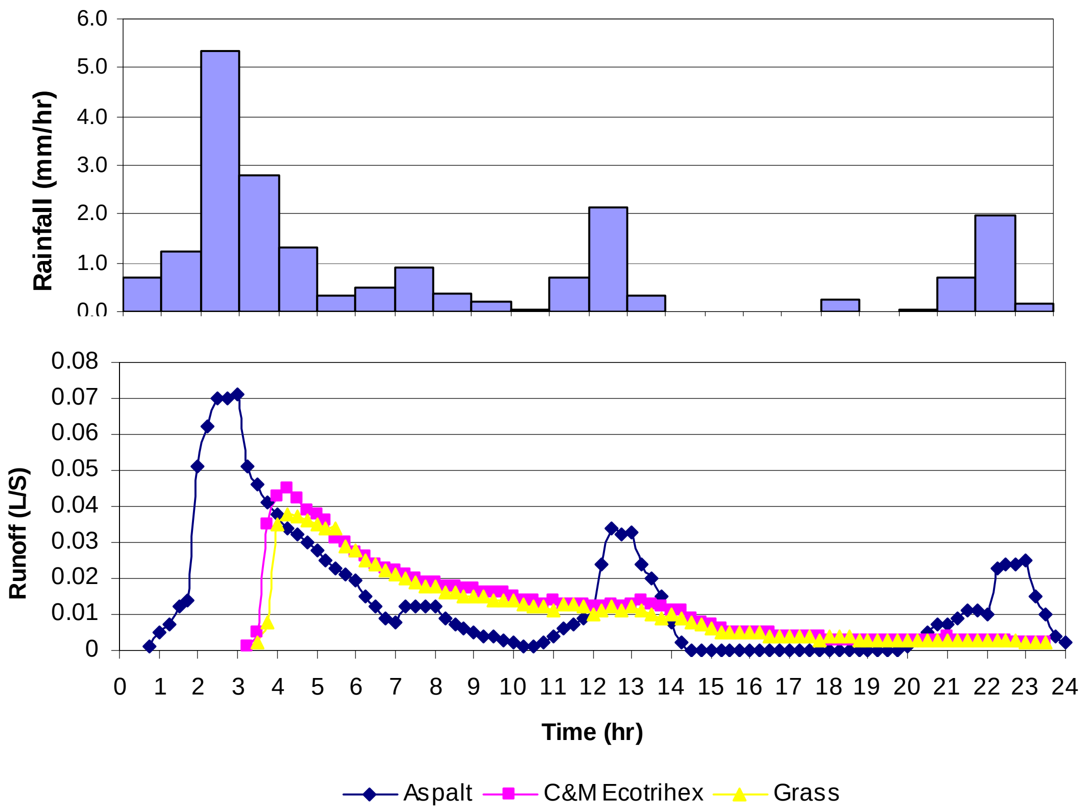


Figure 4.25 Runoff hydrographs produced by the asphalt, C&M Ecotrihex and Atlantis Turf Cell pavements from 27th June 2007 storm event

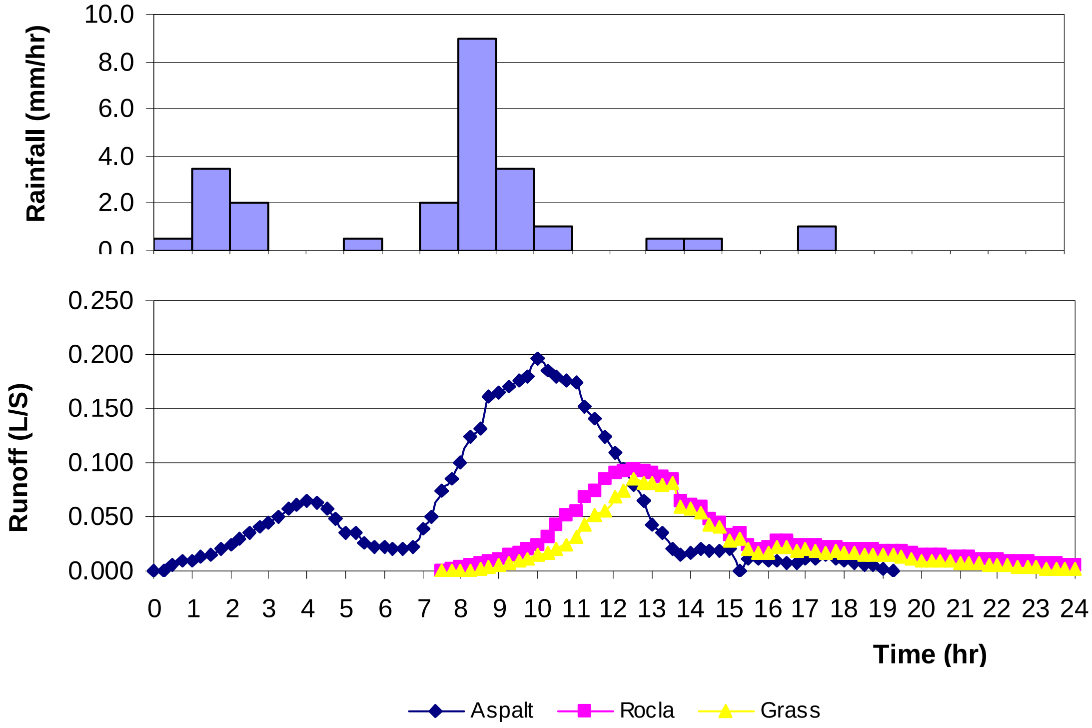


Figure 4.26 Runoff hydrographs produced by the asphalt, C&M Ecotrihex and Atlantis Turf cell pavements from 12th July 2007 storm event

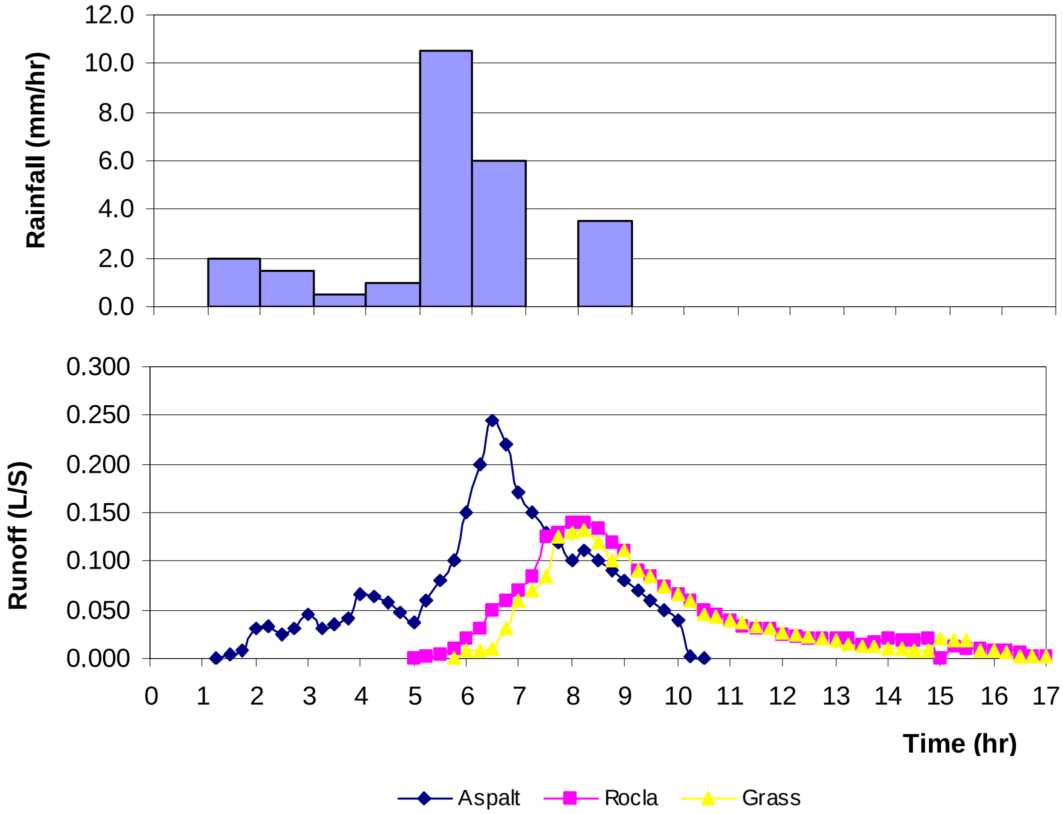


Figure 4.27 Runoff hydrographs produced by the asphalt, C&M Ecotrihex and Atlantis Turf Cell pavements from 04th November 2007 storm event

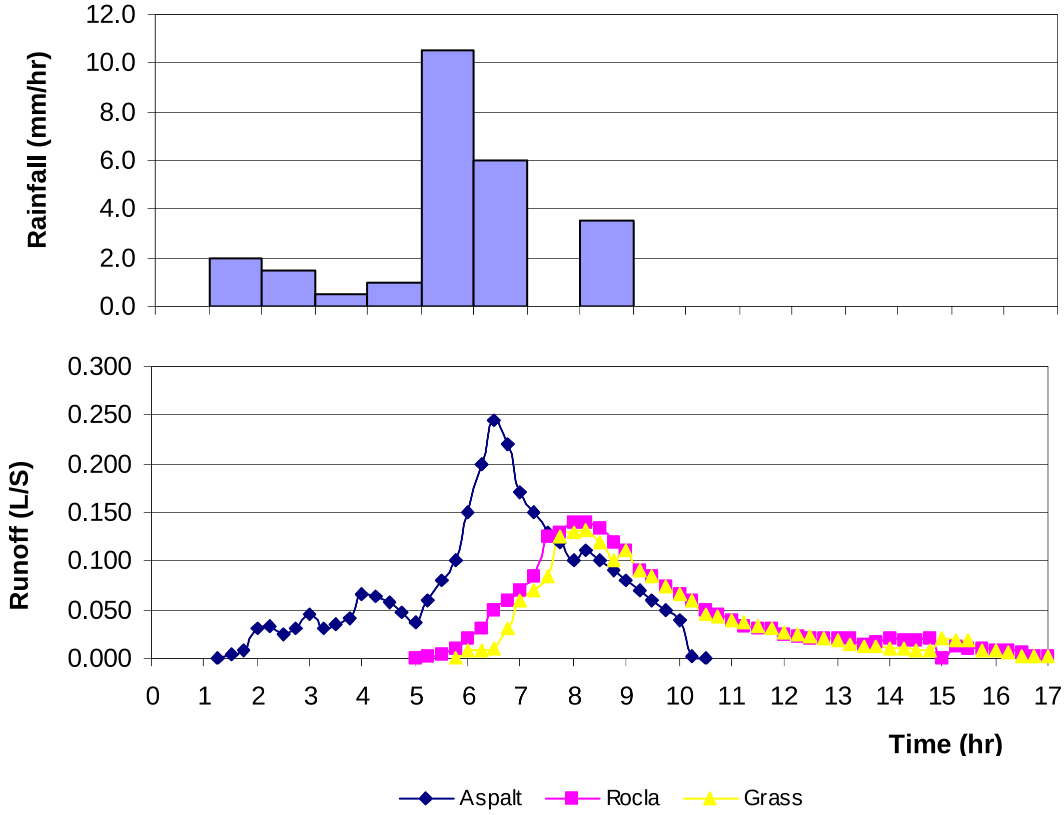
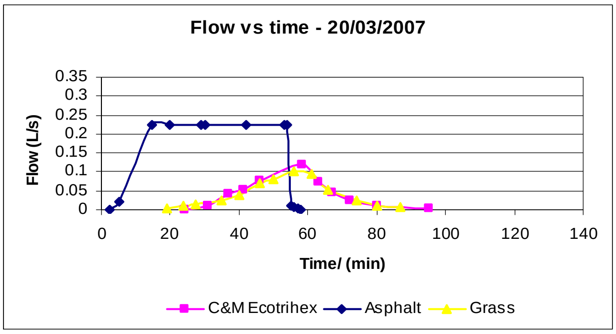
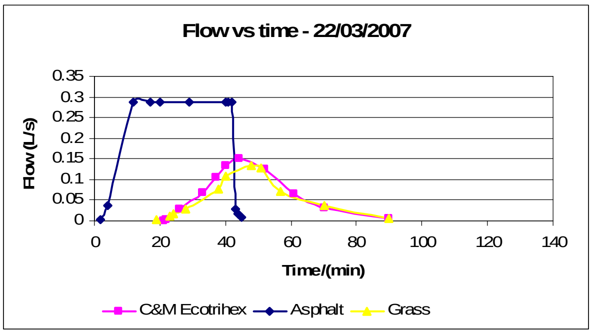
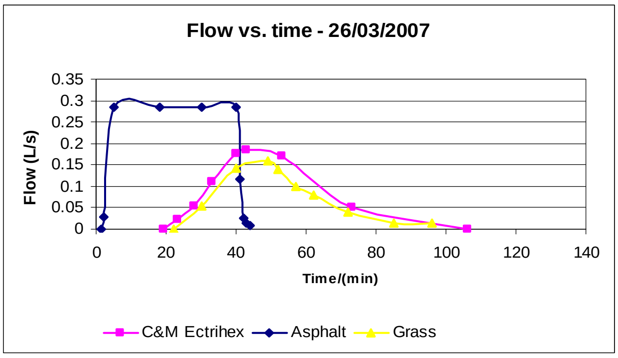
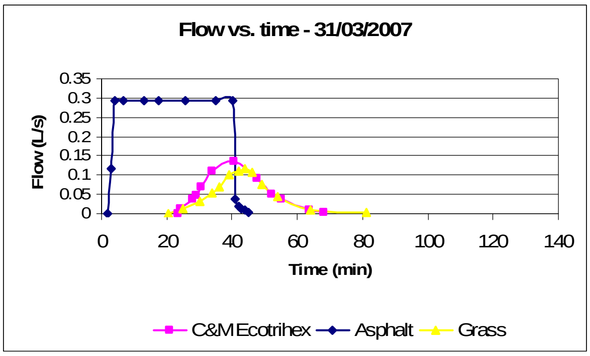


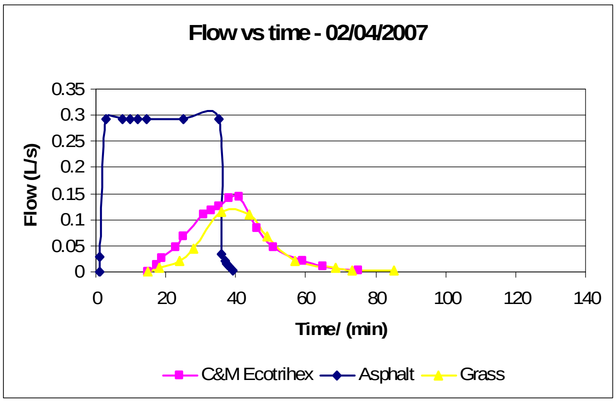
Figure 4.28 Runoff hydrographs produced by the asphalt, C&M Ecotrihex and Atlantis Turf Cell pavements from 21st December 2007 storm event

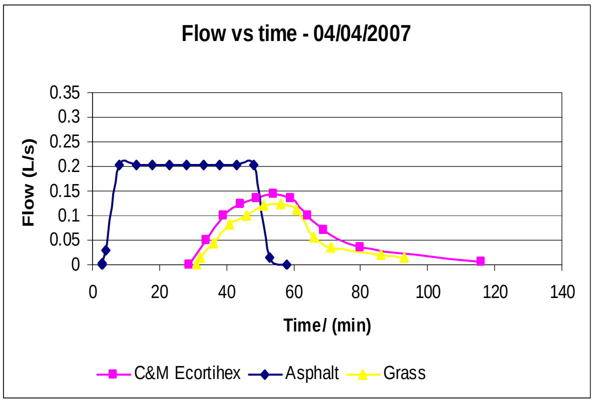

Flow vs time - 20/03/2007
Flow (L/s)
Time/ (min)
C&M Ecotrihex
Asphalt
Grass

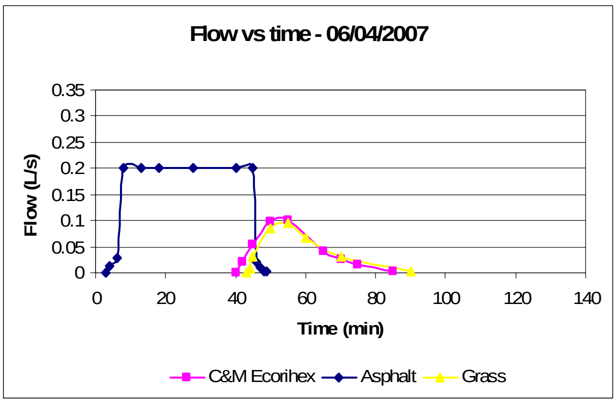

Flow vs time - 22/03/2007
Flow (L/s)
Time/(min)
C&M Ecotrihex
Asphalt
Grass

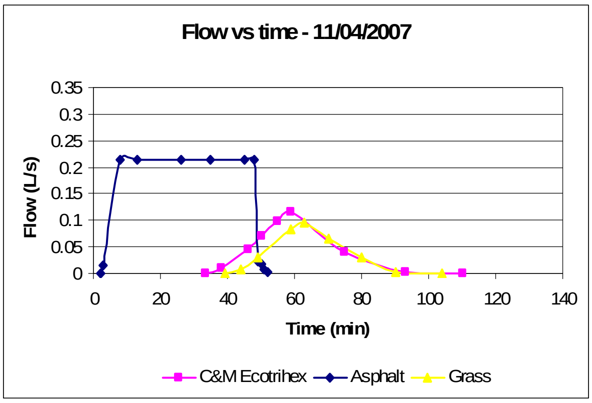

Flow vs. time - 26/03/2007
Flow (L/s)
Time/(min)
C&M Ectrihex
Asphalt
Grass


Flow vs. time - 31/03/2007
Flow (L/s)
Time (min)
C&M Ecotrihex
Asphalt
Grass


Flow vs time - 02/04/2007
Flow (L/s)
Time/ (min)
C&M Ecotrihex
Asphalt
Grass


Flow vs time - 04/04/2007
Flow (L/s)
Time/ (min)
C&M Ecortihex
Asphalt
Grass


Flow vs time - 06/04/2007
Flow (L/s)
Time (min)
C&M Ecorihex
Asphalt
Grass


Flow vs time - 11/04/2007
Flow (L/s)
Time (min)
C&M Ecotrihex
Asphalt
Grass

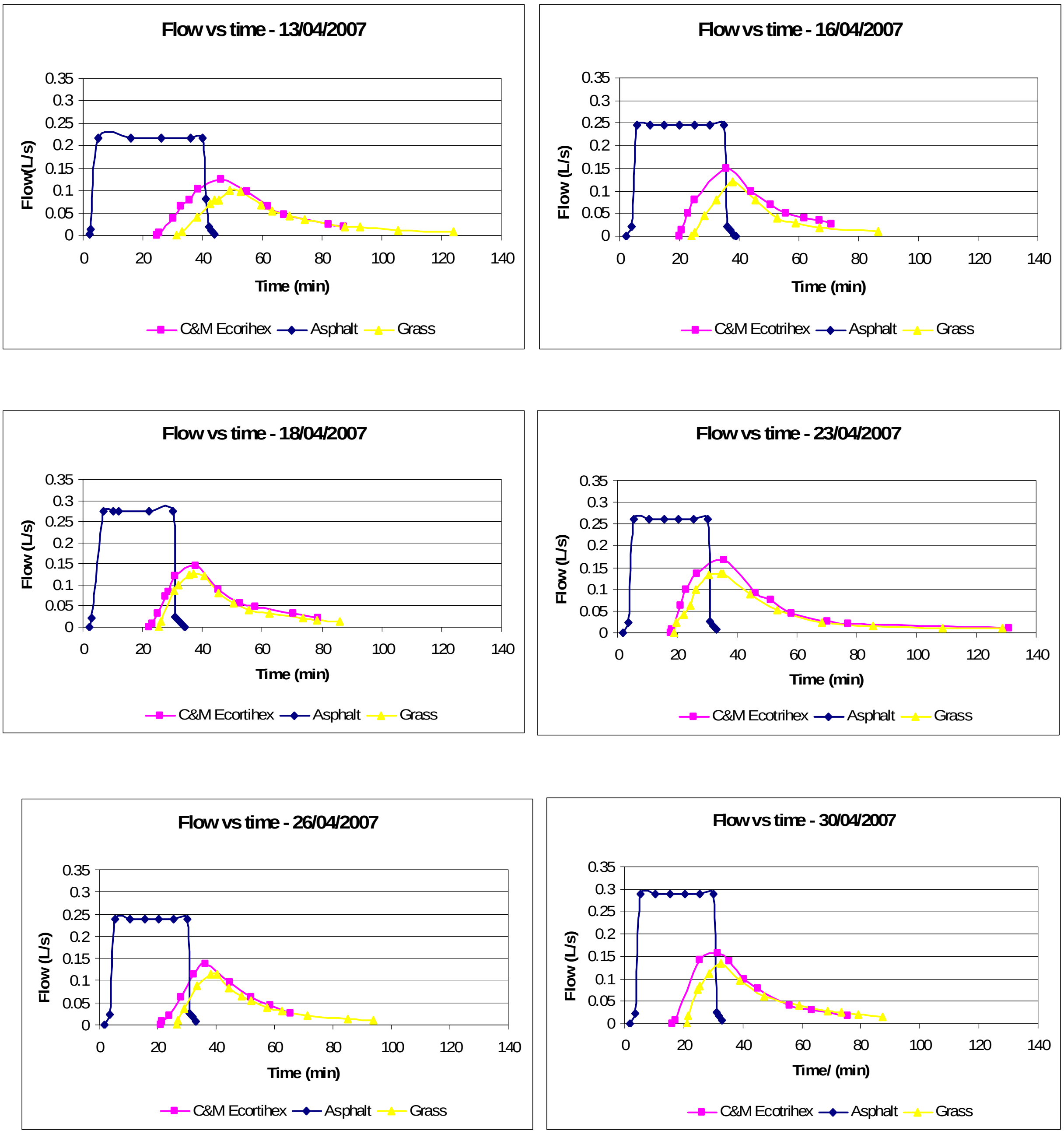


Figure 4.29 Runoff hydrographs produced by the asphalt, C&M Ecotrihex and Atlantis Turf Cell pavements from simulated storm events

Table 4.13 Details of the simulated rainfall events and peak discharges obtained from each pavement

Date	Rainfall Intensity (mm/hr)	Duration (min)	Peak Discharge				
			Asphalt	C&M Ecotrihex		Atlantis Turf	
			(L/s)	(L/s)	(%) reduction	(L/s)	(%) reduction
20/03/2007	16.52	53	0.225	0.12	46.67	0.10	55.56
22/03/2007	21.00	40	0.287	0.15	47.74	0.13	54.70
26/03/2007	20.87	40	0.284	0.17	40.14	0.16	43.66
31/03/2007	21.42	40	0.292	0.13	55.48	0.11	62.33
2/04/2007	21.35	35	0.292	0.15	48.63	0.13	55.48
4/04/2007	14.89	50	0.202	0.14	30.69	0.12	40.59
6/04/2007	14.24	45	0.202	0.11	45.54	0.08	60.40
11/04/2007	15.56	35	0.214	0.12	43.93	0.09	57.94
13/04/2007	15.94	40	0.218	0.12	44.95	0.10	54.13
16/04/2007	18.14	35	0.246	0.15	39.02	0.12	51.22
18/04/2007	19.99	30	0.275	0.15	45.45	0.13	52.73
23/04/2007	18.88	30	0.261	0.17	34.87	0.14	46.36
26/04/2007	17.80	32	0.238	0.14	41.18	0.12	49.58
30/04/2007	21.42	26	0.289	0.16	44.64	0.13	55.02

Table 4.14 Details of the simulated rainfall events and total runoff volumes obtained from each pavement.

Date	Rainfall Intensity (mm/hr)	Duration (min)	Rainfall Volume (L)	Runoff volume				
				Asphalt (L)	C&M Ecotrihex	(%)	Atlantis Turf	(%)
3/20/2007	16.52	53	735.1	727.69	352.5	51.56	289.0	60.29
3/22/2007	21.00	40	698.4	692.8	287.8	58.46	260.0	62.47
3/26/2007	20.87	40	701.2	695.6	290.2	58.28	255.0	63.34
3/31/2007	21.42	40	719.5	713.94	348.4	51.20	300.0	57.98
4/2/2007	21.35	35	627.6	624.37	352.0	43.62	255.0	59.16
4/4/2007	14.89	50	625.5	620.95	350.0	43.63	232.0	62.64
4/6/2007	14.24	45	562.8	558.72	267.0	52.21	245.4	56.08
4/11/2007	15.56	35	457.3	454.16	212.0	53.32	216.0	52.44
4/13/2007	15.94	40	535.6	531.96	269.5	49.33	196.4	63.07
4/16/2007	18.14	35	533.2	530.04	255.8	51.74	194.8	63.25
4/18/2007	19.99	30	503.7	500.97	240.1	52.07	191.5	61.77
4/23/2007	18.88	30	475.8	473.07	243.0	48.63	229.3	51.53
4/26/2007	17.80	32	478.4	475.49	216.1	54.55	175.5	63.10
4/30/2007	21.42	26	467.6	465.32	272.5	41.44	219.4	62.29

From the hydrographs presented above it is clear that the runoff volumes and peak discharges from the pervious pavements are much lower than from the asphalt pavement. As presented in Tables 4.5 to 4.11 and 4.13 and Figure 4.30, the average percentage reduction in peak discharge varied between 40% to 55% for C&M Ecotrihex pavement and 40% - 60% for the Atlantis Turf Cell pavement. Tables 4.12, 4.14 and Figure 4.31 present the reduction in runoff volumes obtained from pervious pavements. C&M Ecotrihex pavement reduced the runoff volume by 43% to 53% whilst the Atlantis Turf Cell pavement reduced the total runoff by 52% to 62%. From the values presented in all above tables and figures it is concluded that pervious pavements are effective in managing stormwater flow, although the Atlantis Turf Cell pavement holds more infiltrated water than the C&M Ecotrihex surface. The water that is retained within the pavement structure will evaporate back in the atmosphere.

Hogland et al. (1987 ; 1990), Larson (1990), Mantle (1993) and Pratt et al., (1989; 1990; 1995) reported that the percentage reduction in volume through pervious pavements is between 34% to 47%. It is clear that the results obtained from C&M Ecotrihex and Atlantis Turf Cell pavements are within the range or better than the values observed or reported by previous researchers.

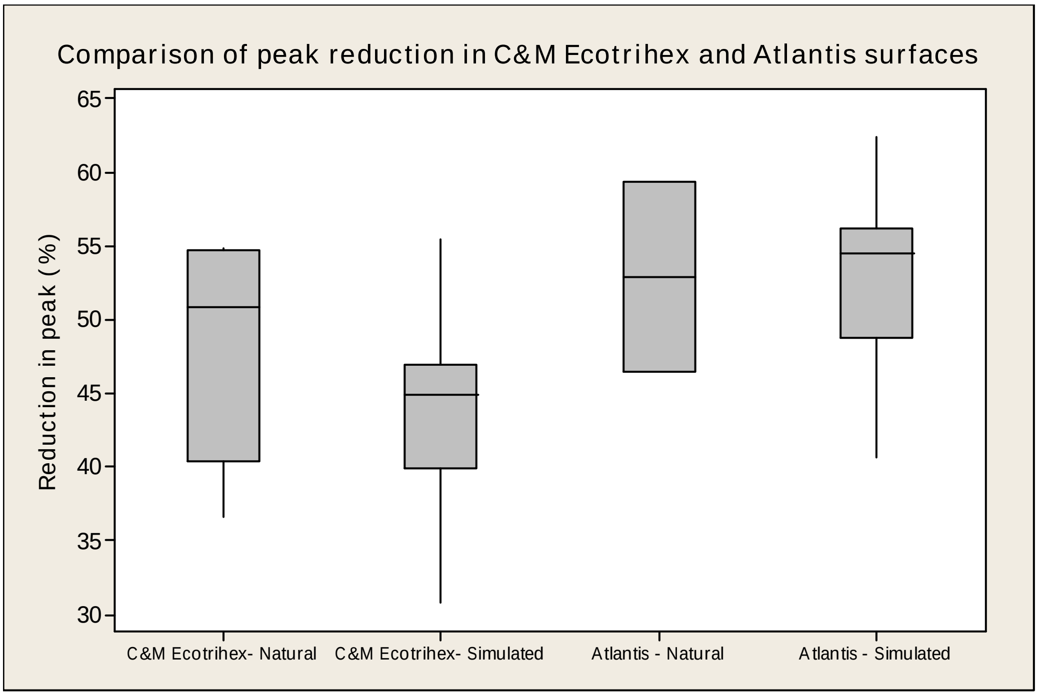


Figure 4.30 Range of % reduction in peak from C&M Ecotrihex and Atlantis Turf Cell pavements

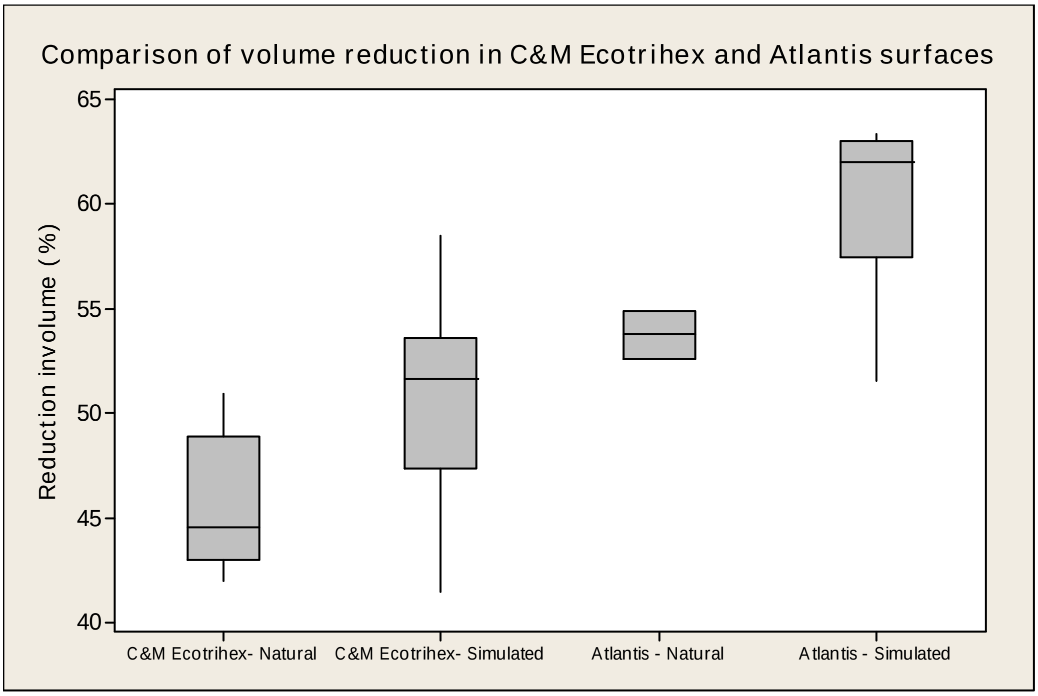


Figure 4.31 Range of % reduction in runoff volume from C&M Ecotrihex and Atlantis Turf Cell pavements

Runoff coefficients

According to Figures 4.32 & 4.33, the total runoff volume to rainfall volume ratio from the asphalt surface is 0.99. However, for the C&M Ecotrihex pavement the runoff coefficient varied between 0.39 and 0.31 and for the Atlantis Turf Cell pavement the runoff coefficient varied between 0.30 and 0.28. It is important to note that these results were obtained with limited amount of data due to lack of rainfall in 2006 and in 2007 in Melbourne.

Table 2.3 in Chapter 2 shows a summary of runoff coefficients obtained by Pratt et al. (1995), Hunt et al. (2002) and Schluter and Jefferies (2001) for different pervious pavements. The runoff coefficients for different pervious pavements obtained by these researchers are between 0.2 and 0.8. The runoff coefficients obtained from C&M Ecotrihex and Atlantis Turf Cell pavements are also consistent with previous findings.

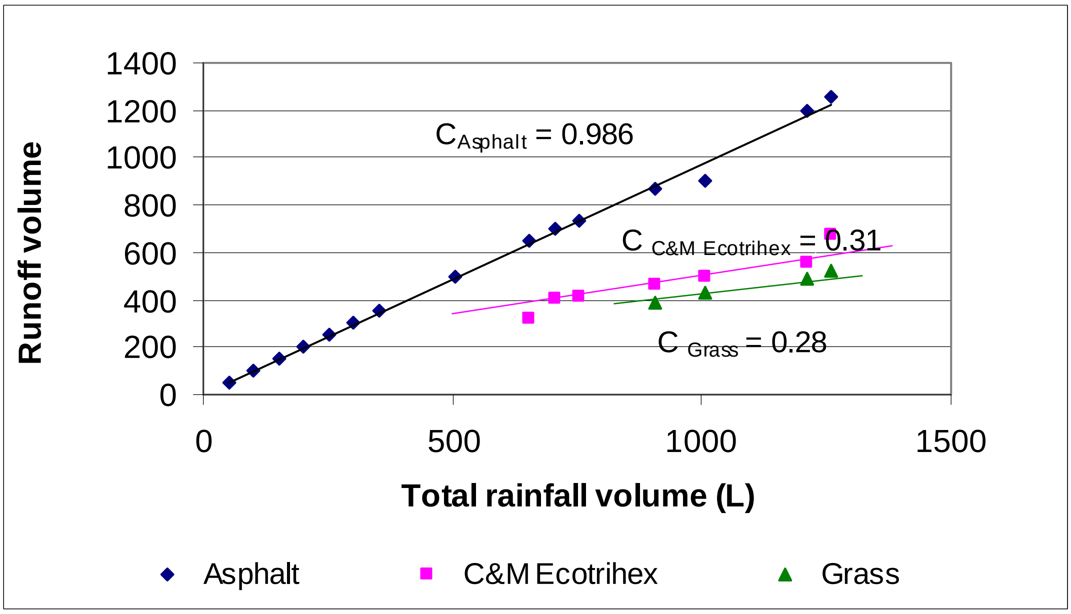


Figure 4.32 Total rainfall and runoff relationships for natural storm events

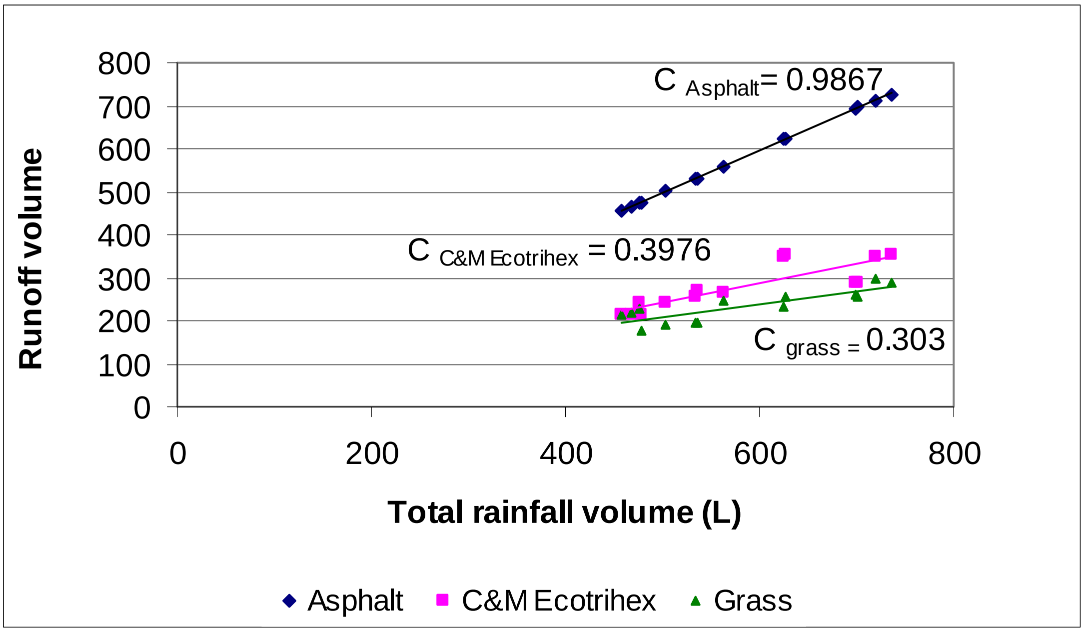


Figure 4.33 Total rainfall and runoff relationships for simulated storm events

4.4.3 Water Balance

Considering both natural and simulated rain events, a water balance was carried out for both C&M Ecortihex and Altantis Turf Cell surfaces. The water balance was carried out with the use of Equation 4.2

$$S_{t+1} = P_t + S_t - E_t - Q_t - D - I \quad (4.2)$$

where,

S_{t+1} = water storage at the end of the day (mm)

S_t	=	water storage at the beginning of the day (mm)
P_t	=	rainfall on the t^{th} day (mm)
Q_t	=	surface runoff on the t^{th} day (mm)
I	=	infiltrated water (mm)
E_t	=	actual evapotranspiration (mm)
D	=	deep percolation (mm)

Actual evapotranspiration (E_t) was calculated using Boughton's (1966) model as shown below. Deep percolation is taken as zero as there was an impermeable geotextile underneath the sub-base. The surface runoff was set to zero for all rain events, as there was no runoff generated from any of the storms.

4.4.4 Estimation of potential evaporations for carrying out the water balance

The potential evaporation rates for Melbourne were obtained from the Bureau of Meteorology web site (www.bom.gov.au). Actual evaporation rates were calculated by the methodology used by Boughton (1966). Figure 4.34 shows the schematic diagram used by Boughton (1966) to calculate actual evapotranspiration. Wilting Point (WP) and Field Capacity (FC) are important parameters in the Boughton model. WP is defined as the water content of a soil when an indicator plant (or common agricultural crop) can no longer draw water from the soil. FC can be defined as the maximum amount of water that a soil can retain after excess water from saturated conditions has been drained away due to gravity.

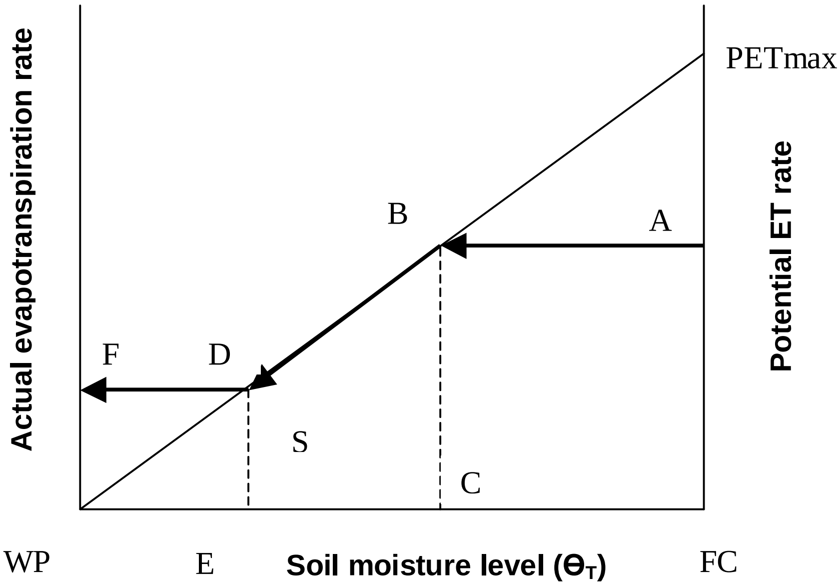


Figure 4.34 Schematic diagram of Bouhton actual evapotranspiration model

According to Zhang (2006), the FC of the pavement material is 4% and the depth of sub-base is 250mm. Hence the field capacity (FC) of the pavement was set to 10 mm and the wilting point (WC) to zero. The maximum potential evapotranspiration (PET) was taken as 6.25 mm/day. This was the maximum potential evaporation rate for Melbourne between November 2006 and January 2008 based on the published data on the Bureau of Meteorology (BOM) web site. According to Boughton (1966), the maximum PET has to be the highest possible PET for the location (Figure 4.34).

A specimen calculation to obtain the actual evapotranspiration (E_t) is given below. Assume the soil moisture level on a particular day (at point E in Figure 4.34) is Θ_E and the PET is 5.33mm (a point A in Figure 4.34). On this particular day, the soil moisture will evaporate at the potential rate if the moisture level is more than Θ_C (at point C in Figure 4.34)

$$\Theta_C = 5.33*10/6.25$$

$$= 8.528mm$$

$$\Theta_C = PET_{max}* (FC-WP)/PET_A$$

If $\Theta_E >= \Theta_C$

$$AET_t = PET_D$$

If $\Theta_E < \Theta_C$

$$AET_t = \Theta_E * PETmax / (FC - WP)$$

The water balance was carried out from November 2006 to January 2008. For the purposes of presentation, part of the graph is presented in Figures 4.35 and 4.36. The graphs clearly indicate that water storages are high in the Atlantis Turf Cell pavement when compared to the C&M Ecotrihex pavement. This was also clear from the runoff coefficients obtained for C&M Ecotrihex 0.43 and Atlantis Turf Cell 0.32 pavements respectively.

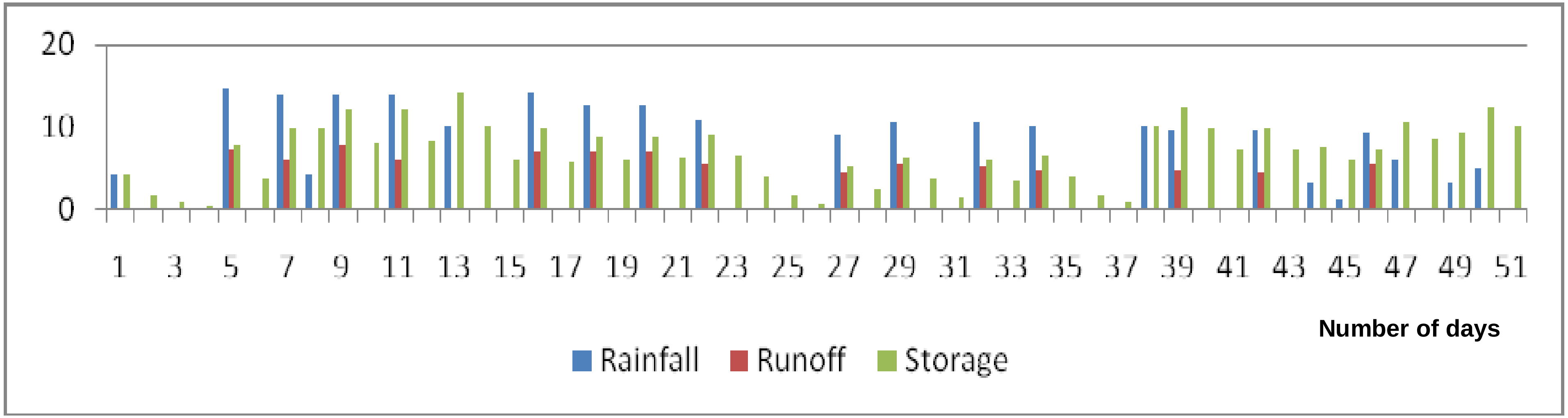


Figure 4.35 Rainfall, runoff and storage relationship obtained for C&M Ecotrihex pavement

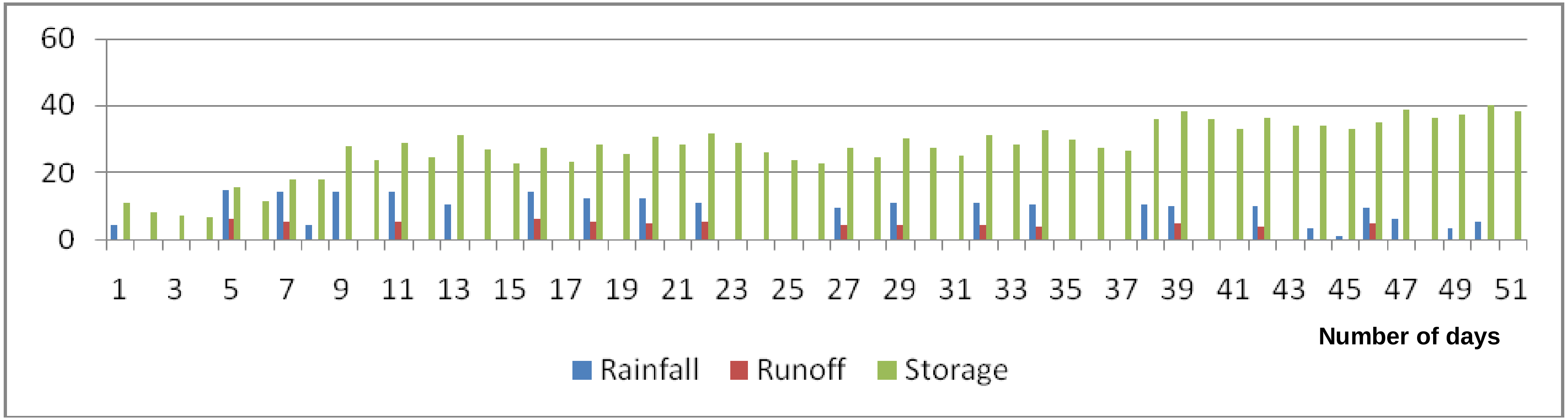


Figure 4.36 Rainfall, runoff and storage relationship obtained for Atlantis Turf Cell pavement

4.5 Water Quality Data Analysis

The literature survey revealed that the number of studies carried out to investigate water quality improvement through pervious pavements is very few in Australia. Even in those few studies, the number of water quality parameters investigated was limited. The current research is aimed at investigating the reduction in TN, TP, Oil and greases, TSS and Heavy metals (Pb, Cd, Cu, and Zn) when stormwater is infiltrated through C&M Ecotrihex and Atlantis Turf Cell pervious surfaces.

To obtain the pollutographs, water samples were collected as soon as the flow commenced from the drainage pipes installed within the pavements. First three samples were collected at 15 minute intervals followed by every 30 minutes interval until outflow ceased. The collected samples were preserved and analysed as described in Section 3.2.4. The pollutographs were drawn for all pollutants for each storm. Event Mean Concentrations (EMC) were calculated using Equation 4.3.

$$EMC = \frac{\sum_{t=0}^{T} Q_t C_t}{\sum_{t=0}^{T} Q_t} \qquad (4.3)$$

where,

EMC = event mean concentration of a particular water quality parameter (mg/L)

Q_t = discharge at a given time t (L/s)

C_t = concentration of the water quality parameter at time t (mg/L)

T = time base of the hydrographs

Figures 4.37 to 4.54 show the pollutographs drawn for the simulated rain event on 20th March 2007. The pollutographs obtained from the natural rain event on the 24th June 2007 are attached to Appendix B in Figures B.1 to B.17. All the EMC values and loads are summarised in Appendix B in Tables B.1 to B.2. The total output pollutant load per rainfall event was calculated by multiplying the EMC by total runoff volume discharged from the pavement. Table 4.15 shows the sampling times, concentration of Zn in each sample collected from C&M Ecotrihex pavement and the relevant discharges for the simulated rain event on the 20th March 2007. The EMC for the above event is equal to $0.2 * 10^{-3}$ mg/L (= $48.2 * 10^{-6} / 0.202$)

Table 4.15 Concentration and discharge data for Zn from C&M Ecotrihex pavement for the simulated storm on 20/03/2007

sample #	Time (s)	Concentration (mg/L)	Q (L/s)	Qt* Ct
1	28	0.0006	0.009	0.0000054
2	43	0	0.055	0
3	58	0.0004	0.105	0.000042
4	73	0	0.025	0
5	104	0.0001	0.008	0.0000008
Total			0.202	0.0000482

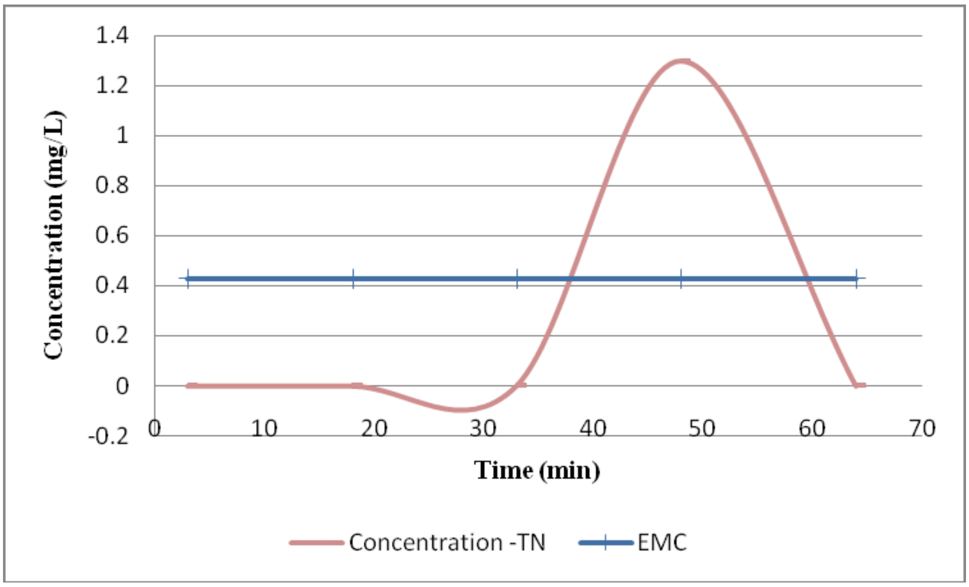


Figure 4.37 Pollutograph for TN from the asphalt pavement for the simulated storm on 20th March 2007

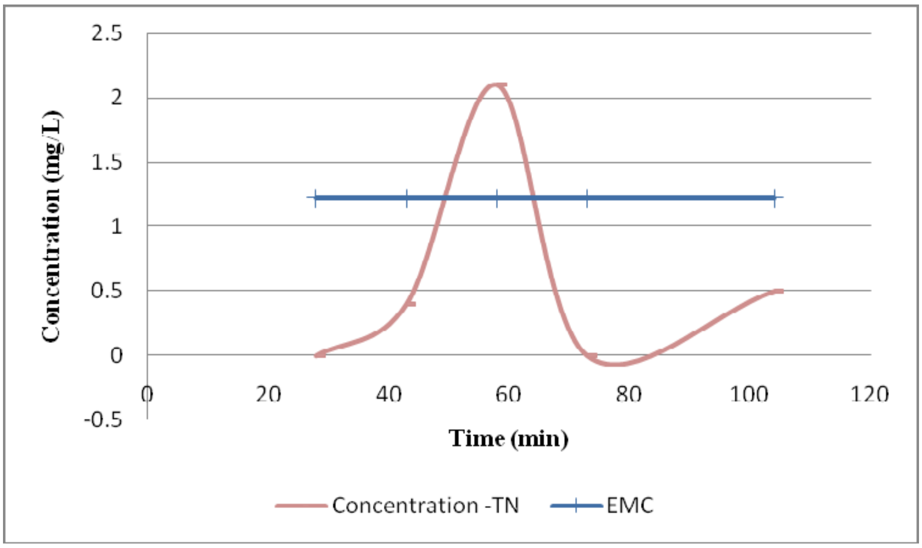


Figure 4.38 Pollutograph for TN from the C&M Ecotrihex pavement for the simulated storm on 20th March 2007

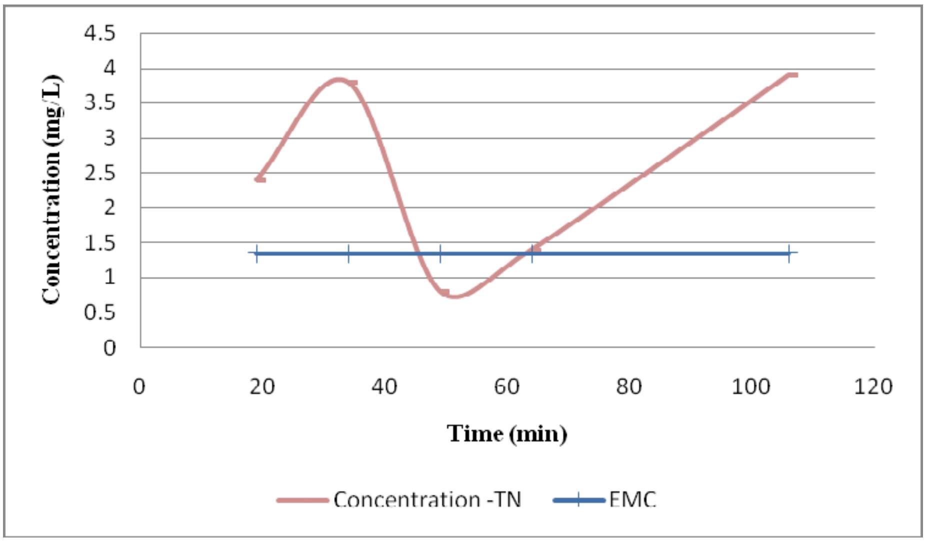


Figure 4.39 Pollutograph for TN from the Atlantis Turf Cell pavement for the simulated storm on 20th March 2007

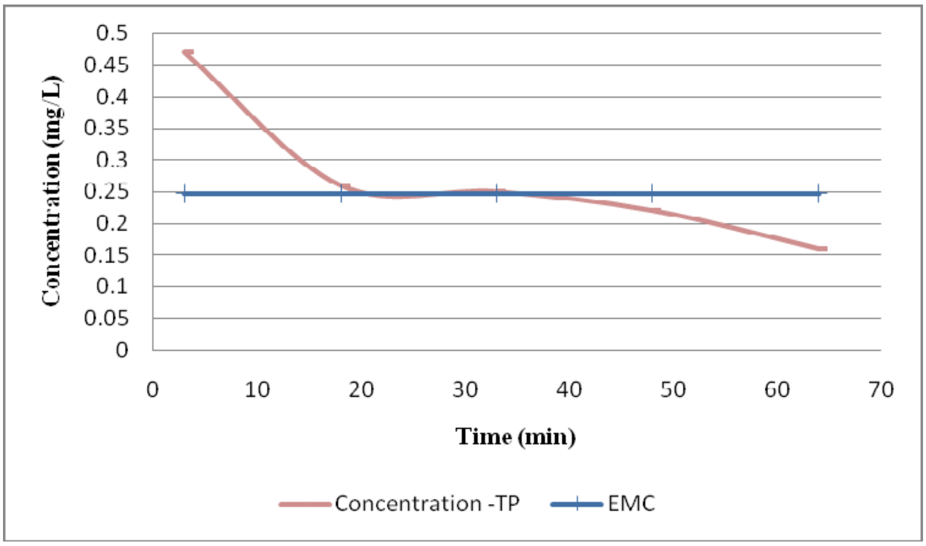


Figure 4.40 Pollutograph for TP from the asphalt pavement for the simulated storm on 20th March 2007

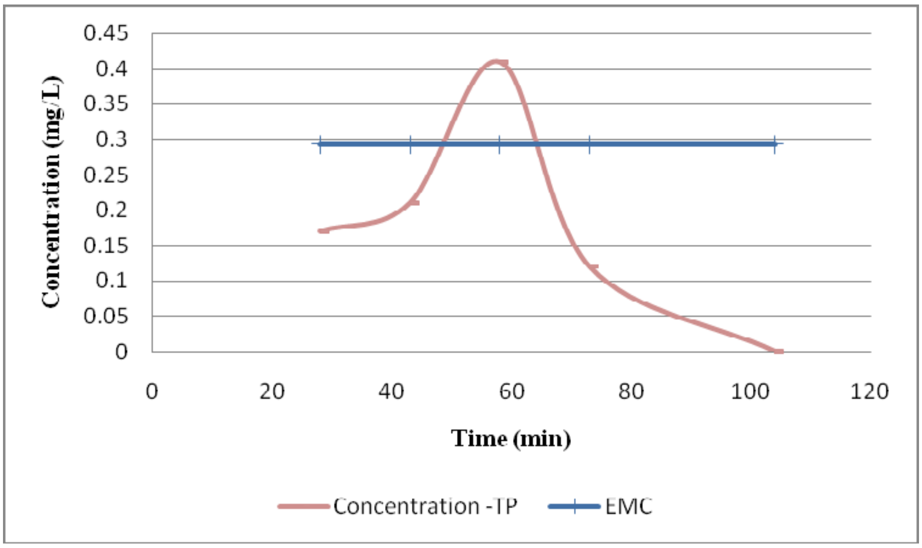


Figure 4.41 Pollutograph for TP from the C&M Ecotrihex pavement for the simulated storm on 20th March 2007

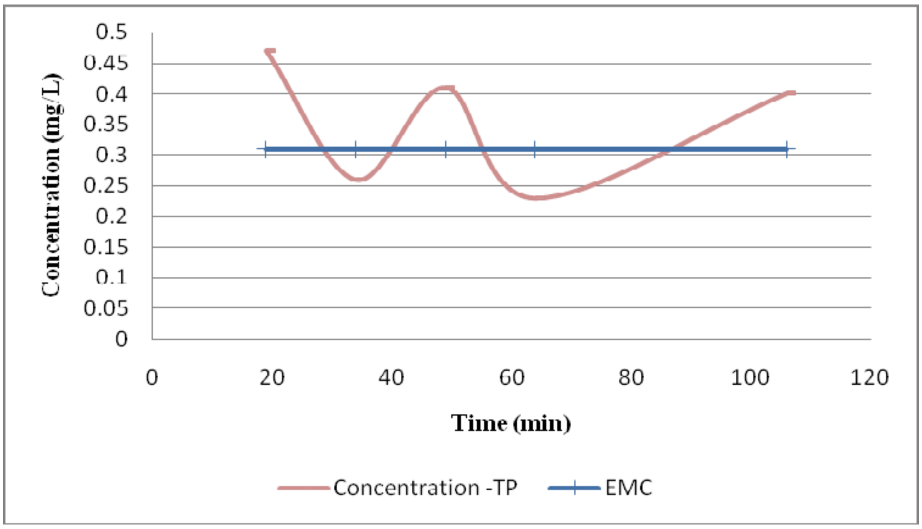


Figure 4.42 Pollutograph for TP from the Atlantis Turf Cell pavement for the simulated storm on 20th March 2007

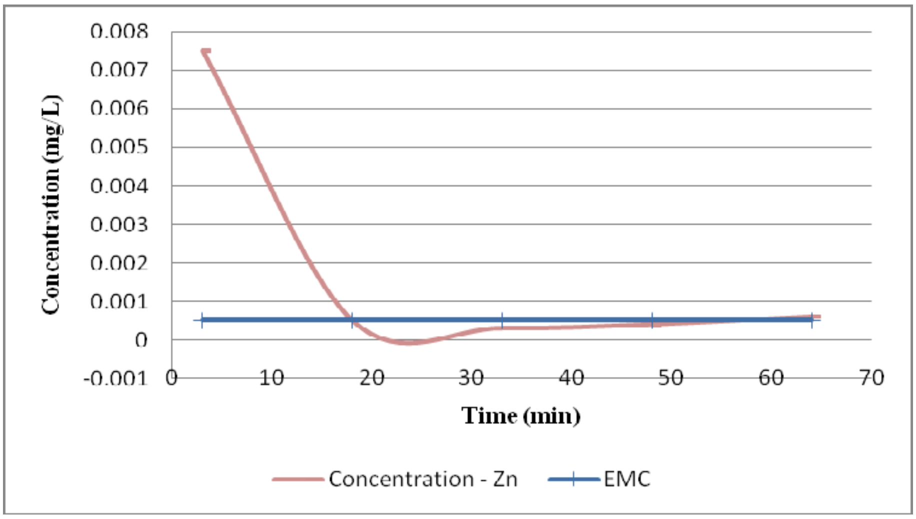


Figure 4.43 Pollutograph for Zn from the asphalt pavement for the simulated storm on 20th March 2007

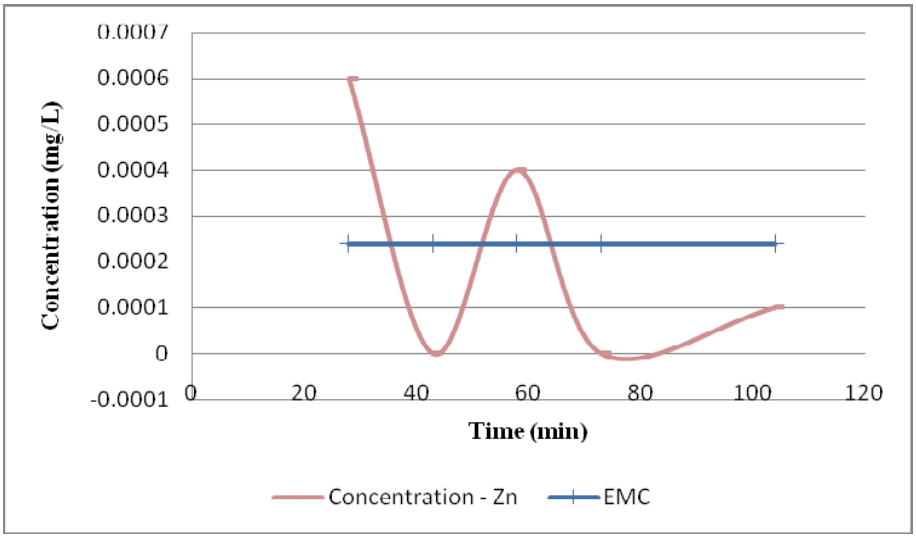


Figure 4.44 Pollutograph for Zn from the C&M Ecotrihex pavement for the simulated storm on 20th March 2007

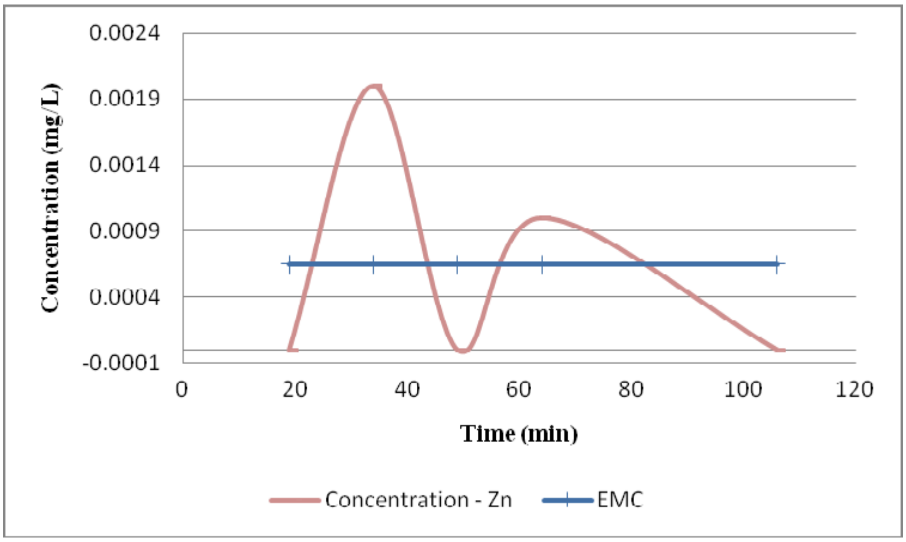


Figure 4.45 Pollutograph for Zn from the Atlantis Turf Cell pavement for the simulated storm on 20th March 2007

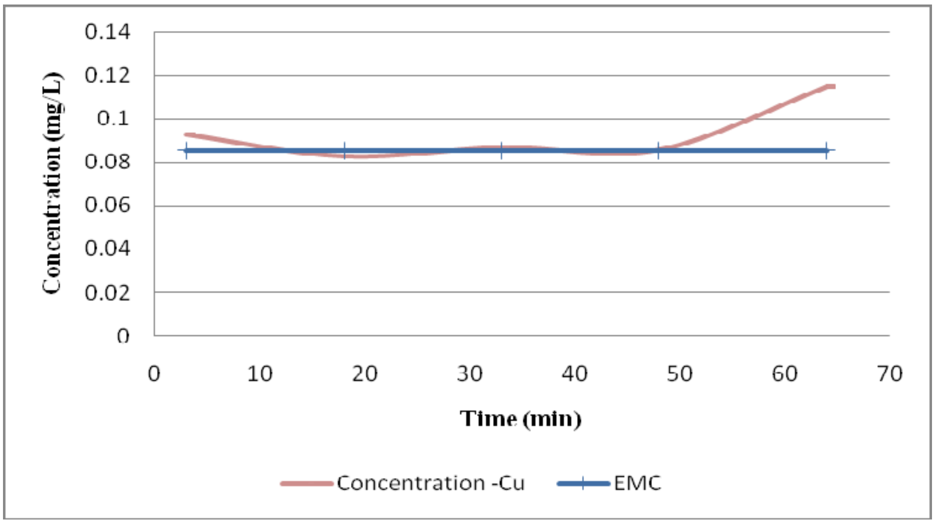


Figure 4.46 Pollutograph for Cu from the asphalt pavement for the simulated storm on 20th March 2007

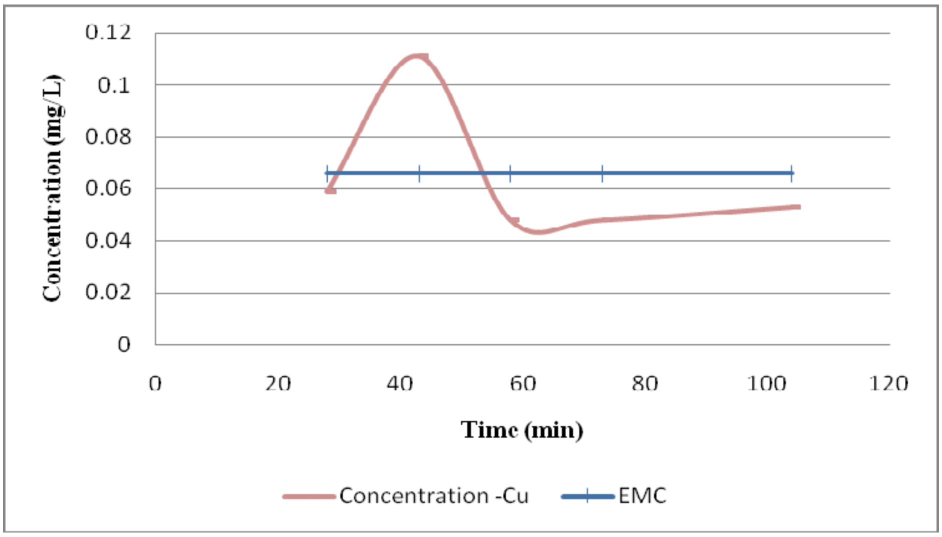


Figure 4.47 Pollutograph for Cu from the C&M Ecotrihex pavement for the simulated storm on 20th March 2007

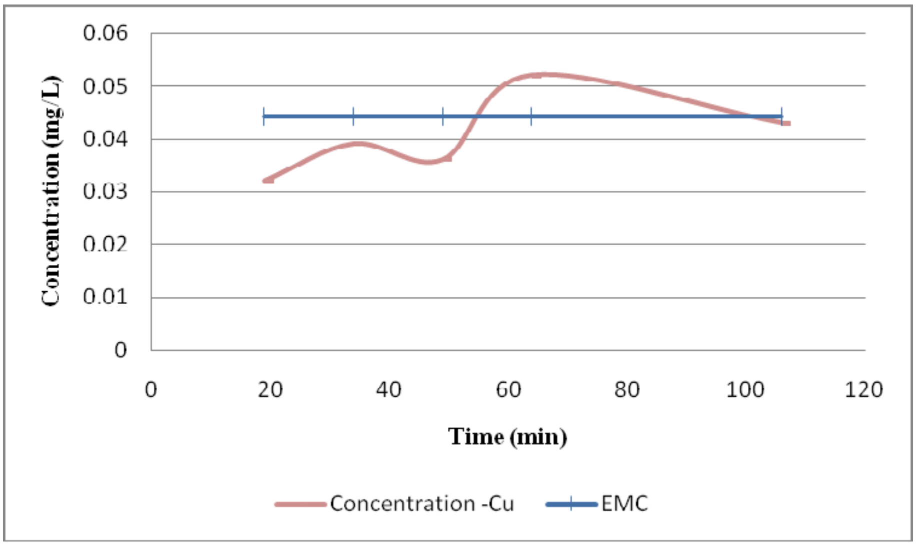


Figure 4.48 Pollutograph for Cu from the Atlantis Turf Cell pavement for the simulated storm on 20th March 2007

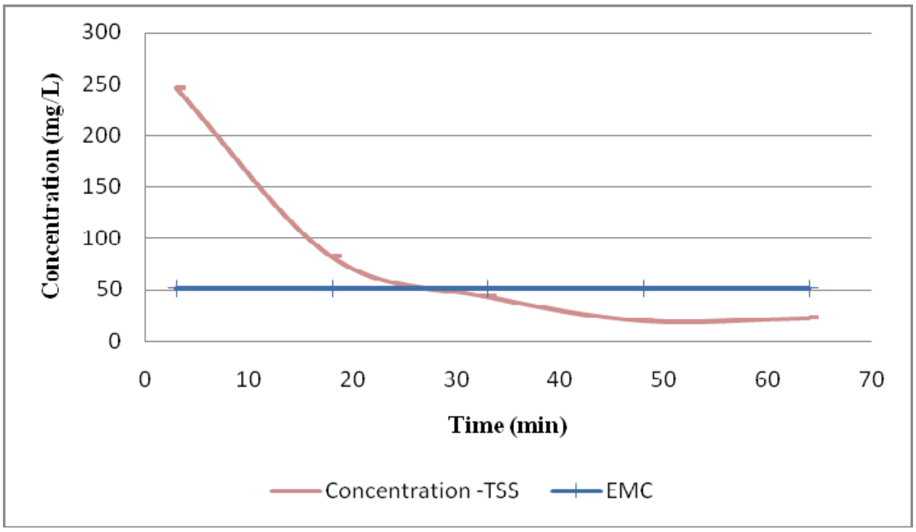


Figure 4.49 Pollutograph for TSS from the asphalt pavement for the simulated storm on 20th March 2007

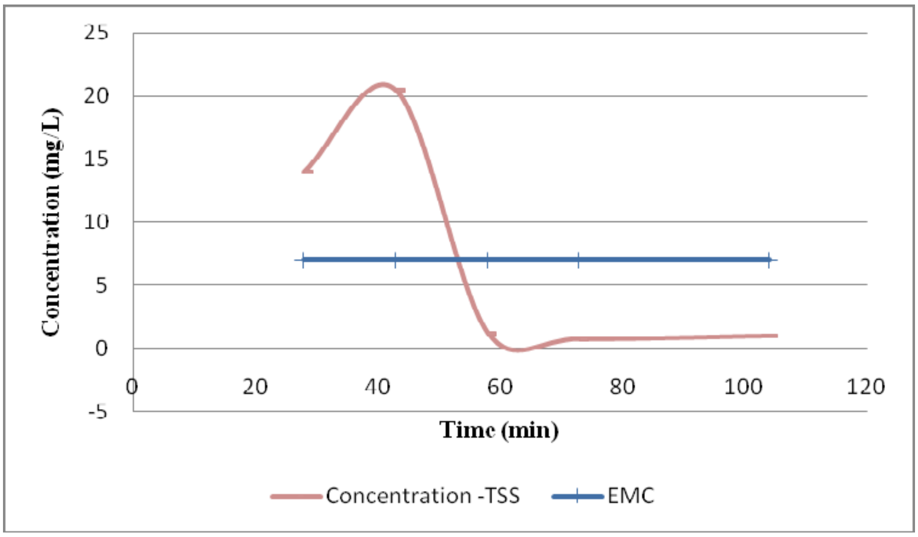


Figure 4.50 Pollutograph for TSS from the C&M Ecotrihex pavement for the simulated storm on 20th March 2007

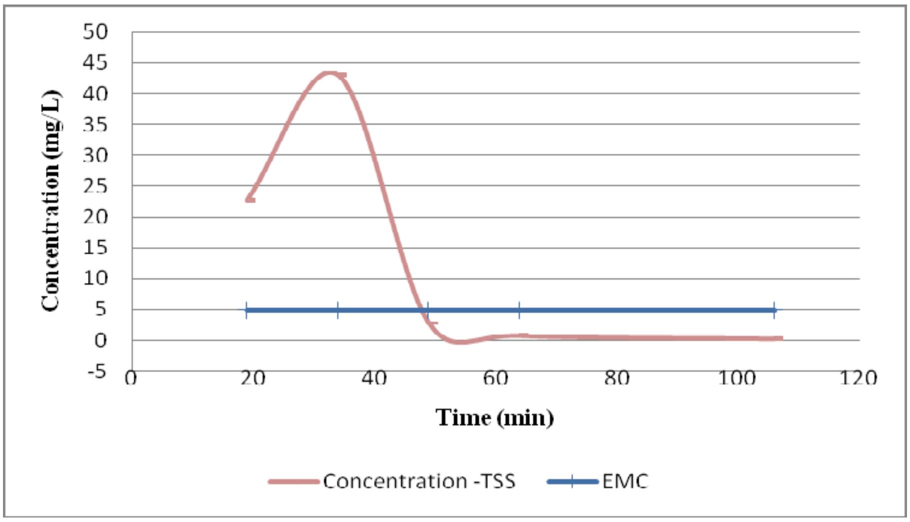


Figure 4.51 Pollutograph for TSS from the Atlantis Turf Cell pavement for the simulated storm on 20th March 2007

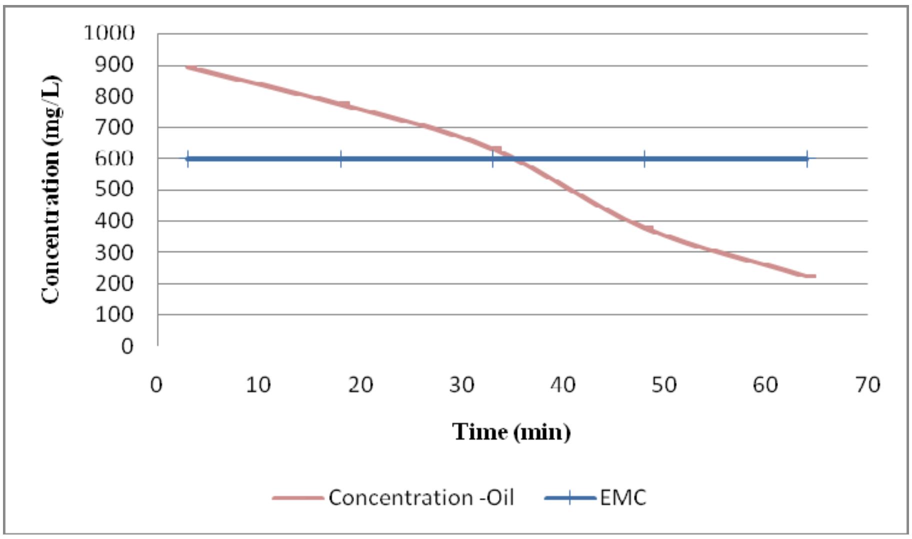


Figure 4.52 Pollutograph for Oil from the asphalt pavement for the simulated storm on 20th March 2007

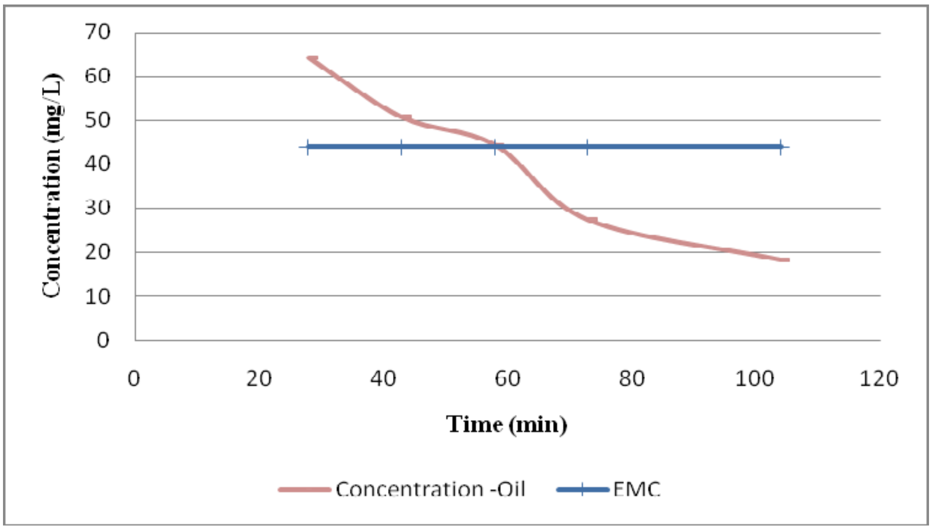


Figure 4.53 Pollutograph for Oil from the C&M Ecotrihex pavement for the simulated storm on 20th March 2007

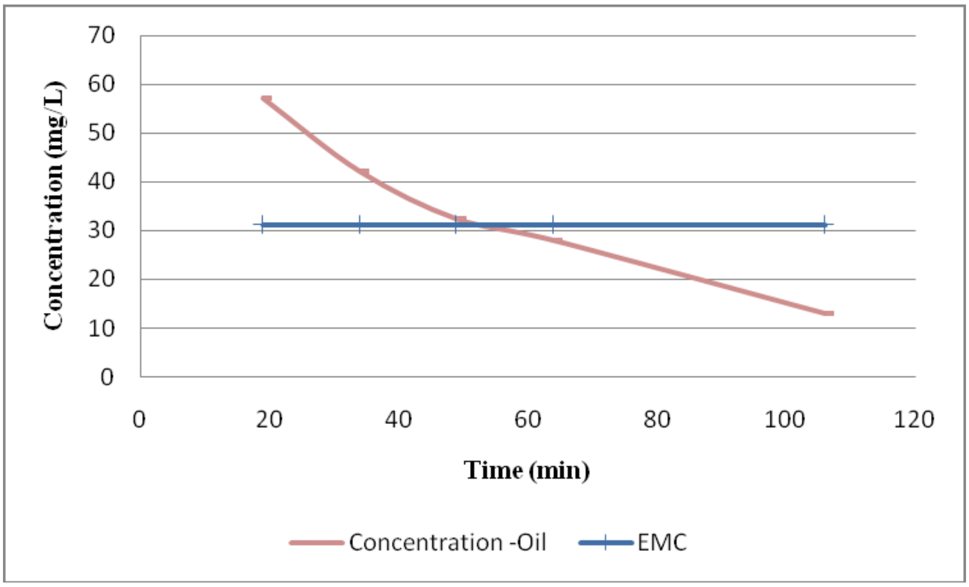


Figure 4.54 Pollutograph for Oil from the Atlantis Turf Cell pavement for the simulated storm on 20th March 2007

Tables 4.16 to 4.22 depict the Event Mean Concentrations (EMC) of the water quality parameters obtained from the runoff water collected from the asphalt, C&M Ecotrihex and Atlantis Turf Cell pavements for the seven actual storms that occurred during the experimental period. Figures 4.55to 4.57 show the comparison of EMCs from asphalt, C&M Ecotrihex and Atlantis Turf Cell pavement for storm events obtained on 18 May 2007, 27 June 2007 and 12 July 2007 respectively. The EMCs for other events are given in Appendix B, Table B.1 to B.6. Tables 4.23 to 4.26 depict the removal efficiencies of pollutant concentrations and loads for all the pollutants from the actual and simulated storms.

Table 4.16 Event Mean Concentrations (EMC) of the water quality parameters from the storm on 02 November 2006

Parameters	Asphalt (mg/L)	C&M (mg/L)	Atlantis (mg/L)	Removal Efficiency (%)	
				C&M	Atlantis
TP	0.02	0.01	N/A	50	N/A
TN	0	1.7	N/A	-	N/A
Zn	BDL	BDL	N/A	BDL	N/A
Cu	BDL	BDL	N/A	BDL	N/A
TSS	218.06	43.00	N/A	80.3	N/A
Oil	540	62.3	N/A	88.46	N/A
Cd	BDL	BDL	N/A	BDL	N/A
Pb	BDL	BDL	N/A	BDL	N/A

BDL – Below Detectable Level N/A- Not Applicable

Table 4.17 Event Mean Concentrations (EMC) of the water quality parameters from the storm on 24 March 2007

Parameters	Asphalt (mg/L)	C&M Ecotrihex (mg/L)	Atlantis Turf Cell (mg/L)	Removal Efficiency (%)	
				C&M	Atlantis
TP	0.4400	0.2000	N/A	54.94	N/A
TN	0.9500	1.5000	N/A	-21.05	N/A
Zn	0.0098	0.0020	N/A	75.90	N/A
Cu	0.0270	0.0170	N/A	37.41	N/A
TSS	104.1900	12.8300	N/A	87.68	N/A
Oil	588.5500	43.4800	N/A	92.61	N/A
Cd	BDL	BDL	N/A	BDL	N/A
Pb	BDL	BDL	N/A	BDL	N/A

BDL – Below Detectable Level N/A- Not Applicable

Table 4.18 Event Mean Concentrations (EMC) of the water quality parameters from the storm on 18 May 2007

Parameters	Asphalt (mg/L)	C&M (mg/L)	Atlantis (mg/L)	Removal Efficiency (%)	
				C&M	Atlantis
TP	0.5295	0.2340	N/A	55.81	N/A
TN	2.4000	1.1000	N/A	54.17	N/A
Zn	0.00765	0.0007	N/A	91.08	N/A
Cu	0.0239	0.0143	N/A	40.17	N/A
TSS	117.0600	13.1200	N/A	88.79	N/A
Oil	649.5800	69.2000	N/A	89.35	N/A
Cd	BDL	BDL	N/A	BDL	N/A
Pb	BDL	BDL	N/A	BDL	N/A

BDL – Below Detectable Level N/A- Not Applicable

Table 4.19 Event Mean Concentrations (EMC) of the water quality parameters from the storm on 27 June 2007

Parameters	Asphalt (mg/L)	C&M (mg/L)	Atlantis (mg/L)	Removal Efficiency (%)	
				C&M	Atlantis
TP	1.410	0.546	0.700	61.3	50.4
TN	2.760	0.750	1.320	72.8	52.2
Zn	0.295	0.0314	0.025	89.4	91.5
Cu	0.061	0.038	0.028	37.7	54.9
TSS	121.400	13.200	9.980	89.1	91.8
Oil	573.000	54.600	33.200	90.5	94.2
Cd	BDL	BDL	BDL	BDL	BDL
Pb	BDL	BDL	BDL	BDL	BDL

BDL – Below Detectable Level

Table 4.20 Event Mean Concentrations (EMC) of the water quality parameters from the storm on 12 July 2007

Parameters	Asphalt (mg/L)	C&M (mg/L)	Atlantis (mg/L)	Removal Efficiency (%)	
				C&M	Atlantis
TP	0.936	0.356	0.410	62.0	56.2
TN	7.100	1.943	2.830	72.6	60.1
Zn	0.076	0.005	0.006	93.4	91.2
Cu	0.0589	0.035	0.024	40.4	59.6
TSS	134.300	10.300	13.200	92.3	90.2
Oil	624.000	61.600	42.400	90.1	93.2
Cd	BDL	BDL	BDL	BDL	BDL
Pb	BDL	BDL	BDL	BDL	BDL

BDL – Below Detectable Level

Table 4.21 Event Mean Concentrations (EMC) of the water quality parameters from the storm on 04 November 2007

Parameters	Asphalt (mg/L)	C&M (mg/L)	Atlantis (mg/L)	Removal Efficiency (%)	
				C&M	Atlantis
TP	1.010	0.432	0.376	57.2	62.8
TN	9.100	2.400	3.120	73.6	65.7
Zn	0.090	0.009	0.008	90.2	90.8
Cu	0.060	0.034	0.029	43.3	51.7
TSS	142.300	12.300	14.800	91.4	89.6
Oil	702.000	39.700	49.300	94.3	93.0
Cd	BDL	BDL	BDL	BDL	BDL
Pb	BDL	BDL	BDL	BDL	BDL

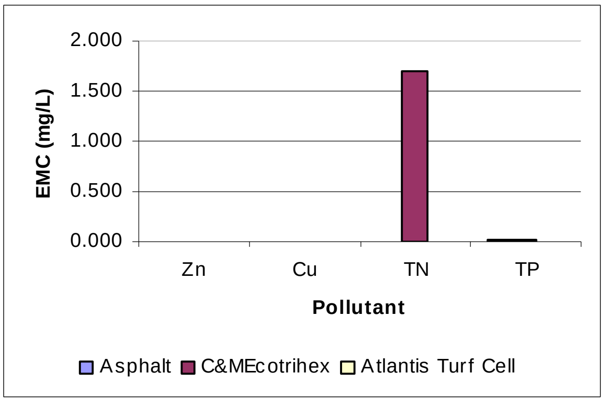
BDL – Below Detectable Level

Table 4.22 Event Mean Concentrations (EMC) of the water quality parameters from the storm on 21 December 2007

Parameters	Asphalt (mg/L)	C&M (mg/L)	Atlantis (mg/L)	Removal Efficiency (%)	
				C&M	Atlantis
TP	1.210	0.532	0.482	56.0	60.2
TN	11.400	4.200	3.540	63.2	68.9
Zn	0.110	0.009	0.009	91.5	92.1
Cu	0.074	0.042	0.039	43.2	47.8
TSS	132.700	11.400	12.300	91.4	90.7
Oil	762.000	43.500	39.800	94.3	94.8
Cd	BDL	BDL	BDL	BDL	BDL
Pb	BDL	BDL	BDL	BDL	BDL

BDL – Below Detectable Level

As presented in Tables 4.23 to 4.26 although the TN concentrations were initially higher than from the asphalt pavement, the TN loads were lower than from the impervious pavement.This is mainly due to leaching of nutrients in the aggregate used for the sub-base and bedding layers. Also the degradation of granular material may have increased the nutrient levels in the infiltrated water. The removal efficiencies of Oil, TSS and Zn concentrations and loads are close to 90%. The filtration processes through the porous media remove the sediments from stormwater. The removal efficiencies of oil and Zn also show 90% to 95% reduction. Heavy metals and oils mostly travel with sediment particles. This phenomenon is called adsorption. Cd and Pb concentrations in the infiltrated water were below detectable levels.



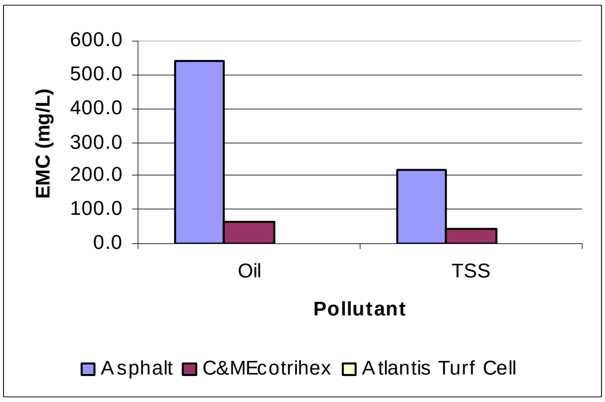


Figure 4.55 Comparison of EMC for asphalt, C&M Ecotrihex and Atlantis Turf cell pavementsfrom natural rain event – 02/11/2006

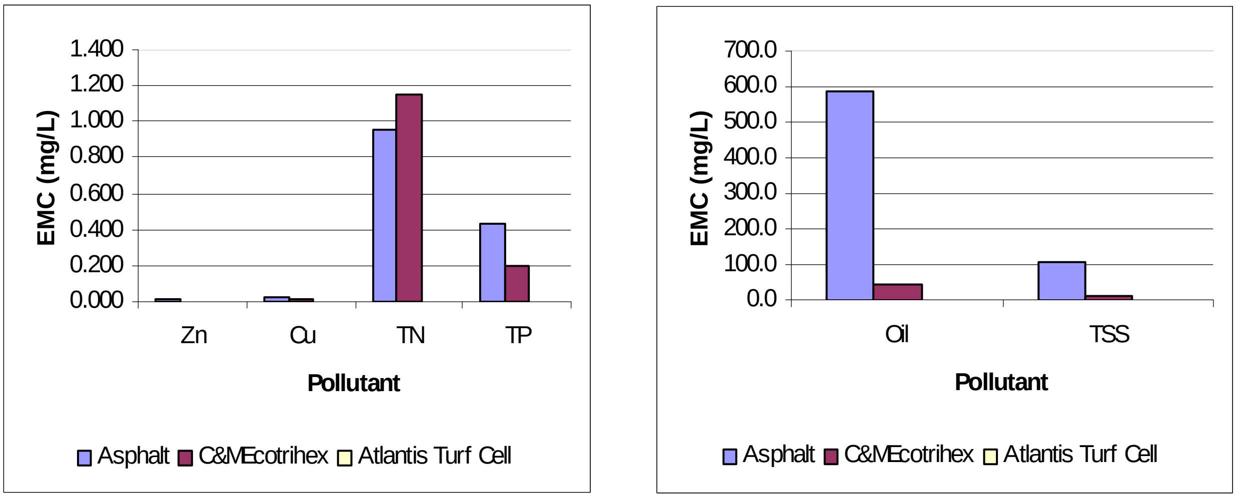


Figure 4.56 Comparison of EMC for asphalt, C&M Ecotrihex and Atlantis Turf cell surfaces from natural rain event – 24/03/2007

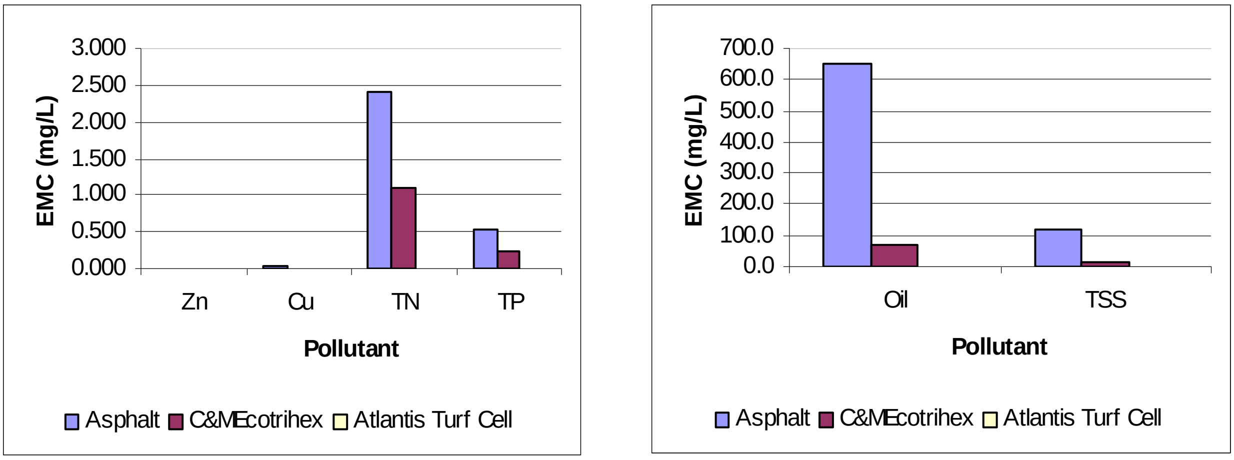


Figure 4.57 Comparison of EMC for asphalt, C&M Ecotrihex and Atlantis Turf cell pavements from natural rain event – 18/05/2007

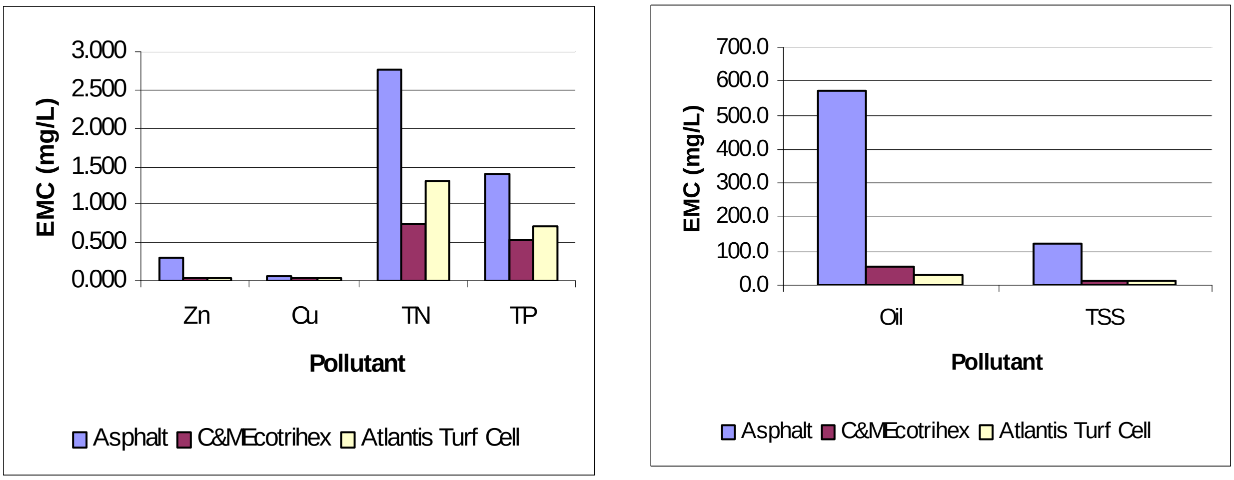


Figure 4.58 Comparison of EMC for asphalt, C&M Ecotrihex and Atlantis Turf cell pavements from natural rain event – 27/06/2007

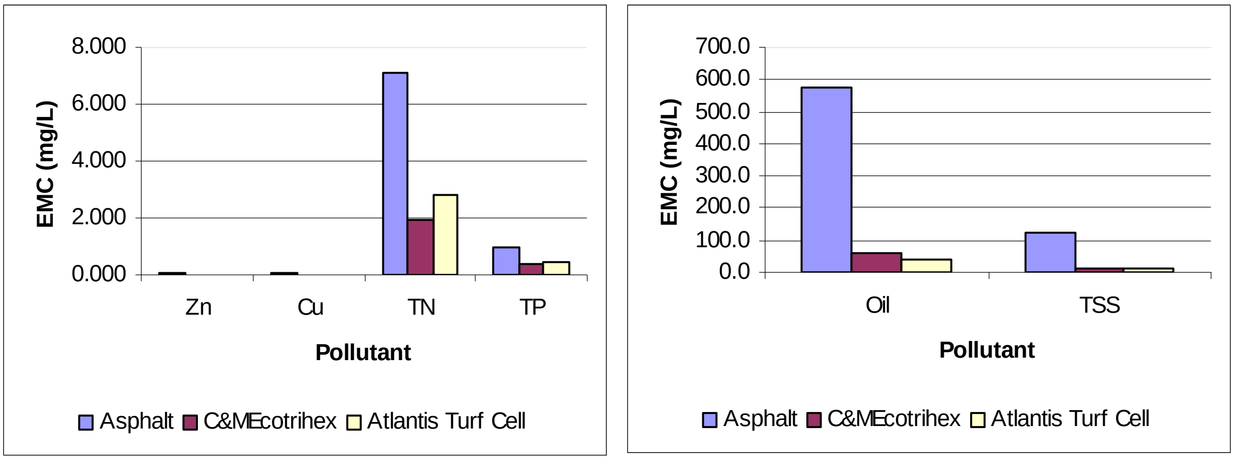


Figure 4.59 Comparison of EMC for asphalt, C&M Ecotrihex and Atlantis Turf cell pavements from natural rain event – 13/07/2007

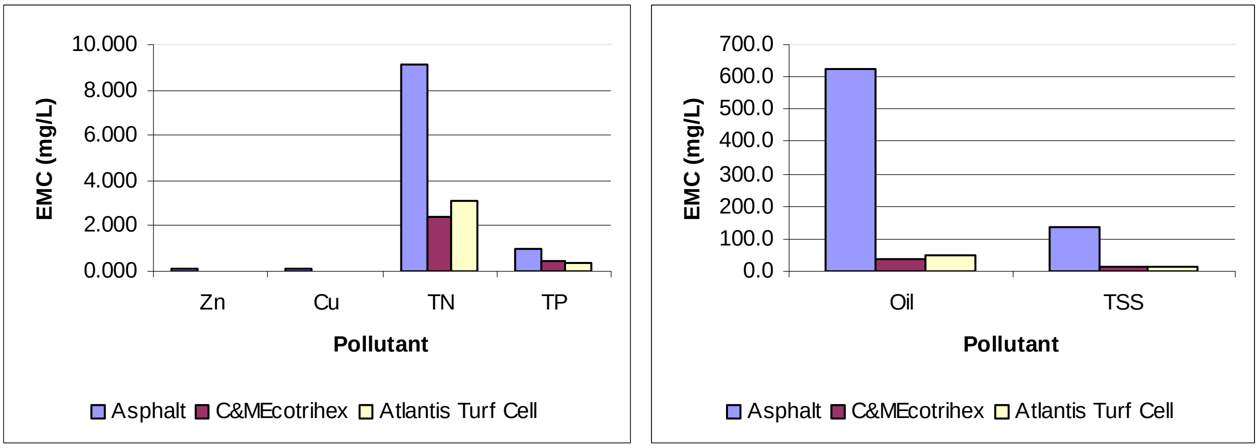


Figure 4.60 Comparison of EMC for asphalt, C&M Ecotrihex and Atlantis Turf cell surfaces from natural rain event – 04/11/2007

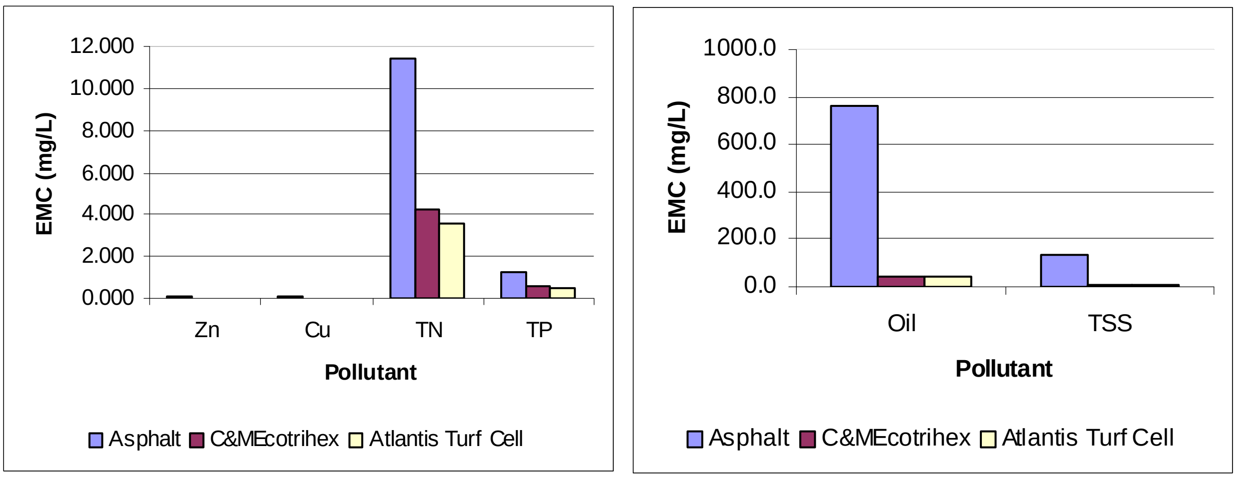


Figure 4.61 Comparison of EMC for asphalt, C&M Ecotrihex and Atlantis Turf cell pavements from natural rain event – 21/12/2007

Table 4.23 Removal Efficiencies of pollutant concentrations from the simulated events

Date	% Removal Efficiency in Concentration															
	Zn		TN		Cu		TN		TSS		Oil		Cd		Pb	
	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis
20/03/07	88.2	67.7	-130.8	-846.2	31.3	56.5	33.1	-26.8	91.0	88.4	92.9	94.0	BDL	BDL	BDL	BDL
22/03/07	91.0	81.9	-22.3	-352.1	10.4	89.9	31.5	33.7	91.2	92.7	89.6	95.4	BDL	BDL	BDL	BDL
26/03/07	88.1	83.7	-37.1	-42.9	33.3	46.7	68.8	47.0	90.5	90.0	90.7	95.9	BDL	BDL	BDL	BDL
31/03/07	79.1	88.6	-64.3	-4.3	31.7	48.7	35.7	33.2	88.4	88.1	91.1	95.7	BDL	BDL	BDL	BDL
2/04/07	94.4	87.2	42.2	18.8	32.2	46.8	25.8	50.0	93.5	94.7	89.3	95.5	BDL	BDL	BDL	BDL
4/04/07	93.5	97.4	49.2	3.2	36.9	50.7	42.3	30.9	89.9	86.5	91.5	95.3	BDL	BDL	BDL	BDL
6/04/07	96.3	95.1	61.1	29.3	32.1	47.7	63.1	50.8	90.9	88.8	91.0	95.0	BDL	BDL	BDL	BDL
11/04/07	90.3	95.5	59.9	43.6	36.5	52.4	37.5	52.8	89.9	87.7	91.1	93.4	BDL	BDL	BDL	BDL
13/04/07	94.8	92.2	59.4	40.0	36.2	57.4	66.0	40.2	91.1	89.3	91.6	95.1	BDL	BDL	BDL	BDL
16/04/07	87.5	87.5	70.8	47.7	31.8	54.5	55.8	55.8	89.1	87.4	91.6	92.4	BDL	BDL	BDL	BDL
18/04/07	90.6	88.6	79.7	53.1	35.7	51.4	60.5	42.1	90.8	89.3	90.8	95.1	BDL	BDL	BDL	BDL
23/04/07	91.3	88.0	68.1	57.8	33.9	48.2	57.2	44.0	89.6	90.9	90.0	96.0	BDL	BDL	BDL	BDL
26/04/07	90.3	92.8	70.0	59.2	37.7	59.0	62.0	45.8	91.8	91.3	90.2	94.5	BDL	BDL	BDL	BDL
30/04/07	92.3	89.3	72.5	57.8	36.7	51.0	64.0	51.2	92.0	89.3	89.8	93.9	BDL	BDL	BDL	BDL
Average	90.5	88.3	63.3	41.0	32.6	54.4	50.2	39.3	90.7	89.6	90.8	94.8	BDL	BDL	BDL	BDL

Table 4.24 Removal Efficiencies of pollutant concentrations from natural events

Date	% Removal Efficiency in Concentrations															
	Zn		TN		Cu		TP		TSS		Oil		Cd		Pb	
	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis
2/11/06	N/A	N/A	N/A	N/A	N/A	N/A	50.00	N/A	88.46	N/A	80.28	N/A	BDL	BDL	BDL	BDL
24/3/07	75.90	N/A	37.41	N/A	-21.05	N/A	54.91	N/A	92.61	N/A	87.69	N/A	BDL	BDL	BDL	BDL
18/5/07	91.08	N/A	40.17	N/A	54.17	N/A	55.85	N/A	89.35	N/A	88.73	N/A	BDL	BDL	BDL	BDL
27/6/07	89.36	91.49	37.70	54.92	72.83	52.17	61.28	50.35	90.47	94.21	89.13	91.78	BDL	BDL	BDL	BDL
13/7/07	93.29	92.11	40.41	59.59	72.63	60.14	61.97	56.20	90.13	93.21	92.33	90.17	BDL	BDL	BDL	BDL
4/11/07	90.00	91.11	43.33	51.67	73.63	65.71	57.23	62.77	94.34	92.98	91.36	89.60	BDL	BDL	BDL	BDL
21/12/07	91.82	91.82	43.24	47.30	63.16	68.95	56.03	60.17	94.29	94.78	91.41	90.73	BDL	BDL	BDL	BDL

Table 4.25 Removal Efficiencies of water quality parameters from simulated events

Date	% Removal Efficiency in Load															
	Zn		TN		Cu		TP		TSS		Oil		Cd		Pb	
	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis
20/03/07	80.62	48.37	62.39	79.44	32.41	-24.04	43.23	50.75	96.45	97.93	93.44	96.20	BDL	BDL	BDL	BDL
22/03/07	96.25	93.22	62.80	96.23	49.18	-69.68	71.55	75.12	95.66	98.27	96.37	97.25	BDL	BDL	BDL	BDL
26/03/07	95.04	94.03	72.19	80.45	42.78	47.63	87.00	80.56	96.14	98.50	96.05	96.32	BDL	BDL	BDL	BDL
31/03/07	89.79	95.20	66.65	78.43	19.83	56.18	68.64	71.93	95.63	98.21	94.35	94.99	BDL	BDL	BDL	BDL
2/04/07	96.85	94.76	61.75	78.29	67.41	66.82	58.16	79.58	93.96	98.16	96.32	97.83	BDL	BDL	BDL	BDL
4/04/07	96.31	99.05	64.45	81.57	71.36	63.84	67.47	74.17	95.23	98.23	94.31	94.94	BDL	BDL	BDL	BDL
6/04/07	98.22	97.84	67.54	77.04	81.42	68.93	82.36	78.40	95.68	97.80	95.63	95.09	BDL	BDL	BDL	BDL
11/04/07	95.47	97.87	70.36	77.35	81.30	73.17	70.84	77.53	95.86	96.88	95.27	94.16	BDL	BDL	BDL	BDL
13/04/07	97.37	97.11	67.66	84.29	79.46	77.84	82.79	77.94	95.75	98.20	95.48	96.04	BDL	BDL	BDL	BDL
16/04/07	92.30	95.42	67.10	83.29	85.90	80.78	78.66	83.75	95.96	97.20	94.73	95.38	BDL	BDL	BDL	BDL
18/04/07	95.48	95.63	69.19	81.43	90.26	82.08	81.08	77.87	95.57	98.13	95.61	95.90	BDL	BDL	BDL	BDL
23/04/07	95.51	94.16	66.06	74.90	83.59	79.53	78.02	72.86	94.89	98.08	94.68	95.60	BDL	BDL	BDL	BDL
26/04/07	95.61	97.33	71.69	84.87	86.37	84.94	82.73	80.01	95.54	97.95	96.29	96.78	BDL	BDL	BDL	BDL
30/04/07	95.47	94.97	62.95	76.91	83.88	80.12	78.89	76.97	94.03	97.11	95.34	94.94	BDL	BDL	BDL	BDL
Average	94.31	92.50	66.63	81.04	68.22	54.87	73.67	75.53	95.45	97.90	95.28	95.81	BDL	BDL	BDL	BDL

Table 4.26 Removal Efficiencies of water quality parameters from natural events

Date	% Removal Efficiency in Load															
	Zn		TN		Cu		TP		TSS		Oil		Cd		Pb	
	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis	C&M	Atlantis
2/11/06	N/A	N/A	N/A	N/A	N/A	N/A	75.50	N/A	94.35	N/A	90.34	N/A	BDL	BDL	BDL	BDL
24/3/07	86.02	N/A	63.70	N/A	29.79	N/A	73.85	N/A	95.72	N/A	92.86	N/A	BDL	BDL	BDL	BDL
18/5/07	95.00	N/A	66.41	N/A	74.27	N/A	75.22	N/A	94.02	N/A	93.67	N/A	BDL	BDL	BDL	BDL
27/6/07	94.34	96.16	66.85	79.67	85.54	78.43	79.39	77.61	94.93	97.39	94.21	96.29	BDL	BDL	BDL	BDL
13/7/07	96.28	96.25	66.93	80.83	84.81	81.09	78.89	79.22	94.52	96.78	95.74	95.34	BDL	BDL	BDL	BDL
4/11/07	95.34	96.41	73.59	80.47	87.71	86.15	80.06	84.96	97.36	97.16	95.97	95.80	BDL	BDL	BDL	BDL
21/12/07	95.60	96.58	69.49	77.98	80.20	87.02	76.37	83.35	96.93	97.82	95.38	96.13	BDL	BDL	BDL	BDL

Tables 4.23 and 4.24 present removal efficiencies of pollutant concentrations from simulated and natural rain events respectively. As summarised in Table 2.5, the pollutant removal efficiencies reported by Fletcher et al. (2003), Pagotto et al. (2000), Legret et al. (1996) and Booth et al. (2003) were compatible with the results obtained from the current research.

4.6 Maintenance

As reported by Kobayashi (1999), Rushton (2001), Dierkes et al. (2002) and Pratt (1997) (see Chapter 2), maintenance of pervious pavement plays role an important role in ensuring its on-going performance.

Maintenance of a pervious pavement depends on the pavement type and the environment in which it is constructed. Proper maintenance is essential to its operation, but is similar to that required for a traditional pavement. The main difference is that a pervious pavement should be vacuumed rather than swept. Vacuuming removes sediment and debris which block the percolation of runoff. Frequency of vacuuming depends on the amount of sediment carried by wind, vehicles or pedestrians etc. into the pervious pavement from neighbouring areas.

The EPA (1999) recommended sweeping the pavement at least four times a year and hosing the top layer with high pressure water to remove pavement clogging.

In the C&M Ecotrihex pavement one of the problems that encountered was to ensure weeds did not grow in the gaps in concrete blocks (Figure 4.62). When considering the Atlantic Turf Cell surface, the major issue was to keep the vegetation alive in drought periods (Figure 4.63). It is important to have a healthy grass cover for optimal performance from the pavement.

Figure 4.62 C&M Ecotrihex with weeds

Figure 4.63 Atlantis Turf Cell with grass

4.7 Summary and Conclusion

A car parks with three different surfaces was constructed in Centre for Education and Research at the Environmental Strategies (CERES) at Brunswick in Melbourne. Two of the surfaces were pervious, namely C&M Ecotrihex (Permeable - concrete block pavement) and Atlantis Turf Cell (Porous - grass pavement). Each car park was designed to occupy two cars at a time. The third surface was a conventional asphalt surface. The results from this pavement were used as a control for experimental purposes. The experimental site was fully automated with flow meters and autosamplers to collect flow data and stormwater samples.

The site was monitored from September 2006 to January 2008 to investigate the hydraulic performance and water quality improvements through the pervious pavement. Water quantity reduction and water quality improvement data obtained from the field experimental car park have been presented in this Chapter. As Melbourne is in the midst of a record drought a rainfall simulator had to be used to augment the natural storm events.

Results revealed that for the C&M Ecotrihex pavement the runoff coefficient varied between 0.40 and 0.44, and for the Atlantis Turf Cell pavement varied between 0.30 and 0. 37. Reduction in peak flow observed from the two pervious pavements was consistent with previous studies. The percentage reduction in peak discharge varied between 30% to 55% for C&M Ecotrihex pavement and 40% to 60% for Atlantis Turf

Cell pavement. The C&M Ecotrihex pavement reduced the runoff volume by 43% to 53% whilst the Atlantis Turf Cell pavement reduced the total runoff by between 52% and 62%. From these results it can be stated that both pervious pavements are effective in managing stormwater flow, although the Atlantis Turf Cell pavement holds more infiltrated water than the C&M Ecotrihex pavement. The water that is retained within the pavement structure will evaporate back to the atmosphere. The reduction of peak discharge and volume reduces the stress on infrastructure. Furthermore, both C&M Ecotrihex and Atlantis Turf Cell pavements show at least a one hour lag time on peak discharge compared to asphalt pavement. This would further reduce the pressure on the infrastructure during a large storm event by leaving room for attenuation.

The efficiency of pervious pavement in water quality improvement is of vital importance. Therefore the samples collected through the auto-samplers from the automated field car park at CERES were analysed for water quality improvement. Stormwater samples were collected for seventeen months starting from September, 2006.

The removal efficiencies of water quality parameters from C&M Ecotrihex and Atlantis Turf Cell pavements were calculated by comparing concentrations and loads from the asphalt pavement. On average TSS, TP, Zn and oil concentrations reduced between 87% to 92%, 55% to 62%, 76% to 93% and 89% to 92% respectively from the C&M pavement and 90% to 92%, 50% to 56%, 91 to 92% and 93% to 94% from the Atlantis Turf Cell pavement. The removal efficiency of Cu is around 40 % and 60% from C&M Ecotrihex and Atlantis Turf Cell pavements respectively. However, initially the TN concentration levels from the water infiltrated through both pervious pavements were very high. This is due to reducing flow values and leaching of TN from the subbase of the pavement.

The results obtained from the field scale experiments clearly prove that pervious pavements have an ability to reduce peak discharges while filtering the pollutants in urban stormwater. Consistent water quality improvements were observed from pervious paver studies, with reductions in TSS, TP and TN of around 70% to 100%, 40% to 80% and 60% to 80% respectively by previous researchers.

Maintenance of a pervious pavement depends on the pavement type and the environment in which it is constructed. Proper maintenance is crucial to its operation, but is similar to that required for a traditional pavement. The main difference is that a pervious pavement should be vacuumed rather than swept. Vacuuming removes sediment and debris which block the pores that infiltrate. The EPA (1999) recommended sweeping the pavement at least four times a year and hosing the top layer with high pressure water to remove clogging of the pavement. Frequency of vacuuming depends on the amount of sediments carried by wind, vehicles or pedestrians etc. into the pervious pavement from neighbouring areas.

5 WATER QUALITY AND QUANTITY MODELLING

The application of pervious pavements as a water sensitive urban design measure in Australia is still in its infancy. It is important to design a structurally sound pavement structure to hold the dynamic loadings whilst improving the water quality as well as reducing the runoff peaks. The Concrete Association of Australia has developed a LOCKPAVE (LOCKPAVE-PRO, 2001) software package to design concrete block pervious pavements and Atlantis (www.atlantiscorp.com.au) has their own design guidelines for Atlantis Grass pavements As discussed in Chapter 2, the Storm Water Management Model for Permeable Pavements (PCSWMMPP) software package was especially developed by James et al (2003) to design drainage from pervious pavements. The MUSIC software package (CRCCH, 2002) was developed to simulate water quality improvement from the application of water sensitive urban design features in the urban environment. These two models were applied to data collected from the pervious pavements constructed at CERES. The field data obtained from the study were compared with the simulated results from the above two models.

James et al (2003) developed the PCSWMMPP computational model to predict hydraulic performance and assist the design of the drainage systems to remove runoff from pervious pavements. Shackel et al. (2003) used PCSWMMPP to design drainage systems of pervious pavements. Zhang et al (2006) successfully estimated the parameters of PCSWMMPP in the laboratory. Jayasuriya et al (2006b) reported that algorithms in the PCSWMMPP model (James et al, 2003) could be successfully used in hydraulic calculations when designing pervious pavements. After a thorough study of the work carried out by above authors, PCSWMMPP was identified as the most suitable software package to use in designing drainage systems from pervious pavements.

The PCSWMMPP model is useful for stormwater and sanitary system modelling and designing. The model can be run with different design parameters such as depth of pavement layer and sub-base, with different grading curves for particular locations, until the designer achieves the required reduction in water quantity. It is equally important to ensure that the designed structure is capable of handling the dynamic loadings safely.

The MUSIC model was developed in Australia by the Cooperative Research Centre for Catchment Hydrology (CRCCH) in 2002. The MUSIC model has been widely used in Australia as a WSUD tool that helps to model most of the treatment techniques such as swales, ponds, rainwater tanks and sedimentation basins. However, pervious pavements have not yet been incorporated into the MUSIC model as a direct treatment node. Recently Deletic and Fletcher (2007) developed a model for flow and water quality transfer functions to use with the MUSIC to study the water quality improvement capabilities of pervious pavements using the Permapave pavement (www.permapave.com) surface. The treatment node “Pond” was used to model the flow component and the “Generic” node was used to model the water quality component.

The water quality and quantity data obtained from C&M Ecotrihex and Atlantis Turf Cell pervious pavement field studies at CERES were used to calibrate the above two models. This chapter initially introduces the PCSWMMPP model structure, input and output parameters and explains the model calibration process. Results obtained from the calibration will be compared with the water quantity data collected from the C&M Ecotrihex and Atlantis Turf Cell pavements at CERES. A sensitivity analysis will be carried out to identify the parameters that need to be estimated accurately. The features of the MUSIC water quality model to estimate water quality improvements will also be discussed. Similar to the PCSWMMPP model, the MUSIC model was first applied as is with the flow and water quality transfer functions developed for pervious pavements with the Permapaver pavement to pervious pavements at CERES. The field data collected at CERES were compared with MUSIC model outputs. Finally the flow and water quality transfer functions of the MUSIC model were modified in line with the pervious pavement data collected at CERES (with C&M Ecotrihex and Atlantis Turf Cell pavements).

5.1 PCSWMMPP Computational Model Analysis

The introduction of computers into the field of hydrology in 1960s promoted the simulation of complex water problems as complete systems. A group of researchers at Stanford University developed the first comprehensive hydrological model available to the water resources community in 1966 (Bedient and Huber, 1992). The Stanford Watershed Model simulated all the major processes in the hydrologic cycle.

Thereafter Bedient and Huber (1992) developed process screening criteria for the Stanford Watershed Model. These authors summarised some of the deterministic models available such as the Soil Conservation Service TR-55 (SCS TR-55) model, the Illinois Urban Drainage Area Simulator (ILLUDAS), the Penn State Urban Runoff Model (PSURM), The Hydrologic Simulation Program-Fortran (HSPF), the Storage Treatment Overflow and Runoff Model (STORM) and the Stormwater Management Model (SWMM). After a thorough study of deterministic stormwater computational models, Bedient and Huber (1992) concluded the SWMM model to be the most comprehensive model available for modelling urban runoff in stormwater systems. James et al. (2003) enhanced the general SWMM model to PCSWMMPP which can be used to design drainage from pervious pavements.

5.1.1 Introduction to the PCSWMM Interface

PCSWMMPP is an interface between the user and the US EPA's SWMM (James et al., 2003) program. This model is a product of Computational Hydraulics International, Canada. This interface can be divided into three main sections: the Input Wizard, the Summary Report and the Graph(s). Under Input Wizard the main input parameters are infiltration capacity of the pervious pavement, storage volume of the sub-base layers and percolation through the sub-grade soil. The main objective of introducing pervious pavements is to infiltrate the surface runoff whilst reducing the peak of the surface runoff hydrograph.

Figure 5.1 shows the components of a pervious pavement. The structure consists of four different components, namely the paver and bedding layer; the unsaturated zone of the base material; the saturated zone of the base material; and the sub-grade (Figure 5.1). These components are assumed to be spatially homogenous, at least as far as the modeled hydrological processes are concerned. Five processes control the movement of water through the pervious pavement installation, as shown in Figure 5.2.

The development of the PCSWMMPP model is based on the following hydraulic model algorithms:

- Manning's Equation (Manning, 1889) for the calculation of surface runoff

- Green and Ampt infiltration model (Mein, 1980) to calculate infiltration through the bedding layer
- Darcy's Law (Darcy, 1856) to calculate percolation of infiltrated surface water to the drainage system or to groundwater.

There are several input parameters necessary to run the PCSWMMPP model. They are parameters related to the surface, aggregate properties and rainfall characteristics. Under surface parameters, it is necessary to input the area of the pervious pavement and the area of runoff contributing to the pavement, slope and the construction life of the perviuos pavement. When considering the aggregate properties, the infiltration rate of the bedding layer, depth of the sub-base layer, saturated hydraulic conductivity, porosity, field capacity and the initial moisture content of the sub-base material are important. Design storm intensity, allowable surface runoff in terms of percentage of the total rainfall and allowable water depth in the sub-base layer are to be considered under rainfall characteristics. PCSWMMPP model developers recommend default input parameters and the users can adjust these parameters according to the field conditions.

Figure 5.1 shows the schematic diagram of a pervious pavement structure. The PCSWMMPP model results include the volume of surface water infiltrated, percolation into the sub-grade, surface runoff and the water depth in the sub-base layer (Figure 5.2). Graphical presentation of the variation of surface runoff, sub-base drainage rate and the water depth in the sub-base layer with time are also available for analysis.

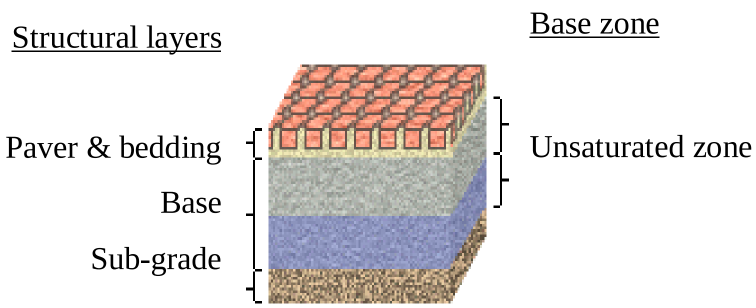
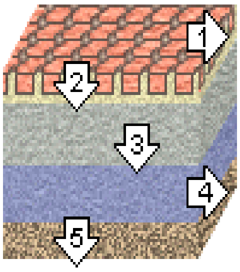


Figure 5.1 Pervious paver model component (James et al., 2003)



1. Surface runoff (If any)
2. Infiltration through paver bedding
3. Percolation through unsaturated zone or base

Figure 5.2 Pervious paver process model (James et al., 2003)

The process parameters referred to Figures 5.1 and 5.2 can be described by using Manning's equation, the Green and Ampt infiltration equation (Mein, 1980) and Darcy's equation that were used to develop PCSWMMMPP computational model

Manning's equation

Manning's equation is used to calculate surface runoff. When rainfall falls on the surface of a pervious pavement, part of it infiltrates to the base material and the rest will evaporate, while sometimes for high rainfall intensities there can be a surface runoff (overland flow). The model's conversion of rainfall excess (rainfall less infiltration and/or evaporation) into runoff is calculated using the Equation 5.1:

$$Q = W\,(1.49/n)\,(d-d_p)^{5/3} S^{1/2} \qquad (5.1)$$

where,

Q = runoff

W = width of catchment

n = Manning's roughness coefficient

d = depth of surface water

d_p = depth of depression storage

S = slope of catchment

Green and Ampt infiltration equation

The Green and Ampt infiltration equation is of paramount importance when calculating infiltration rates. Mein (1980) modified the Green and Ampt infiltration equation to present a relationship between time and the infiltration rate. The Green and Ampt infiltration equation presented in Section 3.1.4.

Darcy's equation

When developing PCSWMMPP model, Darcy's law (Equations 5.6 and 5.7) was used to calculate the percolation through the unsaturated zone of the sub-base (James et al., 1992):

$$K_{perc} = K(\theta)*[1+ PCO*(\theta- \theta_{FC})/(d_{average}/2)] \quad (5.6)$$

$$K(\theta) = Ks*EXP[(\theta- \theta_{FC})*HCO] \quad (5.7)$$

Where,

K_{perc} = percolation rate and is only nonzero when θ is greater than θ_{FC} (m/s)

$K(\theta)$ = hydraulic conductivity as a function of moisture content (m/s)

Ks = saturated hydraulic conductivity (m/s)

PCO = the average slope of the soil water suction and moisture content curve (m/fraction)

θ = moisture content

θ_{FC} = filed capacity

$d_{average}$ = average depth of the unsaturated zone (m)

HCO = calibration parameter

Saturated hydraulic conductivity (Ks):

Zhang (2006) conducted the hydraulic conductivity test to obtain this parameter for the ROCLA Ecotrihex surface built in the laboratory. The value of saturated hydraulic conductivity of the sub-base material is $6.35*10^{-5}$m/s (228.6 mm/hr).

The average slope of the soil water suction and moisture content curve:

To obtain the average slope of the soil water suction and moisture content curve for the ROCLA Ecotrihex surface, Zhang (2006) developed a relationship between soil water suction and moisture content. According to Smettem and Gregory (1996), the value of parameter α is 0.044. PCO was determined as 5m/fraction by Zhang (2006).

Field capacity (θFC):

The field capacity of a soil can be obtained from the soil moisture retention curve (Turner et al., 1984). Zhang (2006) found the field capacity of the sub-base soil to be 0.04. The soil water suction assigned to field capacity is 0.1 bar for sandy soils.

Average depth of the unsaturated zone:

As there was no water stored in the sub-base layer (the pavement was dry) at the beginning of the infiltration test, the depth of the saturated zone in sub-base material is assumed as 0 (zero) mm. As a result, the average depth of the unsaturated zone is equal to the thickness of the sub-base layer, which is 250mm.

5.1.2 Model calibration for C&M Ecotrihex surface

The PCSWMMPP model recommends default values as input parameters for some variables. With a proper understanding of the components of the pervious pavement and the hydrological processes, the parameters were carefully estimated for the model. Some of the input parameters were obtained from studying aggregate physical properties or from tests carried out under field conditions. The rest of the values were assigned default values as recommended by James et al. (2003).

Figure 5.3 shows the details of pervious pavement that are required in the model. The pervious paved area is 50.4 m^2 (4.8mx10.5m). The average slope of the surface is 2% according to the initial design. The length of the pervious pavement is taken as the maximum length of overland flow which is 10.5m.

Clogging potential for the pervious pavement was set cleaned to 18 mm. Zhang (2006) reported the infiltration capacity of the bedding material to be equal to 160mm/hr. Figures 5.4 and 5.5 show the data entry interface on clogging potential.

Run-on from adjacent areas was avoided by providing a drainage system around the pervious pavement using agricultural pipes. Hence, as shown in Figure 5.6 the type of adjacent impervious area was selected as no run-on.

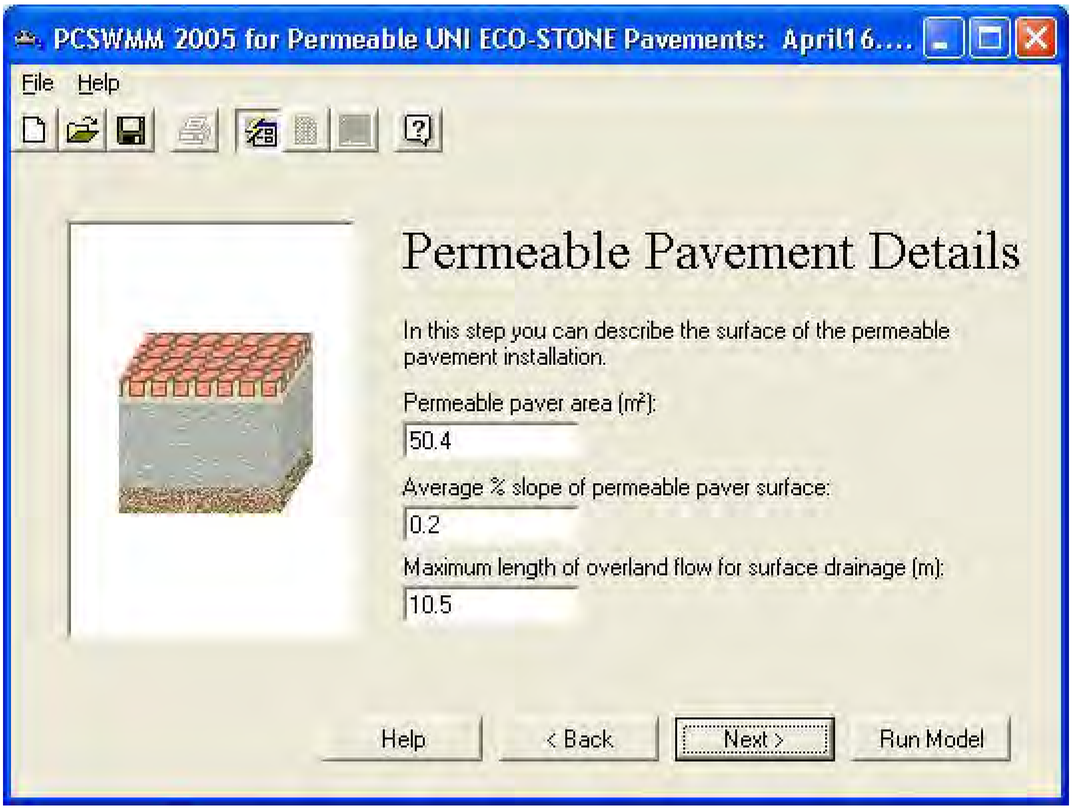


Figure 5.3 PCSWMMPP model pervious pavement detail interface

Figure 5.4 Data entry interface of PCSWMMPP model for clogging potential

Figure 5.5 Data entry interface of PCSWMMPP for clogging parameters

Figure 5.6 Interface for run-on from adjacent surface

When considering the base details, type of base material was set to custom and substituted with the predetermined values found at RMIT by Zhang (2006) for porosity (0.36), saturated hydraulic conductivity (228mm/hr) and field capacity (0.04). Curve fitting parameter (10) and tension-soil moisture (5) were set to their default values as shown in Figure 5.7.

As shown in Figure 5.8, the depth of the base was positioned to 250mm according to its initial design. The initial depth of water in the base layer was assumed to be zero as the data for the calibration run was taken after a dry period between rainfall simulations. Initial moisture content of the unsaturated zone was assumed to be 3% recommended by James et al. (2003). Table 5.1 summarizes all the input values used in calibration runs for the C&M Ecotrihex pavement.

As shown in Figure 5.9, the drainage parameters were substituted. Threshold elevation was set to zero (Zhang, 2006). The flow coefficient was set to 500 after a manual trial and error process which started with the default PCSWMMPP value (8000). Flow coefficient was set to the default value recommended by James et al. (2003). As there was no percolation due to the impermeable membrane being installed underneath the pervious pavement, the percolation coefficient was set to 0mm/hr as shown in Figure 5.10.

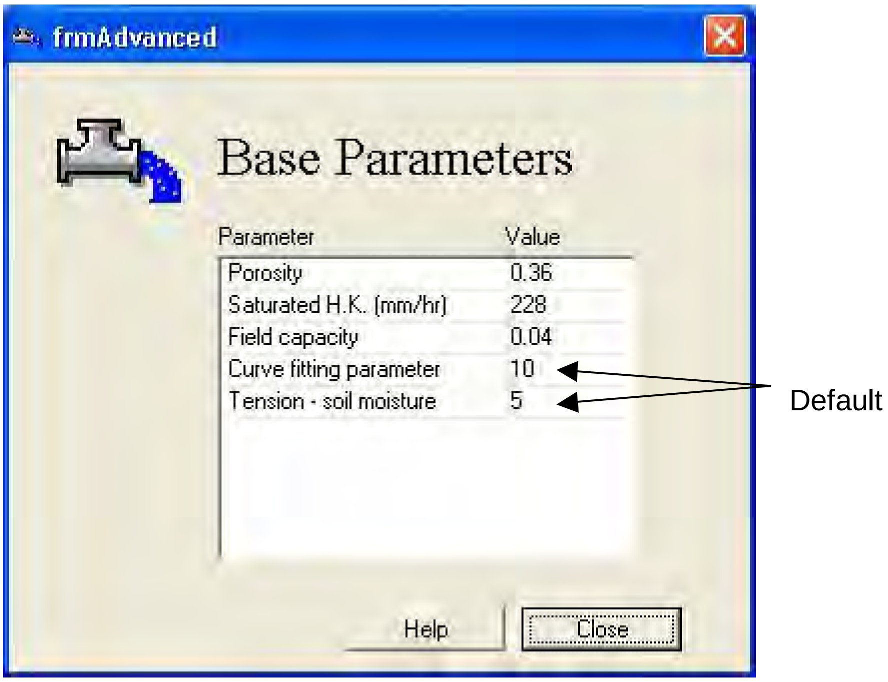


Figure 5.7 Interface for base parameters

Figure 5.8 Interface for base parameters

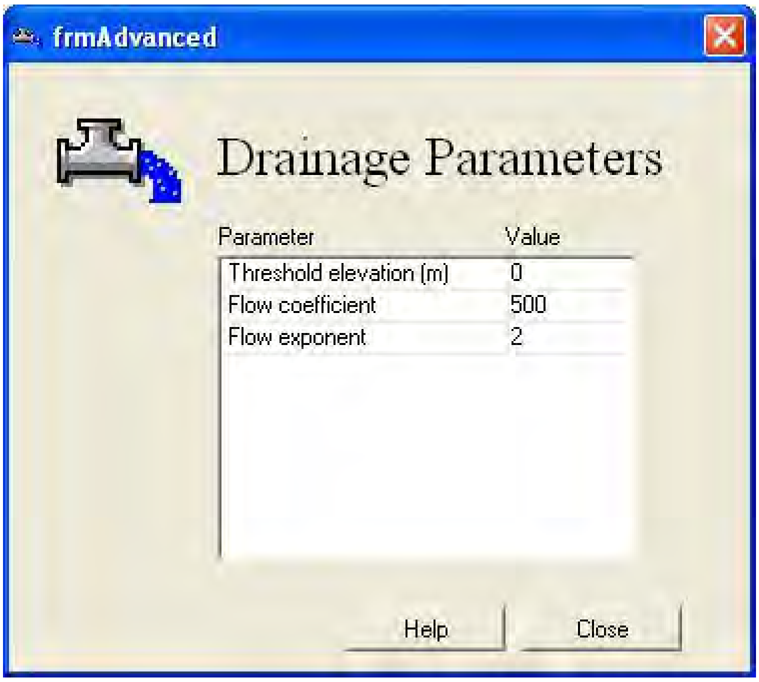


Figure 5.9 Interface for drainage parameters

Figure 5.10 Interface for sub-grade parameters

Table 5.1 Initial PCSWMMPP model input values used in C&M Ecotrihex pavement

Interface	Parameter	Value	Method of parameter estimation
Permeable pavement details	Permeable paver area (m2)	50.4	Field
	% slope of permeable pavement (%)	2	Field
	Maximum length of overland flow (m)	10.5	Field
Clogging potential	Cleaned to 18 mm (mm/hr) infiltration rate	160	Laboratory Experiment
Run-on from adjacent surface	Type of adjacent impervious surface	No run-on	Field
	Area of contributing surface (m2)	0	Field
	Average % slope contributing surface	0	Field
	Maximum length of overland flow for contributing surface (m)	0	Field
Base Parameters	Porosity	0.36	Laboratory Experiment
	Saturated Hydraulic conductivity (mm/hr)	228	Laboratory Experiment
	Field Capacity	0.04	Laboratory Experiment
	Curve fitting parameter	10	Default
	Tension-soil moisture	5	Default
Drainage parameters	Threshold elevation (m)	0	Laboratory Experiment
	Flow coefficient	8000	Default
	Floe exponent	2	Default
Sub-grade parameters	Percolation coefficient (mm/hr)	0	Laboratory Experiment

The field data obtained from the simulated event on 02 April 2007 were used when calibrating the PCSWMMPP model parameters. Design storm was set to custom and the actual simulated rainfall intensity and duration of the event as shown in Figure 5.11 were entered.

Figure 5.11 Interface for design storm and simulation length

The calibration was carried out through a manual trial and error process. Table 5.2 depicts the names of all the calibrated parameters, the default values given in the PCSWMMPP model (James et al., 2003), initial input model parameters used (values obtained from the field and calculated from physical properties as given in Table 5.1) and the calibrated parameter values obtained for the C&M Ecotrihex pavement. The default values recommended by the program developers were used for parameters that could not be obtained by the aggregate physical properties. As the PCSWMMPP model was especially designed for permeable pavements, the model was initially calibrated and verified with the data obtained from the C&M Ecotrihex pavement collected at the CERES field site. (C&M Ecotrihex pavement is categorised as a permeable pavement.) The model parameters obtained from the calibration run are almost equal to the parameters obtained from aggregate physical properties or to the default values used, except for the flow coefficient. The flow coefficient values changed from the default 8000 to 500 in the calibration process. Tables 5.3 and 5.4 depict the percentage of errors obtained by comparing the runoff peak and total runoff volume obtained in the field from the C&M Ecotrihex pavement with the application of the PCSWMMPP model, together with the recommended default model parameters and model calibrated parameters and simulated and actual storm values. Almost all the percentage errors obtained from the independent storms (verification) are within 20% when compared with the actual values. The results obtained from default parameters show higher percentages of errors when compared with the actual values.

Table 5.2 PCSWMMPP model recommended default parameters, input model parameters obtained from aggregate physical properties and model calibrated parameters

Parameter	PCSWMMPP default Parameters	Initial model Parameters	Calibrated parameters
Bedding			
Infiltration rate (mm/hr)	200	160	160
Sub Base			
Saturated Hydraulic conductivity (mm/hr)	Open graded – 90,000	228	228
Porosity	0.38	0.36	0.36
Field Capacity	0.05	0.04	0.04
Curve fitting parameter	10	10	10
Tension – Soil moisture	5	5	5
Drainage	(Fast)	(Custom)	(Custom)
Threshold elevation	0	0	0
Flow coefficient	8,000	8000	500
Flow exponent	2	1.75	2.0
Sub-grade (Impervious)			
Percolation coefficient (mm/hr)	0	0	0

Table 5.3 Comparison of field data obtained from the simulated storms for the C & M Ecotrihex pavement with PCSWMMPP model results by using default parameters and calibrated parameters

Date	Peak Discharge /(L/s)			% Error in peak discharge		Volumes / (L)			% Error in volume	
	Field	Default	Calibrated	Default	Calibrated	Filed	Default	Calibrated	Default	Calibrated
20/03/07	0.168	0.230	0.168	-36.90	0.00	353	458	262	-29.93	25.67
22/03/07	0.150	0.300	0.170	-100.00	-13.33	288	434	309	-50.80	-7.37
26/03/07	0.180	0.300	0.170	-66.67	5.56	290	429	308	-47.83	-6.13
31/03/07	0.145	0.310	0.170	-113.79	-17.24	348	448	316	-28.59	9.30
02/04/07	0.150	0.300	0.15	-100.00	0.00	352	360	295	-2.27	16.19
04/04/07	0.140	0.200	0.140	-42.86	0.00	350	339	235	3.14	32.86
06/04/07	0.120	0.200	0.130	-66.67	-8.33	267	259	218	3.00	18.35
11/04/07	0.120	0.220	0.140	-83.33	-16.67	272	309	240	-13.60	11.76
13/04/07	0.120	0.260	0.130	-116.67	-8.33	270	264	241	2.04	10.58
16/04/07	0.150	0.220	0.14	-46.67	6.67	256	262	231	-2.42	9.70
18/04/07	0.150	0.280	0.140	-86.67	6.67	240	237	232	1.29	3.37
23/04/07	0.170	0.270	0.130	-58.82	23.53	243	210	211	13.58	13.17
26/04/07	0.140	0.250	0.130	-78.57	7.14	216	211	210	2.36	2.82
30/04/07	0.160	0.270	0.120	-68.75	25.00	213	174	190	18.12	10.59

Table 5.4 Comparison of field data obtained from the actual storms for the C & M Ecotrihex pavement with PCSWMMPP model results by using default parameters and calibrated parameters

Date	Peak Discharge /(L/s)			% Error in peak discharge		Volumes / (L)			% Error in volume	
	Actual	Default	Calibrated	Default	Calibrated	Actual	Default	Calibrated	Default	Calibrated
11/2/2006	0.057	0.088	0.045	-54.38	21.0	317.1	425	406	-34.06	-28.1
3/24/2007	0.059	0.091	0.056	-54.23	5.1	405.1	485	518	-19.75	-27.9
5/18/2007	0.042	0.089	0.044	-111.9	-4.8	411.3	416	392	-0.12	4.5
6/27/2007	0.051	0.100	0.056	-96.07	-9.8	461.8	905	466	-95.9	-0.9
7/12/2007	0.045	0.088	0.051	-95.56	-13.3	501.3	434	467	-13.4	6.8
4/11/2007	0.098	0.087	0.086	11.22	12.2	559.5	860	592	-53.7	-5.8
21/12/2007	0.140	0.150	0.140	-7.10	0	675.3	1240	642	-83.6	4.9

The parameters obtained by calibrating the model using the field data obtained from the C&M Ecotrihex pavement were further verified by applying the parameters to the Atlantis Turf Cell surfaced pavement. (Atlantis Turf Cell pavement can be categorized as a porous pavement). As described in Chapter 4, the paver surface is 52mm Atlantis Turf Cell filled with sand overlaid on a 308mm thick sandy gravel sub-base. Jayasuriya et al. (2006b) reported that the C&M Ecotrihex and Atlantis Turf Cell sub-bases were constructed with the same aggregates. Therefore, the same aggregate properties were used for the C&M Ecotrihex and Atlantis Turf Cell sub-bases. The infiltration capacity of Atlantis Turf Cell was taken as 200 mm/hr as recommended by its manufacturer (www.atlantiscorp.com.au). Table 5.5 depicts all the default input values recommended by James et al (2003), calculated values from the aggregates' physical properties, and input values obtained from the C&M Ecotrihex pavement calibration run. The PCSWMMPP model was run with the model parameters obtained from the C&M Ecotrihex calibration run. Tables 5.6 and 5.7 give the goodness-of-fit parameters obtained from the simulation runs with simulated and actual storm events when compared with the actual field data. Although the Atlantis Turf Cell surface is considered a porous surface, similar to the simulation results obtained from the C&M Ecotrihex pavement, the results obtained from the Atlantis pavement were also satisfactory.

Thus in the application of the PCSWMMPP model to pervious (both permeable and porous) pavements the model parameters could be used successfully determined from physical properties of the aggregates. This concludes the finding by Zhang et al. (2006) that the PCSWMMPP model parameters are easily obtainable from aggregate physical properties.

Table 5.5 PCSWMMPP input model parameters used in Atlantis Turf Cell pavement simulations

Parameter in the PCSWMM model	PCSWMM default parameters	Aggregates physical properties	Calibrated parameters from C&M Ecotrihex
Bedding			
Infiltration rate (mm/hr)	200	200	200*
Sub Base			
Saturated Hydraulic conductivity (mm/hr)	Open graded – 90,000	228.6	228.6
Porosity	0.38	0.36	0.36
Field Capacity	0.05	0.04	0.04
Curve fitting parameter	10	10	10
Tension – Soil moisture	5	5	5
Drainage	(Fast)	(Custom)	(Custom)
Threshold elevation	0	0	0
Flow coefficient	8,000	N/A	500
Flow exponent	2	N/A	2.0
Sub-grade (Impervious)			
Percolation coefficient (mm/hr)	0	0	0

*Infiltration rate was obtained as recommended by the Atlantis Turf Cell manufacturers (www.atlantiscorp.com.au)

After calibration, a sensitivity analysis was carried out to identify the most sensitive parameters. When carrying out the sensitivity analysis, one parameter was changed at a time by +10% and -10% while keeping all the other parameters constant. Its impact on the final output was then estimated. Tables 5.8 depicts sensitivity analysis results obtained for the C&M Ecotrihex pavement. Table 5.8 shows that porosity and flow exponent are the most sensitive parameters for both surfaces. However, the parameters that are directly related to aggregate properties have to be experimentally determined to use in PCSWMMPP model to simulate most reliable results.

After the sensitivity analysis, PCSWMMPP calibrated model was run with different parameter values. It is worthwhile noting that the best results were obtained from the calibrated models developed for C&M Ecotrihex and Atlantis Turf Cell surfaces

Table 5.6 Comparison of field data obtained from the simulated storms for the Atlantis Turf Cell pavement with PCSWMMPP model results by using default parameters and calibrated parameters

Date	Peak Discharge /(L/s)			% Error in peak discharge		Volumes / (L)			% Error in volume	
	Actual	Default	Calibrated	Default	Calibrated	Actual	Default	Calibrated	Default	Calibrated
20/03/07	0.10	0.24	0.13	-30.00	-30.00	289	401	227	30.80	21.45
22/03/07	0.13	0.30	0.15	-15.38	-7.69	260	376	309	9.23	-18.85
26/03/07	0.16	0.30	0.16	0.00	6.25	255	371	265	8.24	-3.92
31/03/07	0.11	0.31	0.13	-18.18	-27.27	300	390	272	19.67	9.33
02/04/07	0.13	0.30	0.13	0.00	0.00	255	302	258	10.20	-1.18
04/04/07	0.12	0.21	0.13	-8.33	0.00	232	282	204	23.28	12.07
06/04/07	0.08	0.20	0.10	-25.00	-25.00	245	202	190	31.02	22.45
11/04/07	0.09	0.22	0.10	-11.11	-22.22	216	251	207	15.74	4.17
13/04/07	0.10	0.26	0.12	-20.00	-10.00	196	206	212	1.02	-8.16
16/04/07	0.12	0.23	0.12	0.00	0.00	195	203	202	6.67	-3.59
18/04/07	0.13	0.27	0.12	7.69	7.69	192	179	204	1.04	-6.25
23/04/07	0.14	0.24	0.12	14.29	21.43	229	151	185	24.45	19.21
26/04/07	0.12	0.24	0.12	0.00	8.33	176	153	184	2.27	-4.55
30/04/07	0.13	0.22	0.11	15.38	23.08	219	115	165	28.77	24.66

Table 5.7 Comparison of field data obtained from the actual storms for the Atlantis Turf Cell pavement with PCSWMMPP model results by using default parameters and calibrated parameters

Date	Peak Discharge /(L/s)			% Error in peak discharge		Volumes / (L)			% Error in volume	
	Actual	Default	Calibrated	Default	Calibrated	Actual	Default	Calibrated	Default	Calibrated
11/2/2006	0	0	0	0	0	0	0	0	0	0
3/24/2007	0	0	0	0	0	0	0	0	0	0
5/18/2007	0	0	0	0	0	0	0	0	0	0
6/27/2007	0.046	0.091	0.055	97.0	-19.56	391.4	683	440	-74.57	-12.52
7/12/2007	0.038	0.088	0.056	131.0	-13.33	428.6	350	441	18.00	-2.89
4/11/2007	0.096	0.087	0.085	9.4	11.40	485.0	837	567	-72.60	-16.90
21/12/2007	0.130	0.140	0.130	-7.7	0.00	525.0	1170	615	-122.00	-16.90

Table 5.8 Change in model simulated values by changing the model parameters by + or – 10% from the calibrated values (C&M Ecotrihex)

	Infiltration rate- bedding (mm/hr)	Base Details					Drainage Conditions		Peak	Volume	% Difference	
		Porosity	Saturated H.K.	Field capacity	Curve fitting parameter	Tension-soil moisture	Flow coefficient	Flow exponent			Peak	Volume
-10%	144	0.36	228	0.04	10	5	500	2.00	0.15	295	-16.7	-42.3
Selected	160	0.36	228	0.04	10	5	500	2.00	0.15	295	-	-
10%	176	0.36	228	0.04	10	5	500	2.00	0.15	295	N/A	N/A
-10%	160	0.324	228	0.04	10	5	500	2.00	0.21	368	-66.7	-85.2
Selected	160	0.36	228	0.04	10	5	500	2.00	0.15	295	-	-
10%	160	0.396	228	0.04	10	5	500	2.00	0.11	188	0.17	13.7
-10%	160	0.36	205.2	0.04	10	5	500	2.00	0.14	268	-8.3	-26.9
Selected	160	0.36	228	0.04	10	5	500	2.00	0.15	295	-	-
10%	160	0.36	250.8	0.04	10	5	500	2.00	0.16	313	-25	-53.8
-10%	160	0.36	228	0.036	10	5	500	2.00	0.15	318	-25	-55.5
Selected	160	0.36	228	0.04	10	5	500	2.00	0.15	295	-	-
10%	160	0.36	228	0.044	10	5	500	2.00	0.15	267	-16.7	-24.7
-10%	160	0.36	228	0.04	9	5	500	2.00	0.19	341	-26.6	-15.6
Selected	160	0.36	228	0.04	10	5	500	2.00	0.15	295	-	-
10%	160	0.36	228	0.04	11	5	500	2.00	0.13	219	13.3	25.7
-10%	160	0.36	228	0.04	10	4.5	500	2.00	0.14	257	6.7	12.9
Selected	160	0.36	228	0.04	10	5	500	2.00	0.15	295	-	-
10%	160	0.36	228	0.04	10	5.5	500	2.00	0.16	298	-6.7	-1.0
-10%	160	0.36	228	0.04	10	5	450	2.00	0.15	284	-16.7	-36.3
Selected	160	0.36	228	0.04	10	5	500	2.00	0.15	295	-	-
10%	160	0.36	228	0.04	10	5	550	2.00	0.15	304	-16.7	-47.3
-10%	160	0.36	228	0.04	10	5	500	1.80	0.16	333	-16.7	-61.5
Selected	160	0.36	228	0.04	10	5	500	2.00	0.15	295	-	-
10%	160	0.36	228	0.04	10	5	500	2.20	0.14	255	-8.3	-21.4

5.2 MUSIC Model Analysis

The Model for Urban Stormwater Improvement Conceptualisation (MUSIC) was developed by the MUSIC Development Team of the Cooperate Research Centre for Catchment Hydrology (CRCCH). The MUSIC model is popular among researchers and practitioners in urban stormwater modelling in Australia. MUSIC provides the ability to simulate both water quantity and water quality of the runoff from catchments ranging from a single house block up to many square kilometres, and the effect of a wide range of treatment facilities on the quantity and quality of runoff downstream.

Water quality improvements from pervious pavements have been incorporated into the MUSIC model as a WSUD feature. However, the model has been developed using the Permapaver (www.permapave.com.au) surface which is much more porous (Figure 5.12) than the two surfaces used for the current study. Furthermore, the pavement structure for the Permapaver is quite different from the C&M Ecotrihex and Atlantis Turf Cell pavement structures. As shown in Figure 5.12, unlike the C&M Ecotrihex and Atlantis Turf Cell pavement structures, the Permapave pavement structure cannot hold any water within the structure. Instead it drains almost 100% of the water that infiltrates through the surface. Therefore it was planned to initially compare the water quality improvement data obtained from the field studies with the simulation results from the MUSIC model. If necessary, it was planned to improve on the current transfer functions developed (from Permapaver pavement) for the pervious pavement applications in the MUSIC model with the data obtained from the field for C&M Ecotrihex and Atlantis Turf Cell pavements.

Figure 5.12 Highly porous Permapaver block (www.permapave.com.au)

5.2.1 Introduction to MUSIC

MUSIC is a modelling software for decision making. MUSIC helps users to evaluate conceptual designs of stormwater management systems to ensure required water quality improvement is achieved for a particular catchment from a water quality improvement infrastructure. MUSIC is not a detailed design tool, as it does not contain the algorithms necessary for detailed sizing of structural stormwater quantity and/or quality facilities. By simulating the performance of stormwater quality improvement measures, MUSIC determines if the proposed water quality improvement systems can meet specified water quality objectives (CRCCH, 2002).

MUSIC simulates the performance of a group of stormwater management measures, configured in series or in parallel to form a “treatment train”. MUSIC runs on an event or continuous basis, allowing rigorous analysis of the merit of proposed strategies over the short-term and long-term.

MUSIC is designed to simulate stormwater systems in urban catchments and to operate at a range of temporal and spatial scales suitable for catchment areas from 0.01 km^2 to 100 km^2. Modelling time steps can range from 6 minutes to 24 hours to match the range of spatial scale (MUSIC Modelling toolkit, version 3).

According to MUSIC, the adoption of a continuous simulation approach is recommended in water quality modelling. This stems from the fact that impacts of poor stormwater quality on aquatic ecosystem health are associated with cumulative pollutant loads and frequency of aquatic ecosystem exposure to poor water quality. Pollutant loads delivered to receiving waters from many of the small storm events (e.g. of magnitude less than the 3 month ARI peak discharge) can make up in excess of 90% of the annual loads discharged from the catchment (CRCCH, 2002). However for the current study the model was run on an event basis as the focus was on assessing the performance and capabilities of two types of pervious pavements over a short period of time.

The evaluation of the effectiveness of a stormwater management system is based on a risk-based approach associated with examination of the long-term frequency with which the receiving aquatic ecosystem is subjected to exposure of pollutant concentrations above a pre-specified threshold level and/or the long-term mean annual pollutant load delivered to the receiving waters (CRCCH, 2002).

5.2.2 Modelling C&M Ecotrihex pavement using MUSIC

The primary objective of developing a methodology for modelling stormwater treatment efficiencies of the Australian C&M Ecotrihex and Atlantis Turf Cell (Australian products) is to develop guidelines so that they can be extensively used under Australian field conditions.

There are three possible drainage configurations in pervious pavements that could be modelled using the MUSIC model:

- a lined paver with an underdrain;
- an unlined paver with a drain; and
- an unlined paver without an underdrain.

The drainage system designed at CERES is considered as a lined paver with an underdrain.

Those who are familiar with MUSIC know the essentials of Source Node, Treatment Node and Other Nodes to create a stormwater model (Figure 5.13). In MUSIC, a catchment is made up of a number of Nodes, joined together by Drainage Links. The catchment may contain a number of sub-catchments based on the land use type, which is referred to as “Source Nodes”. There are three default land-uses: Urban, Agricultural and Forested. Users may modify the percentage of impervious area within the sub catchment (Source Node) to simulate runoff and water quality from any type of land-use (e.g. road runoff). A catchment may also have a number of Junction Nodes, which simply act as confluences for water generated from different land use types. Treatment Nodes are used to represent stormwater treatment measures within the Catchment. A range of treatment measures is available within MUSIC including wetlands, ponds, sedimentation basins, which are WSUD techniques (Figure 5.13).

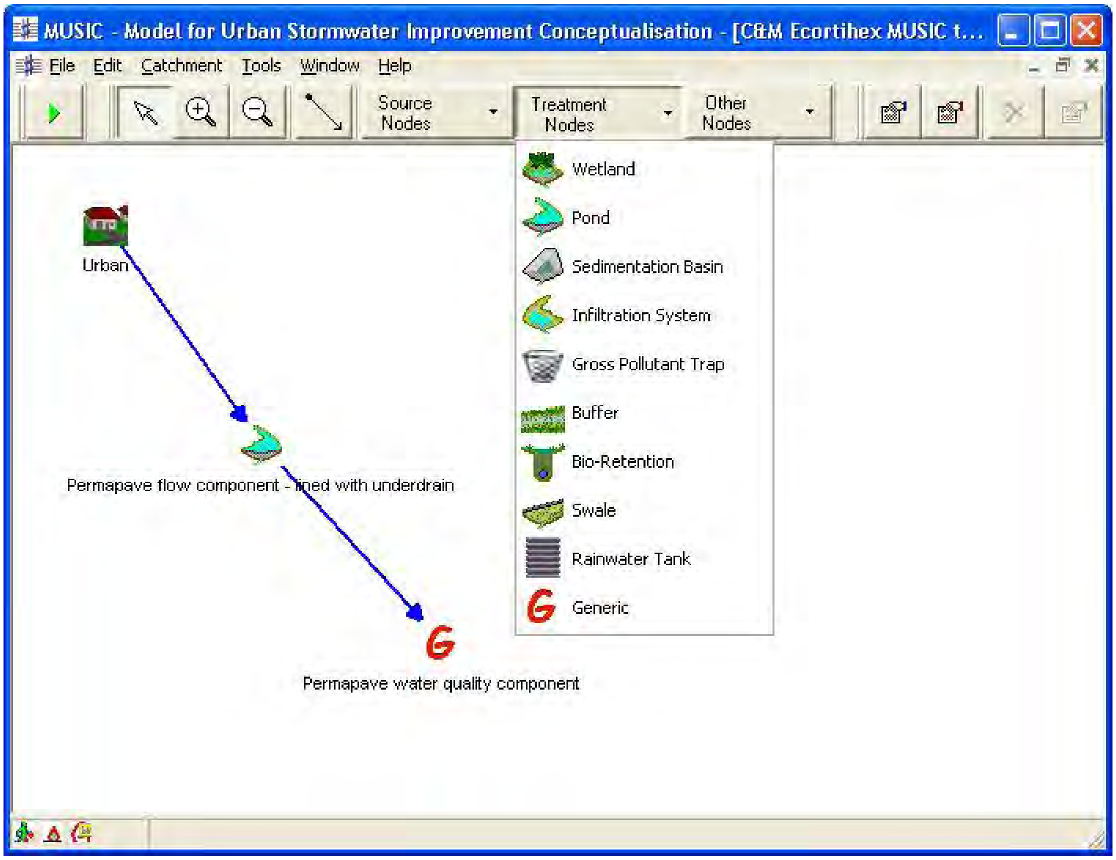


Figure 5.13 MUSIC template used for Permapave pavement

As shown in Figure 5.13, treatment node is assigned for each treatment device in the MUSIC model. However there is no direct treatment node in MUSIC to use for pervious pavement. Deletic and Fletcher (2007) modelled a Permapave pavement using the MUSIC model. The authors used a combination of Pond and Generic treatment nodes (Figure 5.13) to model Permapave pavements. The treatment node "Pond" was used to model the flow component and the "Generic" node was used to model the water quality component. The current research followed the above authors' recommendations after personal communication with A/Prof Ana Deletic from Monash University, one of the developers of the MUSIC model.

According to Deletic and Fletcher (2007), the user can change the parameters of the "Pond" node (flow component) according to the design parameters of the pavement (thickness, width, length and porosity etc.). However, the model developed for the Permapave pavement was initially used with the pavement dimensions and soil parameters of C&M Ecotrihex and Atlantis Turf cell pavements for the simulations. The simulated values were compared with the field observed flow and water quality parameters to investigate the applicability of the current MUSIC model algorithms (from Parmapave pavement data) to C&M Ecotrihex and Atlantis Turf Cell surfaced pavements.

The template shown in Figure 5.14 was used to model the lined C&M Ecotrihex pavement system. The parameters in the interface that represent flow components (Figure 5.14) were edited to represent the pervious pavement structure in the field. These interfaces were modified accordingly to represent the Atlantis Turf Cell pavement as well (Figures 5.16 and 5.17)

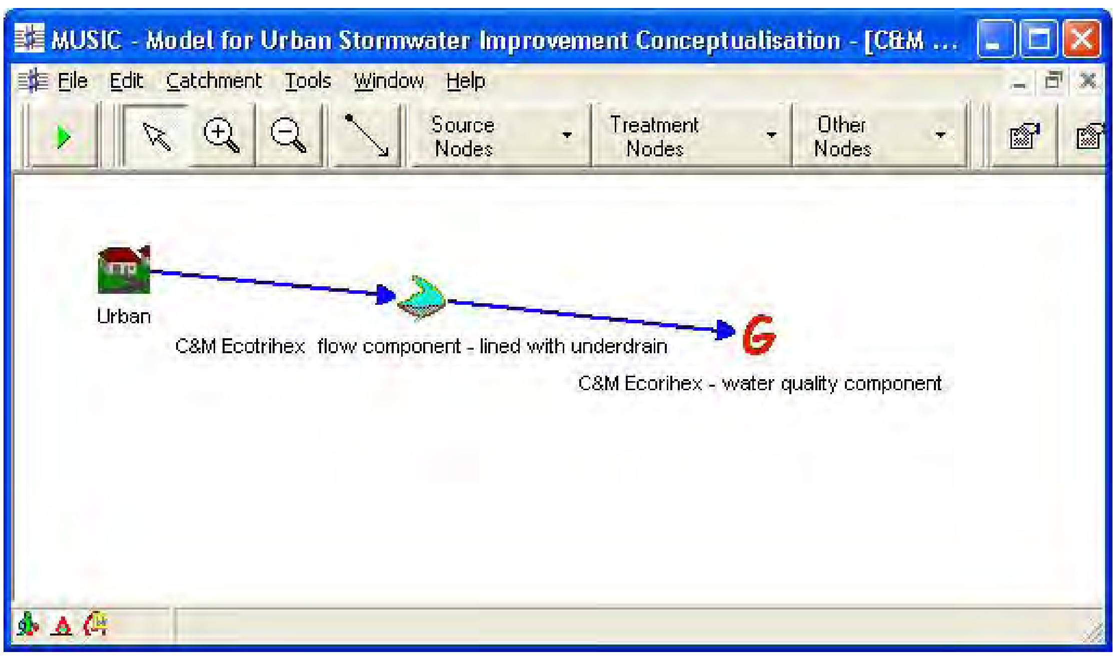


Figure 5.14 MUSIC template for C&M Ecotrihex pavement.

All the inlet, storage and outlet properties were calculated according to the guidelines given by Deletic and Fletcher (2007). Low flow by-pass and high flow by-pass values under inlet properties in Figure 5.15 were set to their default values, 0 and 100m^3/s respectively. Storage properties were calculated from the actual pavement dimensions and aggregate properties. Surface area of the C&M Ecotrihex block surface is 50.4m^2. Depth multiplied by porosity was considered to be the extended detention depth. The porosity of the C&M Ecotrihex pavement is 0.36 and the depth of the pavement is 33 cm (depth of sub-base (25cm) + depth of pavement layer (8cm)). Permanent pool volume was set to "near zero" as it cannot be zero to ensure MUSIC's storage-discharge calculations converge. Evaporation loss was assumed to be very low and set to 5%. When considering outlet properties, equivalent pipe diameter (nominal only) was set to 12.9cm to give the appropriate detention time (= depth/hydraulic conductivity). Consequently, for the C&M Ecotrihex pavement the detention time was 0.13hrs (= 0.33m/0.228m/hr). Table 5.9 summarises the parameters used for Permapave (Default), C&M Ecotrihex and Atlantis Turf Cell pavements.

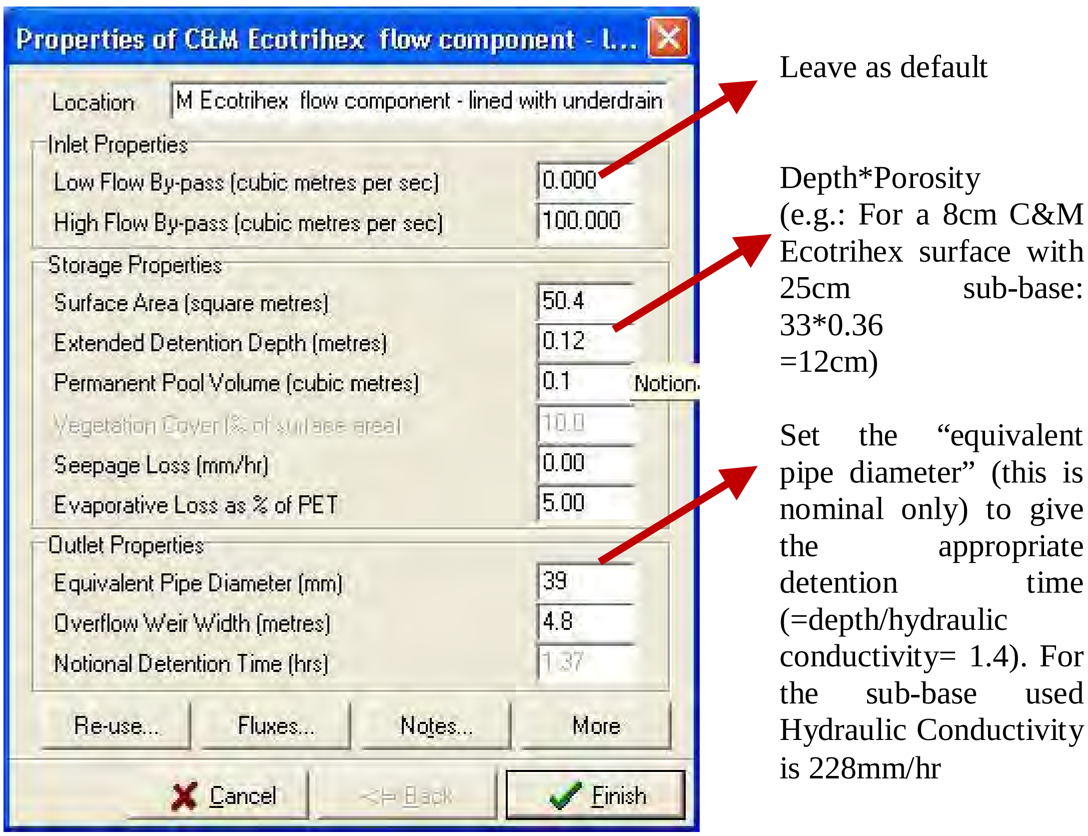


Figure 5.15 Input parameters for the interface flow component for lined C&M Ecotrihex pavement system with an underdrain

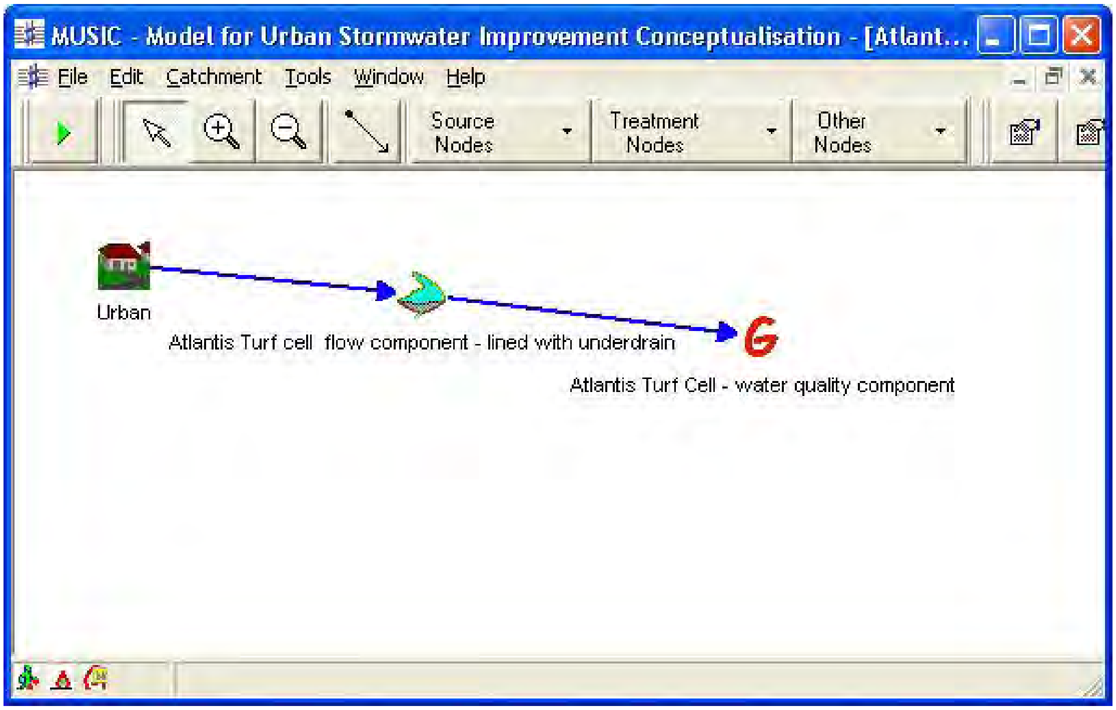


Figure 5.16 MUSIC template for Atlantis Turf Cell pavement

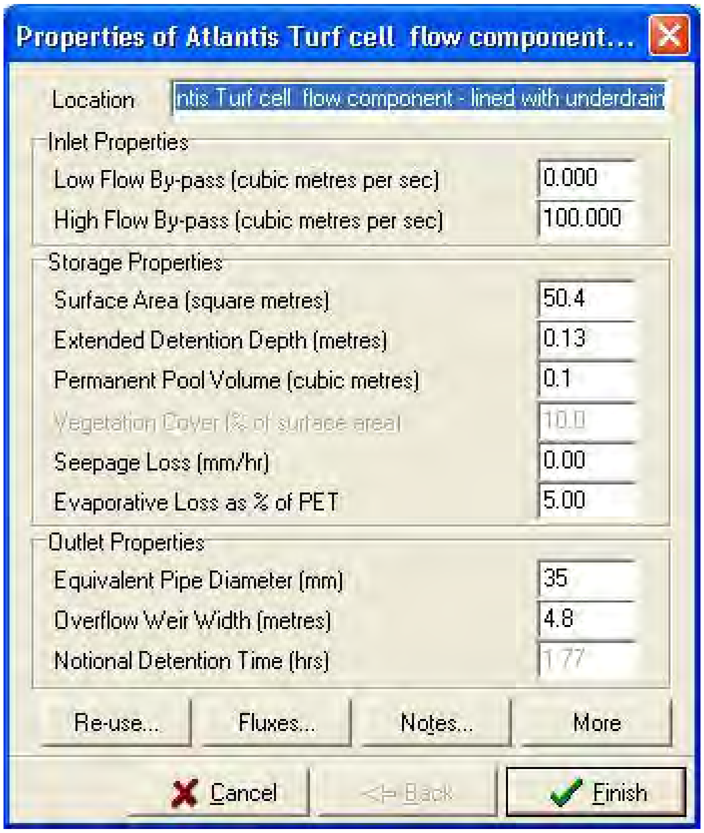


Figure 5.17 Input parameters for the interface of flow component for lined Atlantis Turf Cell pavement system with an underdrain

Table 5.9 Summary of MUSIC model default parameters and parameters used to model C&M Ecotrihex and Atlantis Turf Cell pavements

Parameter		Default (Permapaver)	C&M Ecotrihex	Atlantis Turf Cell
Inlet properties	Low flow by-pass (m3/s)	0	0	0
	High flow by-pass (m3/s)	100	100	100
Storage properties	Surface area (m2)	50.4	50.4	50.4
	Depth (m)	0.35	0.33	0.36
	Extended detention depth (m)	0.17	0.12	0.13
	Permanent pool volume (m3)	0.1	0.1	0.1
	Seepage Loss (mm/hr)	0	0	0
	Evaporative loss % of PET	5	5	5
Outlet properties	Equivalent Diameter (mm)	150	39	35
	Outflow weir width (m)	4.8	4.8	4.8
	Notional detention time (hr)	0.11	1.44	1.8

The “Generic” node consists of transfer functions for flow, TN, TP and TSS as shown in Figure 5.18 to 5.20. Transfer functions describe relationships between pollutant input and output using a graphically-based transfer function editor for each pollutant (Flow, TSS, TN, TP and Gross Pollutants). Once transfer functions are incorporated into the “Generic” node (water quality component), the relationships cannot be changed. Output of the water quality parameters will depend on the input water quality values. Input water quality parameters will depend on the flow components which are entered through the node “Pond”. Deletic and Fletcher (2007) developed transfer functions for application to pervious pavements in the MUSIC model after a series of laboratory experiments on water quality improvement carried out on Permapave pavement.

As mentioned earlier, the MUSIC model was initially applied to C&M Ecotrihex and Atlantis Turf Cell surfaced pavements with the transfer functions derived for the Permapave pavement. This was carried out to investigate the applicability of the existing pervious pavement transfer functions in the MUSIC model to other types of pervious pavements. The results were compared with the water quality improvements obtained from the field car park at CERES (Table 4.10) and are reported in Table 5.10 below.

Table 5.10 Comparison of results obtained from the MUSIC model with Permapave pervious pavement transfer function with actual water quality improvements and runoff volume reductions at the CERES car park.

Parameter	Average % reduction of pollutants		
	MUSIC model (transfer functions developed for Permapave pavement)	Field data	
		C&M Ecotrihex	Atlantis turf cell
Flow	0.0	53.3	60.0
TSS	59.8	95.0	98.0
TN	22.1	66.0	81.0
TP	23.2	73.0	75.0

The above results clearly indicate that the transfer functions defined for Permapave cannot be used with C&M Ecotrihex and Atlantis Turf Cell surfaced pavements. The major difference between Permapave and the other two pervious surfaces (C&M Ecotrihex and Atlantis Turf Cell) is the reduction in flow values. As mentioned earlier and shown in Figure 5.12, the Permapave surface is very porous and it does not retain any infiltrated water within the pavement. 100% of the water that is infiltrated is removed via the drainage system and the flow reduction is 0%. This is a main feature of the Permapaver pavements (www.parmapaver.com.au). According to the literature (Hogland et al., 1987; 1990; Larson, 1990; Mantle, 1993; Pratt et al., 1989; 1990; 1995) the pervious pavements used for the study hold 34% to 47 % of the water that is infiltrated through the pervious surface. This is also evident from the field results obtained from the study and reported in Chapter 4. The major difference between Permapaver and other two pavements (C&M Ecotrihex and Atlantis Turf Cell) is the high porosity of the surface and the water holding capability of the pavement structure. The water quality improvements obtained from the field with C&M Ecotrihex and Atlantis Turf Cell pavements show higher reduction in TN, TP and TSS than MUSIC model simulations with default (Permapave) pervious pavement transfer functions. This is mainly attributed to the difference in reduction of flow.

One of the objectives of the study was to develop a tool to evaluate the reduction in flow and water quality improvement due to infiltration through pervious pavements. This will enable practising engineers, land developers and Local Government engineers to use pervious pavements as Water Sensitive Urban Design (WSUD) features and as a viable alternative to conventional pavements.

It was planned to modify the transfer functions in the MUSIC model based on the field data obtained at CERES from the pervious pavements. Initially it was decided to modify only the flow component transfer function and to retain other transfer functions for Total Nitrogen (TN), Total Phosphorous (TP) and Total Suspended Solids (TSS) as those derived for the Permapave (currently the default functions) pavements. Figures 5.17 and 5.18 depict the transfer functions defined from field data for C&M Ecotrihex and Atlantis pavements respectively. Tables 5.12 and 5.13 give the comparison between the percentage reductions in water quality parameters from the model with modified transfer function for the flow compared to the field observations.

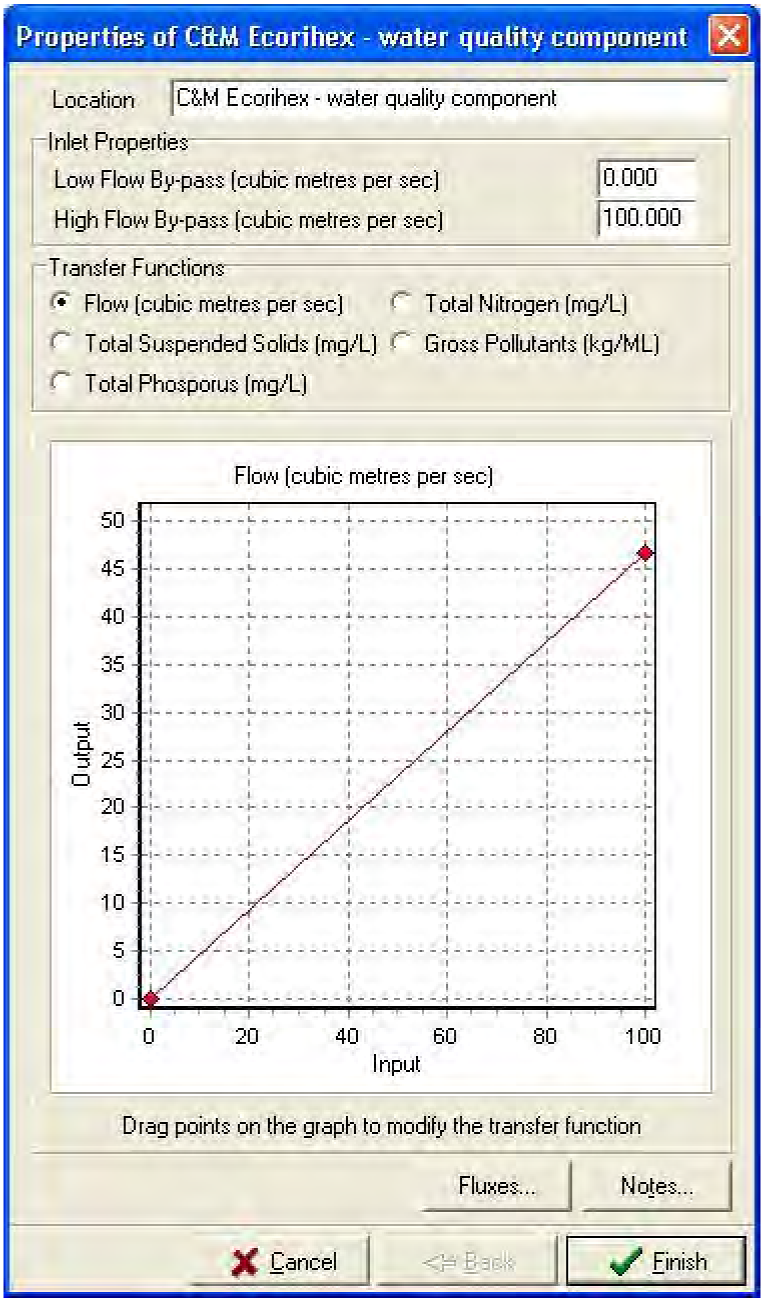


Figure 5.18 The modified transfer function of the flow component for the C&M Ecotrihex pavement system with an underdrain

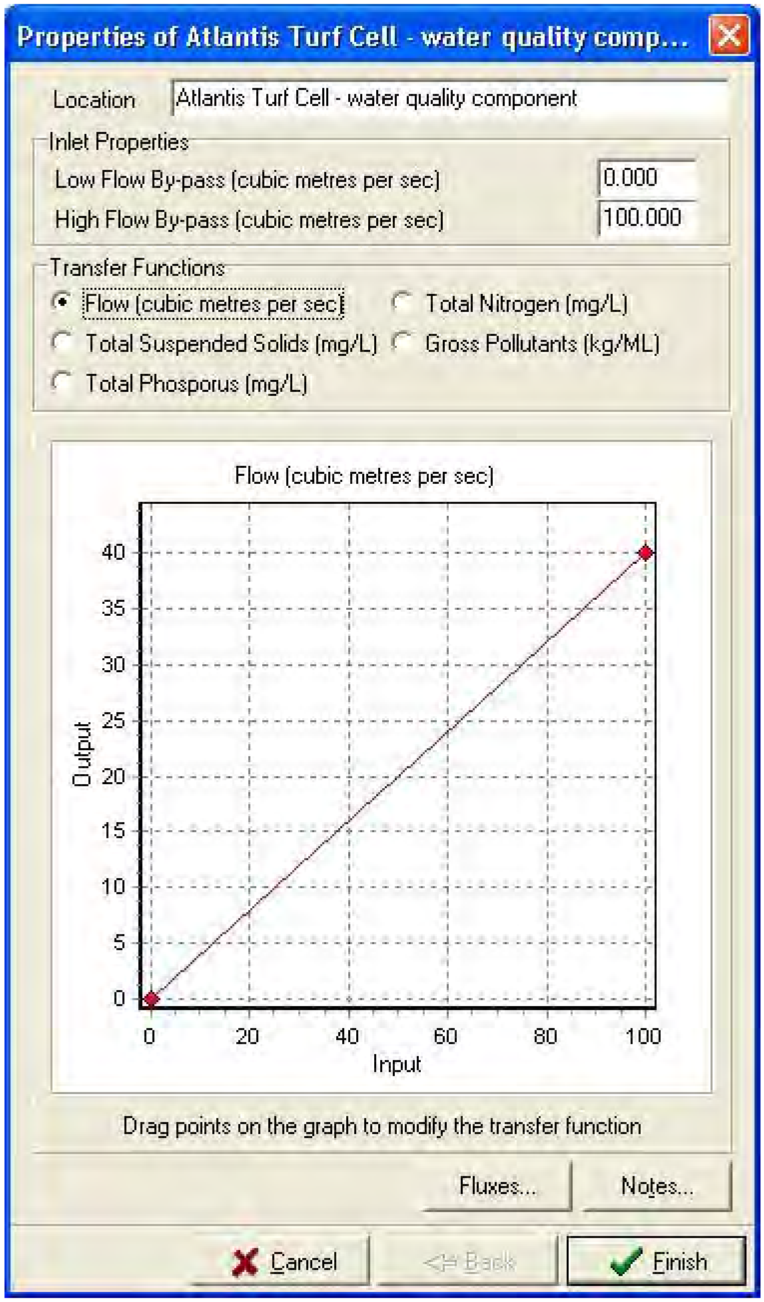


Figure 5.19 The modified transfer function of the flow component for the Atlantis Turf Cell pavement system with an underdrain

With the change in the transfer function for the flow to reflect the behaviour of the surfaces tested, anticipated improvements to water quality from MUSIC model improved considerably when compared with default transfer functions (with Permapave). The results in Tables 5.11 and 5.12 are from the flow transfer functions obtained from C&M

Ecotrihex and Atlantis Turf Cell pavements respectively. The MUSIC model simulated water quality improvements recorded in Table 5.4 are much closer to the field data obtained from the C&M Ecotrihex pavement and, with the results vice versa reported in Table 5.5. It is clear from the results that water quality improvements are highly dependent on accurate estimation of the flow component.

Table 5.11 Comparison of field data with results obtained from the modified flow transfer function in the MUSIC model for C&M Ecotrihex pavement field data (TSS, TN and TP transfer functions are for Permapaver as in the original MUSIC model)

Parameter	Average % reduction of pollutants			
	C&M Ecotrihex		Atlanstis Turf Cell	
	MUSIC	Field	MUSIC	Field
Flow	53.3	53.3	53.3	60.0
TSS	81.2	95.0	81.3	98.0
TN	63.6	66.0	63.6	81.0
TP	65.0	73.0	65.1	75.0

Table 5.12 Comparison of field data with results obtained from the modified flow transfer function in the MUSIC model for Atlantis Turf Cell pavement field data (TSS, TN and TP transfer functions are for Permapaver as in the original MUSIC model)

Parameter	Average % reduction of pollutants			
	C&M Ecotrihex		Atlanstis Turf Cell	
	MUSIC	Field	MUSIC	Field
Flow	60.0	53.3	60.0	60.0
TSS	83.9	95.0	83.9	98.0
TN	68.8	66.0	68.8	81.0
TP	70.3	73.0	70.2	75.0

Finally it was decided to change all the transfer functions in the MUSIC model based on the field data obtained from the two pervious pavements at CERES. Figure 5.18 shows the graph of output vs. input transfer function for TN from the C&M Ecotrihex pavement surface. Similarly, experimental data were used to develop all the transfer functions for both pavements (Flow, TN TSS and TP) and presented in Appendix C Figures C.1 to C.5.

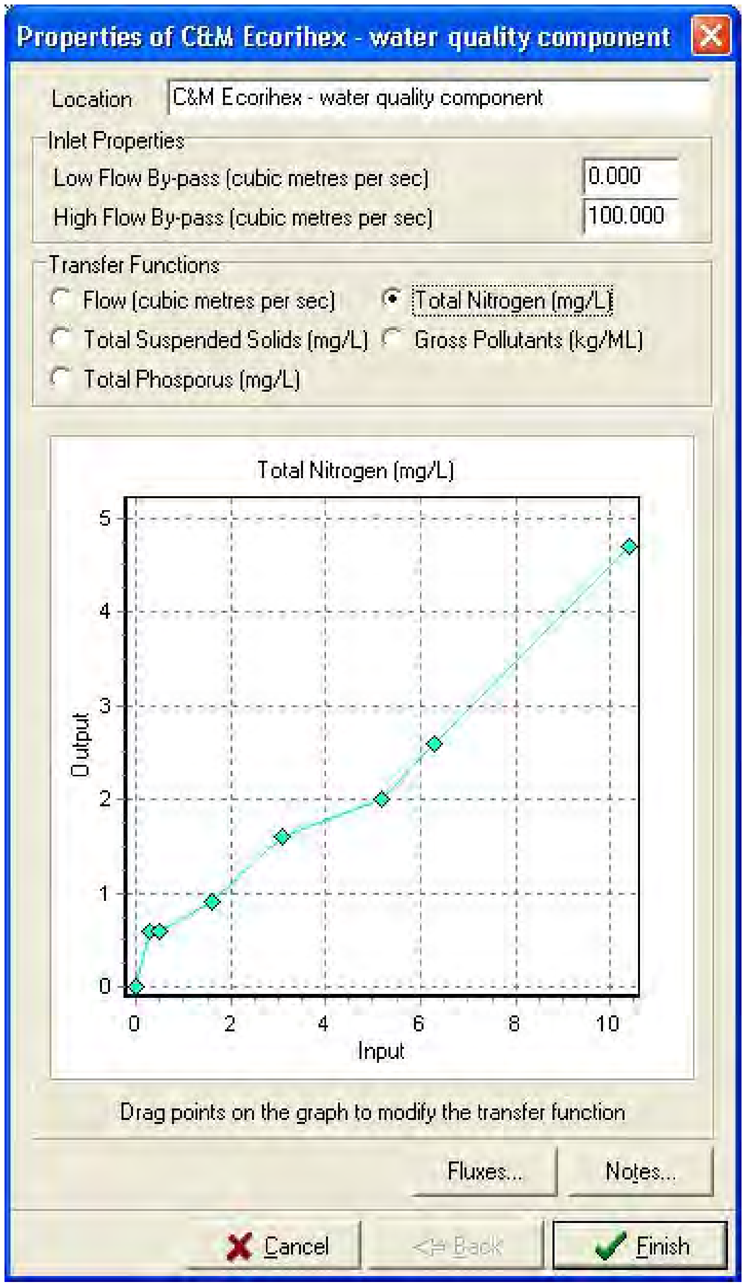


Figure 5.20 Developed transfer function for TN to be applied for a lined C&M Ecotrihex pavement system with an underdrain

Table 5.13 depicts the simulation results from the MUSIC model after incorporating the corresponding transfer functions from field data obtained from C&M Ecotrihex and Atlantis Turf Cell pavements constructed at CERES.

Table 5.13 Comparison of field observed data with MUSIC model simulations with the modified transfer functions to the specific surfaces

Parameter	% Reduction from the field		% Reduction – MUSIC model with specific transfer functions		
	C&M Ecotrihex	Atlantis Turf Cell	Permapave	C&M Ecotrihex	Atlantis Turf Cell
Flow	53.3	60.0	0.0	53.3	60.0
TSS	95.0	98.0	59.8	97.8	96.0
TN	66.0	81.0	22.1	78.0	72.9
TP	73.0	75.0	23.2	76.4	82.9

The major difference between the results obtained from the transfer functions for Permapave and other two pervious pavements (C&M Ecotrihex and Atlantis Turf Cell) is the reduction in flow. Permapave does not show any reduction in volume of water (0%). However C&M Ecotrihex and Atlantis Turf Cell show 53.3% and 60% reduction in volume of water respectively. From the results depicted in Tables 5.11 to 5.13 it is clear that the transfer function to flow component has a more direct effect on the results obtained for water quantity parameters than from the transfer functions of the water quality parameters (TSS, TN and TP).

The guidelines set by the Environment Protection Authority of Victoria for stormwater discharge into receiving waters are as follows:

- TSS must to be less than 25mg/L
- TN must to be less than 0.6mg/L
- TP must to be less than 0.05mg/L

The water quality results obtained from the MUSIC model applied to C&M Ecotrihex pavement meet the guidelines set by the Environment Protection Authority of Victoria. Therefore a properly designed pervious pavement can be used as a good urban stormwater management practice, with proven effectiveness.

Furthermore, the *Urban Stormwater: Best Practices Environmental Management Guidelines; Victorian Stormwater Committee (1999*) require for urban stormwater management a 45% reduction in nitrogen load, a 45% reduction in phosphorus load and an 80% reduction in suspended solids load. Based on the results obtained from the MUSIC model with modified transfer functions for pervious pavements used in the study, the water quality improvements were within the limits specified by these guidelines.

5.3 Conclusion

The experimental results obtained for water quality and quantity parameters were used to develop and validate computational models. The PCSWMMPP computational model was used to investigate the hydraulic performance of C&M Ecotrihex and Atlantis Turf Cell pervious pavements. The PCSWMMPP computational model simulations together with the default parameters recommended by the model developers were initially compared with the field data.

The PCSWMMPP model with default pavement parameters gave percentage errors of -37% to –117% and 131% to –30% in reductions in peak discharge when compared with the field data obtained from C&M Ecotrihex and Atlantis Turf Cell pavements respectively. The above simulation also gave a percentage error of between +18% to -95% and 29% to 74% in runoff volume from the two pavements.

Subsequently the model was calibrated using field data obtained from the C&M Ecotrihex pavement. The calibrated parameters were verified using the data from an independent storm and also with the results obtained from the Atlantis Turf Cell pavement.

The following parameter values were obtained for the PCSWMM model:

- infiltration rate of the bedding material for C& M Ecotrihex - 160 mm/hr
- infiltration rate of the bedding material for Atlantis Turf Cell - 200 mm/hr
- Saturated hydraulic conductivity – 228 mm/hr
- porosity – 0.36
- field capacity – 0.0.04

– curve fitting parameter - 10
– Tension-soil moisture - 5
– threshold elevation - 0
– flow coefficient - 500
– flow exponent - 2

The calibrated PCSWMMPP model parameters for both pavements were the same as those obtained from the aggregate physical properties or, when parameters cannot be estimated from the physical properties, default parameters, except for 'flow coefficient'. The sensitivity of the model parameters on the PCSWMMPP model outputs was investigated. The 'porosity' and 'flow exponent' were identified as the sensitive parameters. The parameter 'flow coefficient' was not considered as a sensitive parameter. A ±10% change in the porosity of the aggregates gave an error range of –40% to 26.7% and -66.7% to 0.17% in peak discharge and 24.7% to 36.3% and -85.2% to13.7% in simulating the runoff volume with C&M Ecotrihex and Atlantis Turf Cell pavements respectively.

The MUSIC model together with the default transfer functions was applied to C&M Ecotrihex and Atlantis Turf Cell pavements and simulation results were compared with the data from the field. The MUSIC model simulated showed no reduction in volume of water (0%) when infiltrated through both C&M Ecotrihex and Atlantis Turf Cell pavements. However, the actual reduction of volume of stormwater obtained in the field from C&M Ecotrihex and Atlantis Turf Cell showed 53.3% and 60% respectively. Furthermore, the reduction in water quality parameters deviated from the field data considerably. It is clear from the above results that the MUSIC model default Permapaver transfer functions cannot be applied to concrete block surface pavements such as C&M Ecotrihex and grass paved pavements such as Atlantis Turf Cell.

The transfer function for flow was modified successfully with the flow data obtained from the C&M Ecotrihex and Atlantis Turf Cell pavements respectively. There was a significant improvement to the simulated water quality improvements over the default flow transfer function (Permapaver). When transfer functions for TSS, TN and TP were also modified with the data obtained from the field of C&M Ecotrihex pavement and Atlantis Turf cell pavement the simulated water quality concentrations improved marginaly. The transfer function of the flow component had a more direct effect on the improvements to water quality simulations than from the transfer functions of the water quality parameters (TSS, TN and TP). It is therefore important that the transfer function of the flow component represents the performance of the pavement type.

New transfer functions which are specific for the pavement surfaces used in the study were introduced into the MUSIC model, showing that the MUSIC model can be successfully used to model pervious pavements by substituting the relevant transfer functions in the model.

6 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

Water Sensitive Urban Design (WSUD) as a concept of sustainably managing stormwater has been emerged as an increasingly accepted concept all over Australia. The management of urban stormwater to achieve hydraulic and environmental objectives such as the reduction in peak discharge and volume, and improvements to water quality entering the receiving waters are now a common practice. Pervious pavements are not widely used in Australia as the performance of pervious pavement systems is not well known and the design criteria not clearly defined. Hence, it is concluded that further research is needed on the performance of pervious pavements before they are accepted by water authorities, city councils and builders as a viable WSUD feature.

A C&M Ecortihex paved test rig was constructed at RMIT laboratories and tested with simulated stormwater events to investigate water quality improvement and potential for clogging. The effective lifetime of the C&M Ecotrihex pavement was studied by subjecting the pervious pavement rig to 17 years of pollutant loading. The test bed was analysed for the effective lifetime of the pavement considering the reduction in infiltration due to sediment trapping inside the pores of the pervious pavement structure.

A car park with three different surfaces was newly constructed at the Centre for Education and Research in Environmental Strategies (CERES) at Brunswick in Melbourne. Two of the surfaces are pervious, namely C&M Ecotrihex (Permeable - concrete block pavement; Figure 1.2) and Atlantis Turf Cell (Porous - grass pavement; Figure 4.12). Each car park was designed to park two cars at a time. The third surface (the base case) is conventional asphalt surface and was used as a control surface for experimental purposes. Water quality samples were taken from the infiltrated stormwater via perforated agricultural pipes that were laid at the bottom of the pavement structure. These pipes were connected to a drain designed at the end of the pavement system. The experimental site was fully automated with flow meters and autosamplers to collect flow data and stormwater samples. The collected stormwater samples from the two pervious pavements were bench marked against the runoff generated from the asphalt pavement. Water quality was measured for Total Nitrogen (TN), Total Phosphorous (TP), Oil and Greases, Total Suspended Solids (TSS), and Heavy metals such as Copper (Cu), Cadmium (Cd), Zinc (Zn) and Lead (Pb).

The site was monitored over a 17 month period for the hydraulic performance of the pavements and water quality improvements (water infiltrated through pervious pavements). Due to lack of significant rainfall events throughout the study period, artificial rainfall was simulated to progress the study. Water quantity reduction and water quality improvement data collected and presented in this thesis provide evidence that a properly designed pervious pavement has an ability to reduce peak discharge and runoff volume as well as filtering pollutants thereby improving the stormwater quantity.

The experimental results obtained for water quality and quantity were used to develop and validate computational models. The PCSWMMPP computational model was calibrated using field data and used for the drainage design. Based on the studies, a method for obtaining the model parameters is recommended. The MUSIC model is one of the Australia's most popular water quality models for urban stormwater management. MUSIC was used to develop a computational model for water quality improvements and was calibrated against the results obtained by the research. Currently the MUSIC model uses the water quality transfer functions obtained from simulating Permapaver pervious pavement behaviour. The water quality improvements obtained from these transfer functions were compared with the field data obtained from the C&M Ecotrihex pavement and the Atlantis Turf Cell pavement. It was not possible to simulate runoff collected from the experimental site with the Permapave based parameters modelling with default parameters. New transfer functions specific for these pavement surfaces were developed in this study and are now incorporated into the MUSIC model.

6.2 Conclusions

Engineers are being challenged to address the environmental impacts of increasing impermeable areas due to rapid urbanisation. Therefore the impacts of runoff, infiltration and stormwater quality have to be considered when designing urban pavements and surface areas such as car parks, driveways and pedestrian pavements. Harvested stormwater properly treated for fit-for-purpose use is seen as a valuable resource. The following conclusions were drawn following experiments in the laboratory as well as in the field (full-scale) to investigate the viability of pervious pavements as a WSUD feature.

6.2.1 Reduction in stormwater runoff

- The reduction in runoff volume from C&M Ecortihex and Atlantis Turf Cell pavements are 50% and 60% respectively of the runoff generated from the conventional asphalt surface.
- C&M Ecortihex and Atlantis Turf Cell pavements reduce the peak discharge by 45% and 55% respectively when compared to the peak discharge produced from the conventional asphalt pavement.
- The average ratios of total runoff to total rainfall (runoff coefficients) from the C&M Ecotrihex and Atlantis Turf Cell surfaces are approximately 0.40 and 0.30 respectively
- The lag time to peak discharge observed from the Atlantis Turf Cell were always greater than those of C&M Ecortihex pavement and are at least 1 hour or greater than the asphalt pavement.
- The reduction in peaks and runoff volume, and the runoff coefficient values are within the range obtained by other researchers and are consistent with published values in previous studies.
- Pervious pavements can be effectively used to manage urban stormwater runoff.

6.2.2 Improvement in stormwater quality parameters

- Removal efficiencies from C&M Ecotrihex when compared with the asphalt pavement show a reduction of TSS, Zn and Oil by 90%. Similarly, removal efficiencies of Atlantis Turf Cell show a 91%, 88% and 95% reduction respectively.
- The removal efficiencies of TN and TP from both pervious pavements were low compared to the removal efficiencies of other water quality parameters mentioned above. TN and TP removal efficiencies from Atlantis Turf Cell were 40% each and those of C&M Ecotrihex were 50% and 60% respectively. The reason for the overall low removal efficiencies of TN and TP is the decomposition of the granular material used in the sub-base, leachate of nutrients and low retention time of infiltrated water in pervious pavements.
- The TN and TP removal efficiencies from Atlantis Turf Cell are low compared to the C&M Ecotrihex pavement. This is due to the application of fertiliser to grow grass on the Atlantis Turf Cell surface at the construction phase.
- The improvements to water quality parameters are within the range obtained by other researchers and are consistent with previous studies.
- The water quality and quantity results obtained from the C&M Ecotrihex pavement and the Atlantis Turf Cell pavements met the water quality guidelines set by the Environment Protection Authority, Victoria.

6.2.3 Clogging in pervious pavements

- There is a 10% reduction in the infiltration rate due to clogging when 17 years of pollutant loading was simulated over the C&M Ecotrihex pavement surface.
- The removal efficiencies obtained at the end of 17 years simulation period revealed that the effectiveness of the C&M Ecotrihex pavement is still at an acceptable level. After 17 years of simulation, the average removal efficiencies of TSS, Oil and Cu were between 80% and 98%, and those of TN and TP were 33%

and 45% respectively. The low nutrient removal efficiencies were due to leachate of TN and TP in the sub-base soil and the decay of granular material used in the pavement sub-base. There was a gain in Zn in the water tested. The reason behind Zn gain is the oxidisation of the test rig which was made out of stainless steel and the infiltrated water removing it.

6.2.4 Modeling of pervious pavements

Drainage Design

- The PCSWMMPP model with default pavement parameters gave an error of -37 % to –117% and +18% to –95% in reductions in peak discharge and runoff volume respectively when compared with the field data obtained from the C&M Ecotrihex pavement.
- The PCSWMMPP model with default pavement parameters gave an error of +131% to –30% and +29% to –74 % in reductions in peak discharge and runoff volume respectively from the Atlantis Turf Cell pavement.
- The calibrated PCSWMMPP model parameters for both surfaces were the same as those obtained from the aggregate's physical properties or default parameters (in the case when parameters could not be estimated from the physical properties) except for the 'flow coefficient'. However, this parameter was not considered to be a sensitive parameter.
- The following parameters values were obtained for the PCSWMM model:
  - The infiltration rate of the bedding material for C& M Ecotrihex- 160mm/hr
  - The infiltration rate of the bedding material for Atlantis Turf Cell - 200 mm/hr
  - Saturated hydraulic conductivity – 228mm/hr
  - porosity – 0.36
  - field capacity – 0.04
  - curve fitting parameter - 10

- Tension-soil moisture - 5
- The threshold elevation - 0
- flow coefficient - 500
- flow exponent - 2

- Porosity and Flow Coefficient are considered to be the most sensitive parameters in the model
- The author recommends the use of the above parameters when designing pervious pavements with C&M Ecotrihex and Atlantis Turf Cell pavements.

Water quality modeling

- The flow and water quality transfer functions in pervious pavement applications in the current MUSIC model were originally developed using data obtained from a Permapave pavement surface. The application of these default transfer functions showed no reduction in surface water runoff (0%) when applied to C&M Ecotrihex and Atlantis Turf Cell pavements. This is obviously an erroneous result. Furthermore the reduction in water quality parameters predicted deviated considerably from the data collected in the field.
- The above application confirmed that the current transfer function in the MUSIC model is not applicable to model pavement material other than Permapave pavers.
- The transfer function for flow was modified successfully with the flow data obtained from the C&M Ecotrihex and Atlantis Turf Cell pavements respectively. By applying these derived relationships there was a significant improvement in accuracy to the simulated water quality improvements over using the default flow transfer function (Permapave).
- When the transfer functions for TSS, TN and TP were also modified with the data obtained from the field for the C&M Ecotrihex and the Atlantis Turf cell pavements, the simulated water quality concentrations improved marginally.
- The transfer function of the flow component has a more direct effect on the improvements to water quality simulations than the transfer functions of the water

quality parameters (TSS, TN and TP). Therefore, when designing the pervious pavements it is important that the transfer function of the flow component represents the performance of the pavement type than any other factor.

- The MUSIC model default Permapave transfer function cannot be applied to Concrete Block surface pavements (e.g. C&M Ecotrihex surface) and Grass paved pavements (Atlantis Turf Cell).
- The MUSIC model can be successfully used to model and design pervious pavements by substituting the relevant transfer functions (depending on the paver material used) to the model where appropriate.

6.2.5 Maintenance

- Weed growth in gaps between concrete blocks in the C&M Ecotrihex surface is recognised as a maintenance issue. Weeds can be controlled by regular maintenance such as the application of weed killers or manual removal (Figure 4.62).

- Keeping vegetation alive in drought periods has been identified as a maintenance issue in the Atlantic Turf Cell surface. If the grass cover suffers due to drought the optimum performance cannot be expected from this surface (Figure 4.63).

6.3 Recommendations

Pervious pavement could increasingly play an important role in Water Sensitive Urban Design as it helps to reduce peak discharge and runoff volumes, improve stormwater quality and, if properly designed, permits the infiltrated water to be harvested to be put to fit-for-purpose use. Pervious pavement studies conducted in the field yielded positive results. The water quality improvements achieved from the pervious pavements met the water quality guidelines set by the Environment Protection Authority, Victoria for urban stormwater runoff.

Both surfaces studied can be recommended as a WSUD feature in managing urban runoff. However, when there is no rainfall for a long period of time the grass in the Atlantis Turf Cell surfaces will become dormant and as a result, users should be cautious when using Atlantis Turf Cells as a pervious pavement.

The PCSWMMPP model can be used as a tool to design drainage systems using pervious pavements. However, it is important to estimate a number of model parameters from physical properties. This can be done as reported in this study. The MUSIC model with a modified transfer function for the flow can be used to simulate water quality improvements from pervious pavements.

The outcomes from the study provide useful information for the design of environmentally friendly car parks, pedestrian paths, light traffic driveways and public areas in the future.

6.4 Future Research

The current research and other research carried out all over the world has shown that pervious pavements are capable of reducing urban runoff volume and improving water quality parameters in stormwater. Further research needs to be carried out on:

- The clogging potential due to accumulation of pollutants
- Retention of pollutants within the structure of the pavement with depth, and their effect on the groundwater table
- Long term effects on water quality due to retained pollutants within the pavement
- The drivers causing the self-decomposition of pollutants deposited in the pavement structure with time.

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APPENDIX A RESULTS OBTAINED EXPERIMENTAL RIG

A.1 Standard Methods to Analyse Storm Water Parameters

A.1.1 Total Nitrogen (Law Range)

HACH Company introduced HACH DR 4000 instrument (Figure A.1) to detect TN and TP in water. HACH method 10071, Test 'N Tube^{TM} Vials is the standard method to analyse water and wastewater samples for TN. The test kit consists of Nitrogen Hydroxide Reagent vials, TN persulphate powder pillows, TN reagent A and B powder pillows, TN reagent C vial and a bottle of deionised water. The detection level of law range of TN is 0 to 25.0 mg/L. This method is also called Persulfate Digestion Method.

- Preserved stormwater samples were neutralised and brought to room temperature.
- One total nitrogen persulphate powder pillow was added to each of two nitrogen hydroxide reagent vials (one vial for the sample and the other for the Reagent Blank as a control).
- 2 ml of the sample was added to one vial (sample) and 2 ml of deionised water was added to the other vial (Reagent Blank).
- Vials were capped and mixed by inverting for 30 seconds and kept in a preheated (105ºC) COD reactor for 30 minutes.
- The samples were removed from the reactor and allowed to cool to room temperature.
- HACH program number 2558 under nitrogen was selected.
- Content of TN reagent 'A' powder pillow was added to each vial, closed the cap and shook for 15 seconds. Three minute reaction time was set.

- TN reagent 'B' powder pillow was added to each vial, closed the cap and shook for another 15 seconds. Two minute reaction time was set.

- 2 ml of sample and 2 ml of Reagent blank were added (the control prepared with deionised water instead of stormwater sample) to TN reagent C vials (Figure 8.2), capped and inverted 10 times to mix well.

- Warm tubes were kept for 5 minutes to cool down.

- Test N tube adapter was inserted into the sample cell module.

- TN reagent 'C' vial (cleaned the outside before insert) with reagent blank was placed and closed the shield.

- The zero soft key was pressed.

- TN reagent 'C' vial containing sample was inserted into the HACH DR 4000 instrument (Figure A.2) and closed the shield.

- The result was measured in mg/L. Multiple samples may be read after zeroing on one reagent blank.

Figure A.1 HACH DR 4000 instrument

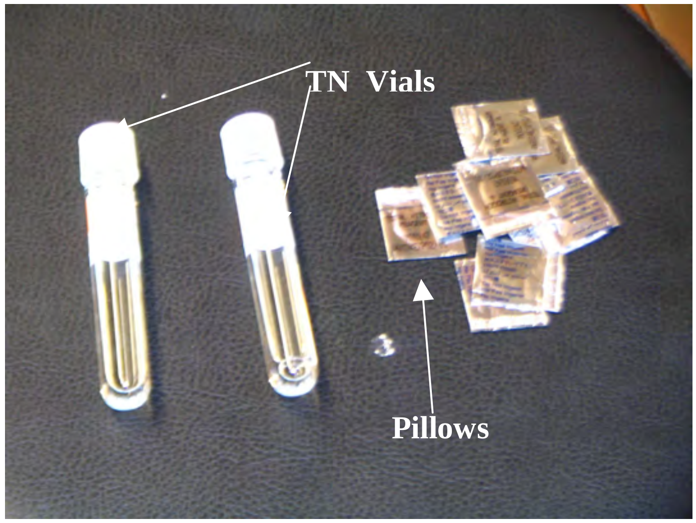

Figure A.2 TN reagent vials and powder pillows

A.1.2 Total Phosphorous

HACH method 8190, Test 'N Tube™ is the standard acid Persulfate Digestion Method to find out the total Phosphorous in water, wastewater and seawater. The minimum and the maximum level of detection is 0.00mg/Lto 1.10 mg/L.

- Preserved stormwater samples were neutralised and allowed them to reach room temperature.
- 5 ml of the stormwater sample was added to Total and Acid Hydrolyzable test vial (Figure A.3).
- 5ml of deionised water was added to another Total and Acid Hydrolyzable test vial to prepare the reagent blank
- One potassium persulphate powder pillow was added to each of the two acid hydrolyzable test vials.
- Vials were capped and shook well.
- Vials were kept in a preheated (150ºC) COD reactor for 30 minutes.

- The samples were removed from the reactor and allowed them to cool to room temperature.

- HACH program number 3036 under phosphorous was selected. 2 ml of 1.54 N sodium hydroxide was added to each of the two test vials.

- Vials were capped and shook well and Test N tube adapter was inserted into the sample cell module. It is important to ensure that the outside of the vials were properly cleaned before they were inserted into the cell module.

- The reagent blank was inserted and pressed zero (display 0.00 mg/L). Then phos ver 3 powder pillow was added to each of two test vials and the vials were caped and shook for 15 seconds.

- Vials were kept aside for two minute waiting period.

- Reagent blank vial was inserted into the cell module calibrate the HACH programme.

- The sample vial was inserted and recorded the reading.

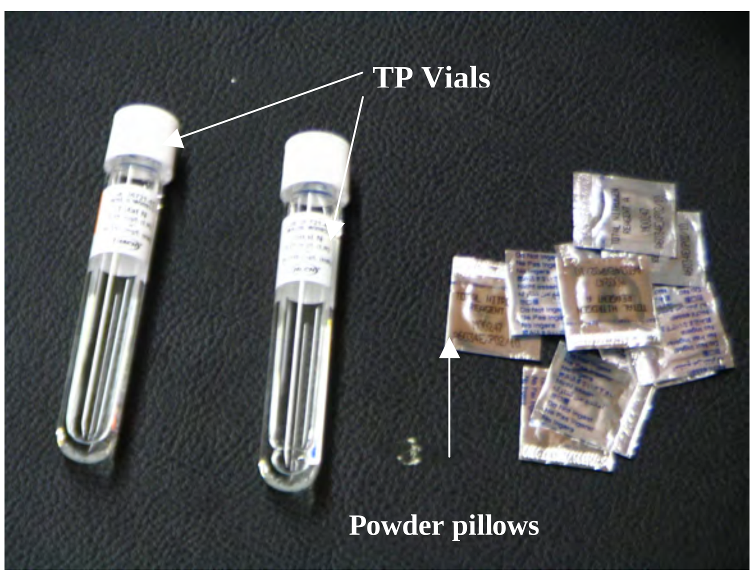

Figure A.3 Vials and powder pillows used for TP

A.1.3 Total Suspended Solids (TSS)

AWWA 2540 D (ASTM, 2006) method is the standard method to determine TSS. When preparing the glass fibre filter disk, filtering and drying has to be carried out with proper care.

- Glass fibre filters were placed in filtration apparatus (Figure A.4) so that the wrinkled side of the filter paper is facing up.
- Three successive 20 ml portions of distilled water were pored into the filtration apparatus while applying suction.
- The filter papers were removed by forceps and placed into a numbered aluminium pan.
- The pan was placed in an oven heated to 103ºC to 105ºC for at least one hour. After removing from the oven the pan was placed in a desiccator to cool for 5 minutes and the sample was weighed.
- Cycle of drying, cooling and weighing was repeated until constant weight was obtained.
- Then filter paper was removed from the desiccator and weight of the filter paper was determined to the nearest 0.0001g.
- Filter paper was placed into filtration apparatus using a clean forcep. Suction was applied to the wet filter paper.
- The stormwater quality sample was measured (at least 250 ml) and shook before filtering.
- The stormwater sample was poured through the filter while suction was applied.
- Filter paper was removed on to an aluminium pan and dried in an oven heated to 103ºC to 105ºC for at least one hour.

- Pan was placed in a desiccator for 5 minutes and the weight was taken to the nearest 0.0001g. Cycle of drying, cooling and weighing was repeated until constant weight was obtained.

Figure A.4 Filtration apparatus used to find TSS

A.1.4 Oil and Greases

AWWA 5520 D (ASTM, 2006), Soxhlet Extraction is the experimental method to analyse the oil and greases in water.

- Volume of the sample was measured and acidified with HCl to pH 2 or lower.
- The filter was prepared using muslin cloth overlaid with filter paper.
- Paper and muslin cloth were wetted and pressed down the edges to each other.
- Filter aid suspension was prepared to a concentration of 10g/L using Diatomaceous- silica filter aid suspension.
- 100 ml of filter aid suspension was passed though the prepared filter and washed with 1000 ml of distilled water.

- Vacuum was applied until no more water passes through the filter and the entire filter was transferred to a watch glass using forceps.

- The Buchner funnel and the collecting vessel were wiped with pieces of filter paper soaked in extraction solvent and added those pieces to the watch glass.

- All the filter material were rolled and fitted into an extraction thimble. Then the thimbles were dried in hot air oven at 103ºC for 30 minutes.

- The Thimble was filled with glass beads. The extraction flask was weighed and 100 ml of extraction solvent added (80% n-hexane and 20% Methyl-Tert- Butyl Ether (MTBE)).

- There after oil and greases were extracted in a Soxhlet apparatus (Figure A.5) at a rate of 20 cycles/hr for 4 hours.

- The extracted sample was weighed and transferred to a separatory funnel.

- Sample bottle was rinsed with 30ml extraction solvent (80% n-hexane and 20% Methyl-Tert- Butyl Ether) and then the extraction solvent layer was transferred to separatory funnel.

- The separatory funnel (Figure A.6) was shook vigorously for 2 minutes. Funnel was kept aside until layers separate.

- Clear solvent layers were not obtained due to low concentration of oil and greases in stormwater.

- The sample was added to glass centrifuge tubes and centrifuged (Figure A.7) for 5 minutes at approximately 2400 rpm.

- The centrifuged sample was transferred to a separatory funnel and drained the solvent layer through a funnel with filter paper and 10g of sodium sulphate.

- The emulsion layer was not appeared.

- The sample was distillate using distillate recovery apparatus (Figure A.8). The sample was transferred to a weighed flat-bottom flask.
- Distillation was carried out in a water bath (85^0C). Maximisation of solvent recovery was carried out by fitting distillation flask with distillation adapter.
- When visible condensation was completely stoped, the flask was removed from the water bath with trace of oil and greases.
- The flask was cooled in a desiccators for at least30mins and weighed.
- The difference of the final weight and the initial weight of the flask gave the amount of oil and greases in a known amount of stormwater sample (the stormwater volume was measured initially).

Figure A.5 Soxhlet apparatus

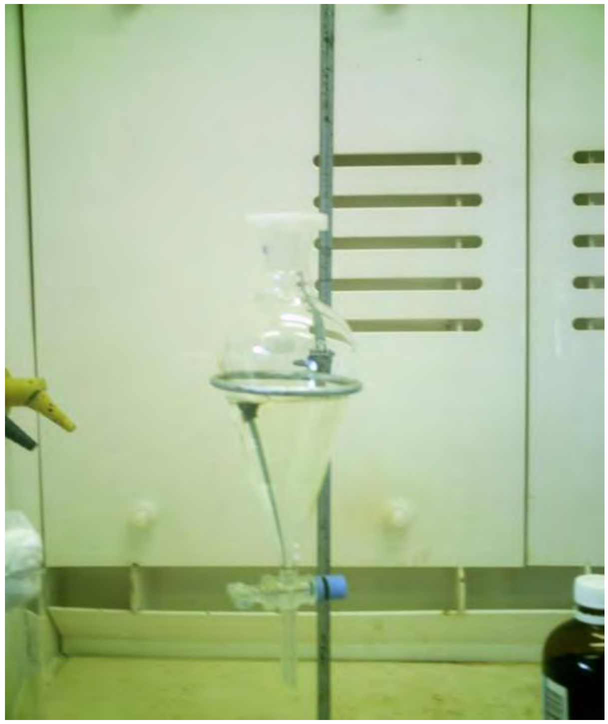

Figure A.6 Separation of emulsion through separatory funnel

Figure A.7 Separation of emulsion through centrifuge machine

Figure A.8 Distillate recovery apparatus

A.1.5 Heavy metals

The standard method AWWA 3111C (ASTM, 2006) is recommended to find out Cadmium (Cd), lead (Pb), Copper (Cu) and Zinc (Zn) in water. Atomic Absorption Spectroscopy instrument was used to determine Pb, Cu, Zn and Cd in stormwater. Before the experiment, there should be a thorough understanding about the constituents of the sample. The high level of some metal traces and chloride can cause interference unless optimum flame conditions are used. Therefore optimum flame conditions were achieved by adding recommended standard solutions for each heavy metal and testing them in a trial and error basis.

- Wavelength, Lamp current and lamp fuel were set in accordance with the manual of "Analytical Methods for flame spectroscopy".

- Table A.1 presents the details of lamp current, fuel, wave length, detection limit and chemical interference of each heavy metal.

Table A.1 Details of settings for flame spectroscopy.

Metal	Lamp Current (mA)	Fuel	Wave length (nm)	Detection limit (µg/ml)	Chemical interference
Pb	6	Acetylene	405.8	0.02	I-, PO4-2,F-
Cu	3	Acetylene	327.4	0.003	High Zn/Cu
Zn	5	Acetylene	213.9	0.002	None
Cd	3	Acetylene	326.1	0.0006	None

- The Variance 600 apparatus (Figure A.9) was programmed to the above mentioned wave lengths, lamp current, fuel and detection limits for Pb, Cu, Zn and Cd.

- Then the standard solutions were added to the stormwater samples and placed in the relevant place of the apparatus.

- Reagent blank was also prepared with deionised water and was used as a control. A 60 test tube rack was taken.

- The test tubes were filled with pre acidified samples and placed on the apparatus.

- Computer and the Variance 600 apparatus were switched on to start the process.

- All the concentrations were automatically recorded in the program.

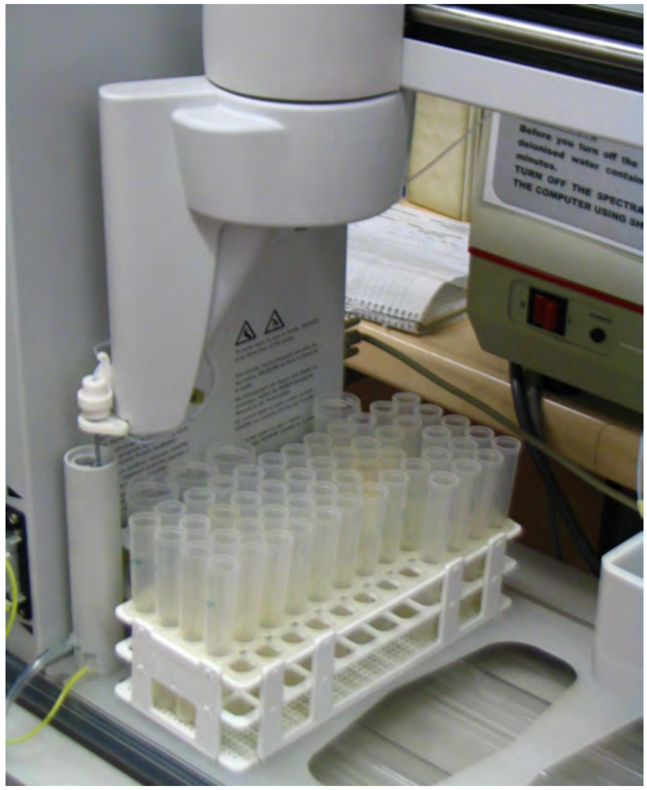

Figure A.9 Variance 600 apparatus

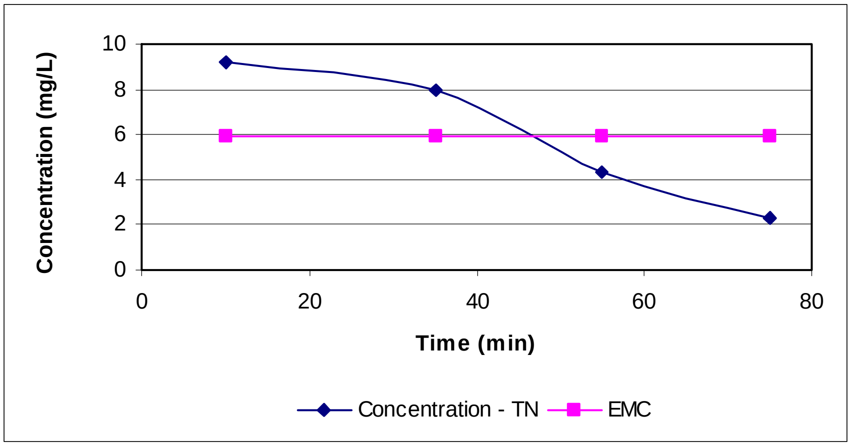

Figure A.10 Pollutograph for TN obtained from C&M Ecotrihex pavement rig when one year equivalent pollutants are simulated

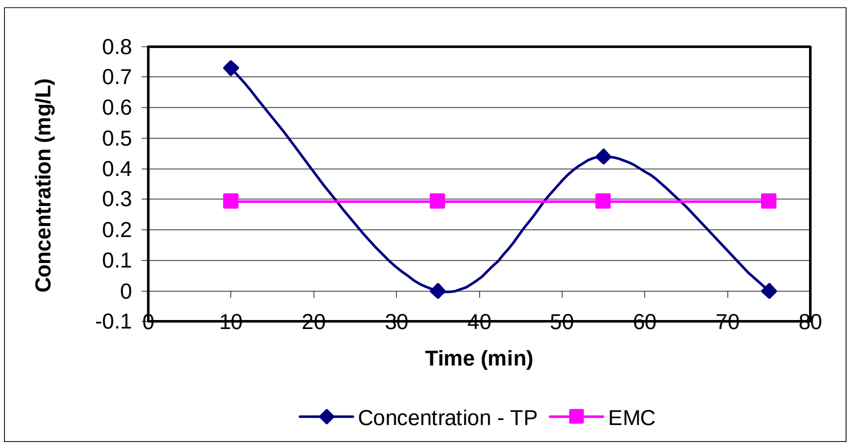

Figure A.11 Pollutograph for TP obtained from C&M Ecotrihex pavement rig when one year equivalent pollutants are simulated

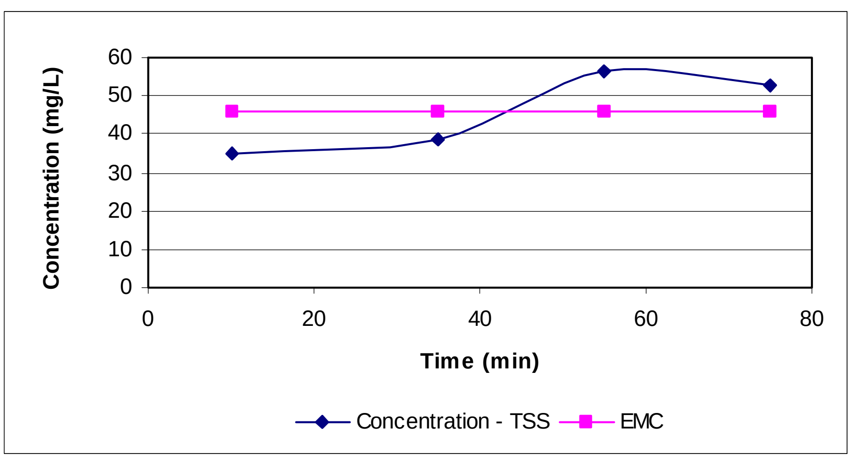

Figure A.12 Pollutograph for TSS obtained from C&M Ecotrihex pavement rig when one year equivalent pollutants are simulated

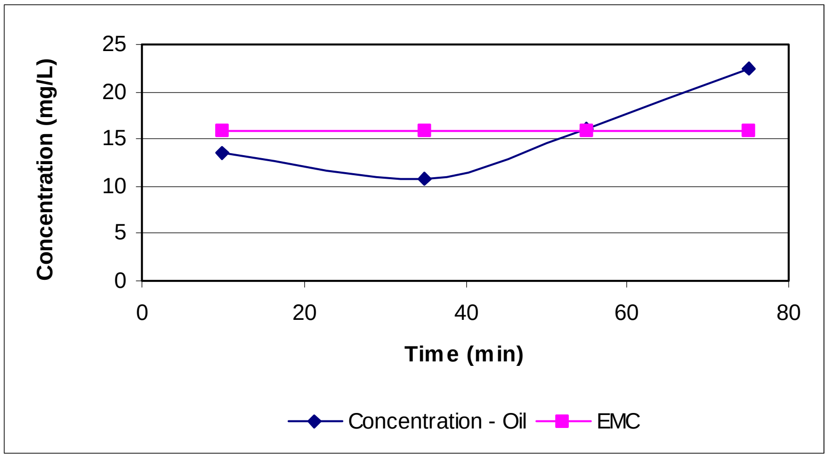

Figure A.13 Pollutograph for oil obtained from C&M Ecotrihex pavement rig when one year equivalent pollutants are simulated

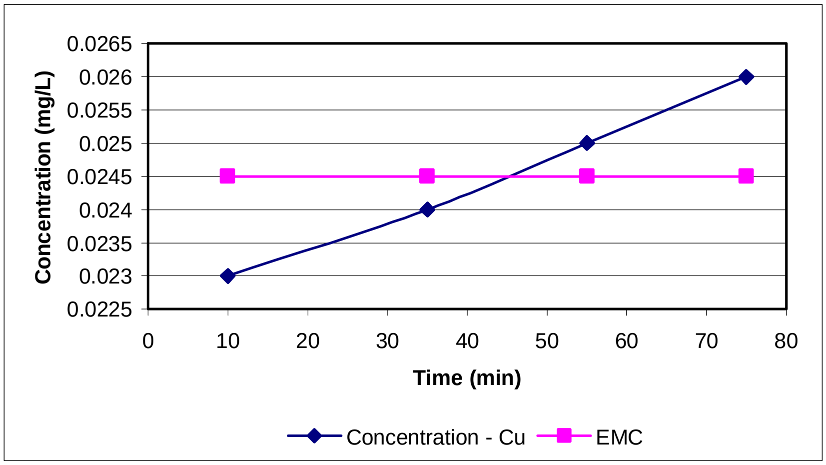

Figure A.14 Pollutograph for Cu obtained from C&M Ecotrihex pavement rig when one year equivalent pollutants are simulated

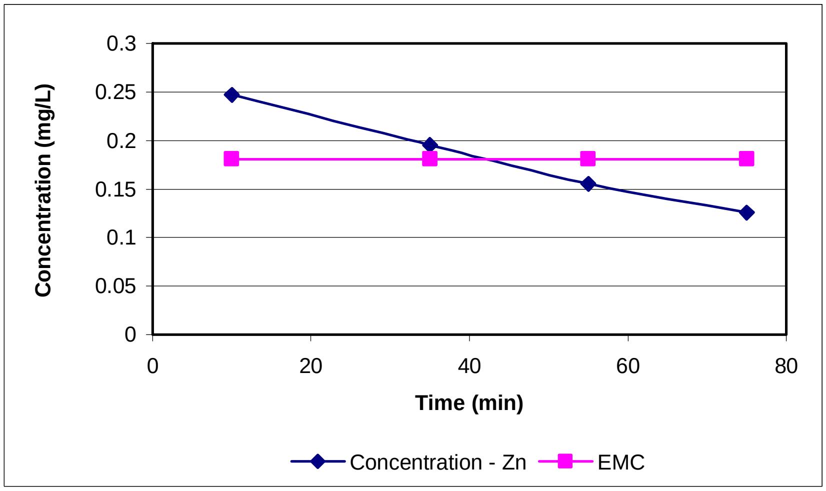

Figure A.15 Pollutograph for Zn obtained from C&M Ecotrihex pavement rig when one year equivalent pollutants are simulated

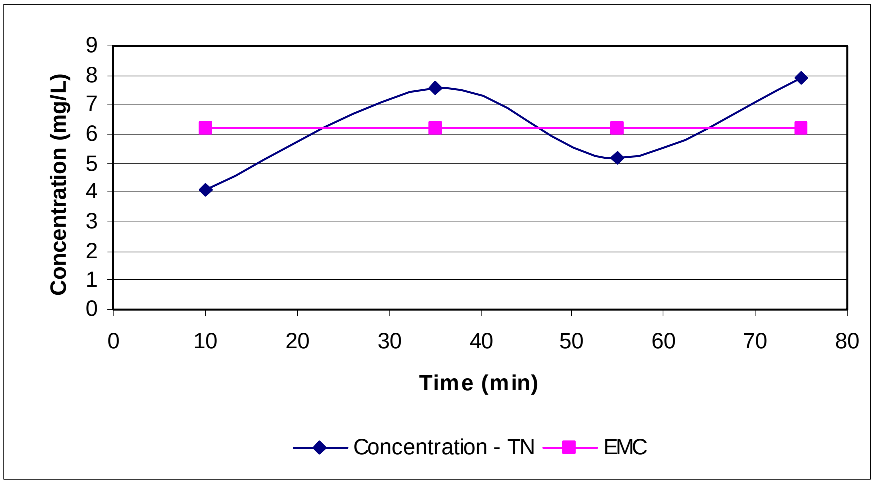

Figure A.16 Pollutograph for TN obtained from C&M Ecotrihex pavement rig when two year equivalent pollutants are simulated

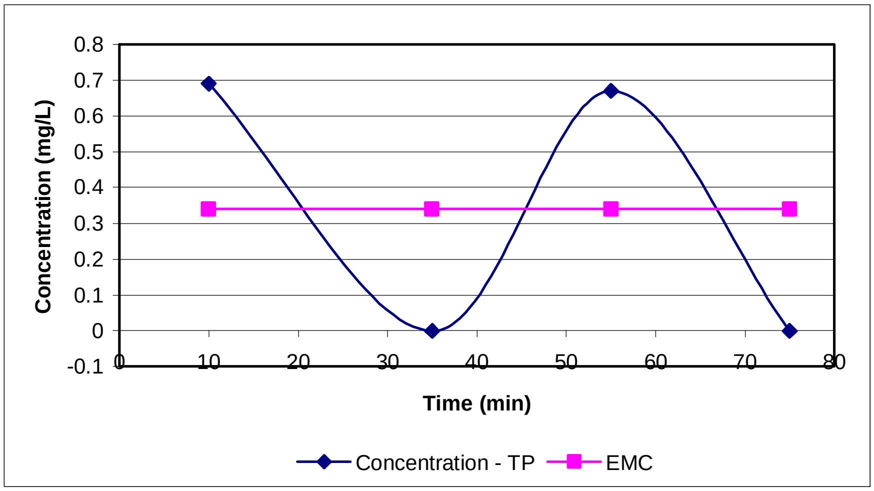

Figure A.17 Pollutograph for TP obtained from C&M Ecotrihex pavement rig when two year equivalent pollutants are simulated

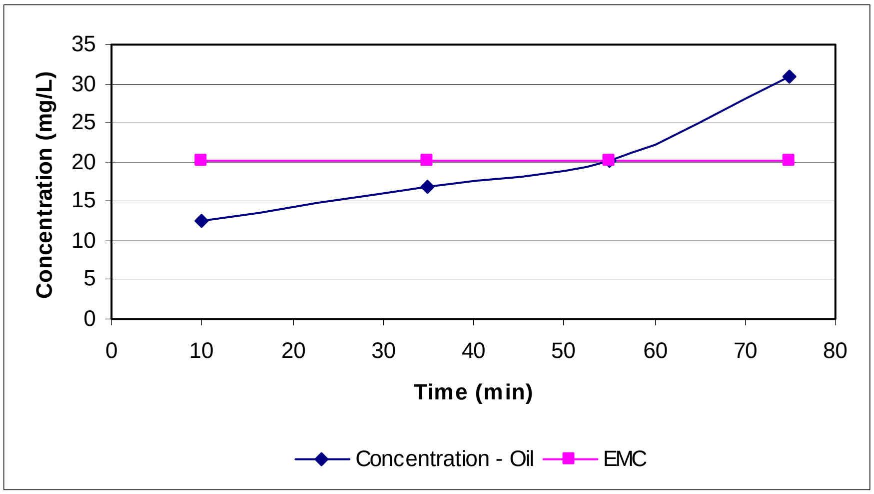

Figure A.18 Pollutograph for oil obtained from C&M Ecotrihex pavement rig when two year equivalent pollutants are simulated

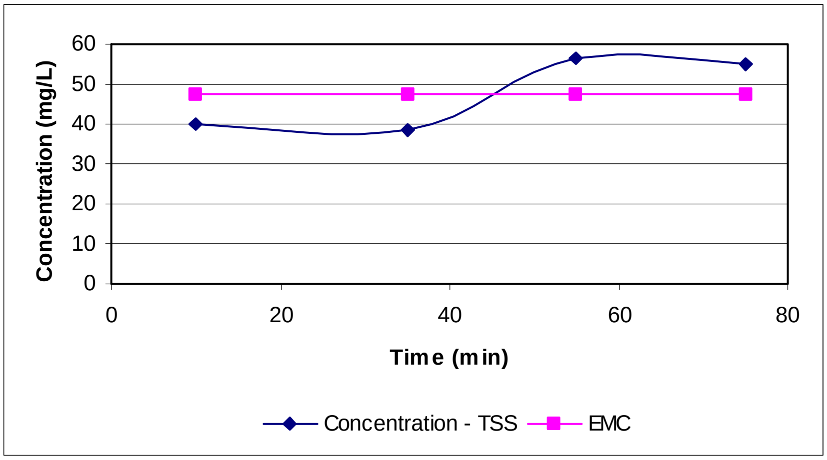

Figure A.19 Pollutograph for TSS obtained from C&M Ecotrihex pavement rig when two year equivalent pollutants are simulated

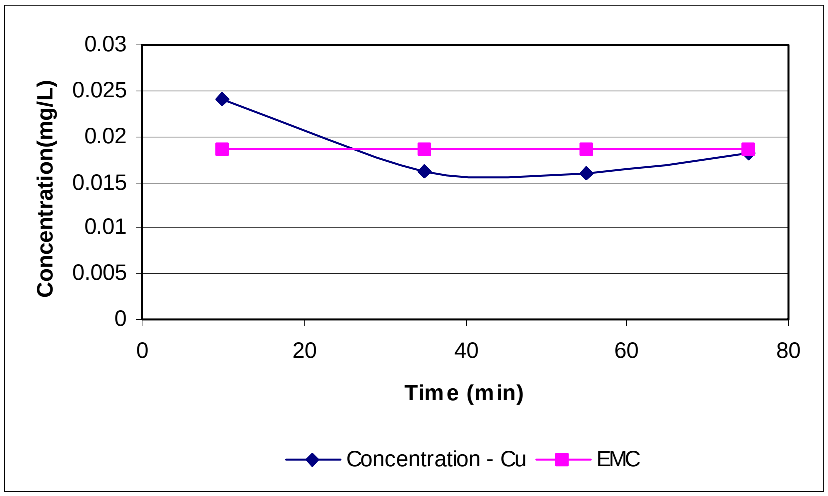

Figure A.20 Pollutograph for Cu obtained from C&M Ecotrihex pavement rig when two year equivalent pollutants are simulated

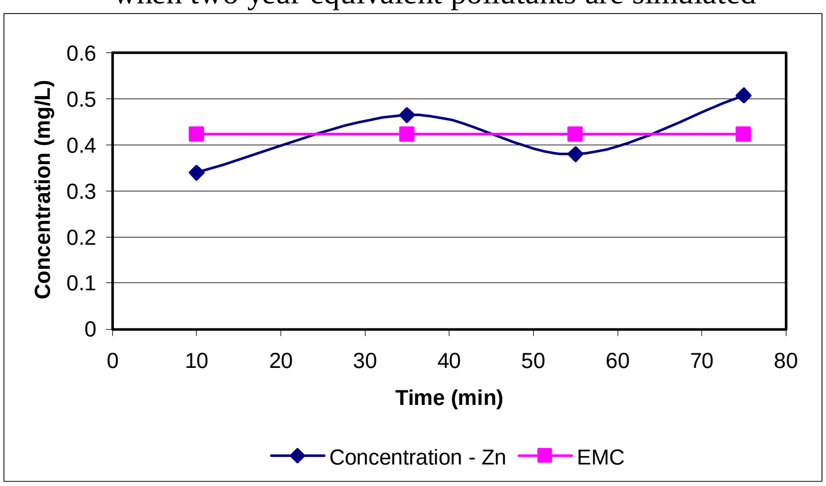

Figure A.21 Pollutograph for Zn obtained from C&M Ecotrihex pavement rig when two year equivalent pollutants are simulated

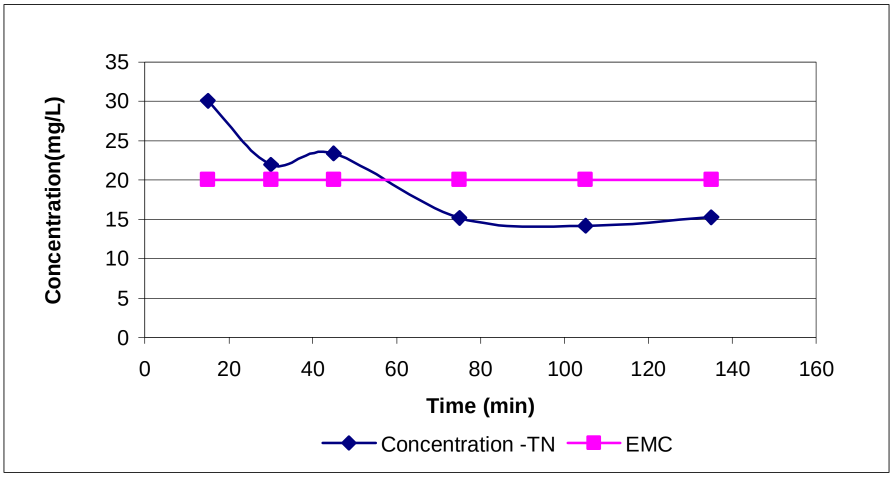

Figure A.22 Pollutograph for TN obtained from C&M Ecotrihex pavement rig when seven year equivalent pollutants are simulated

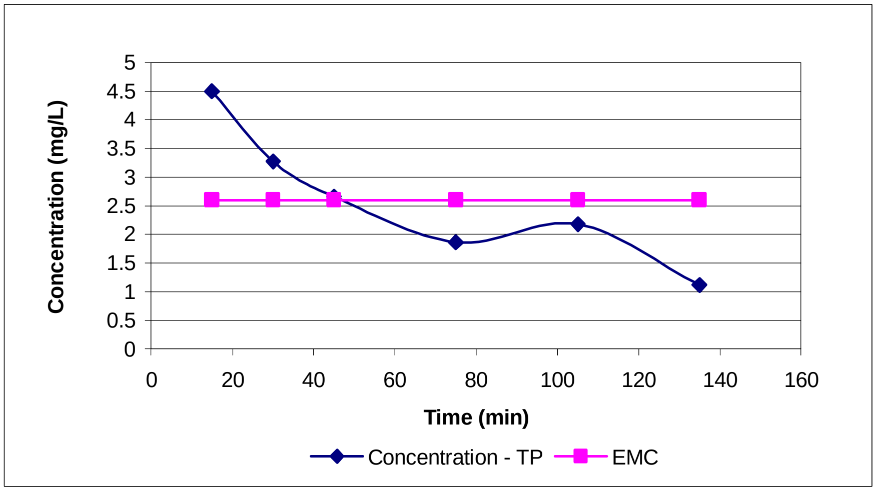

Figure A.23 Pollutograph for TP obtained from C&M Ecotrihex pavement rig when seven year equivalent pollutants are simulated

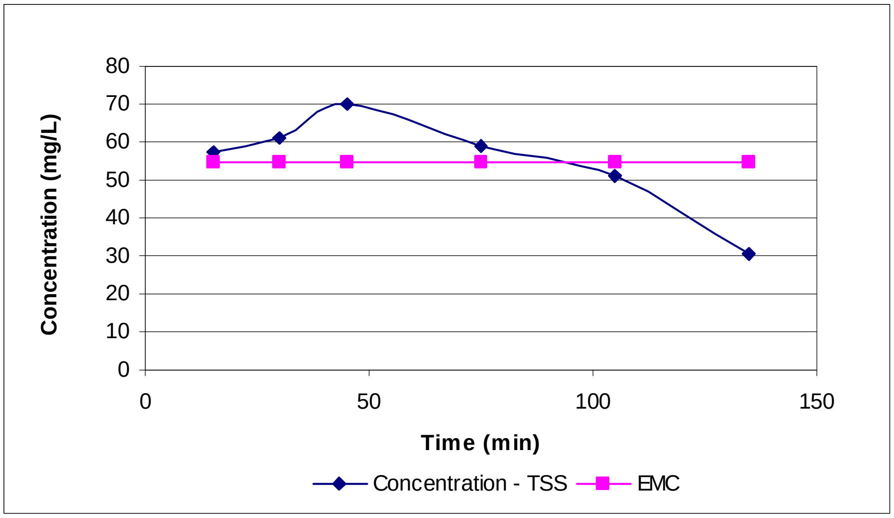

Figure A.24 Pollutograph for TSS obtained from C&M Ecotrihex pavement rig when seven year equivalent pollutants are simulated

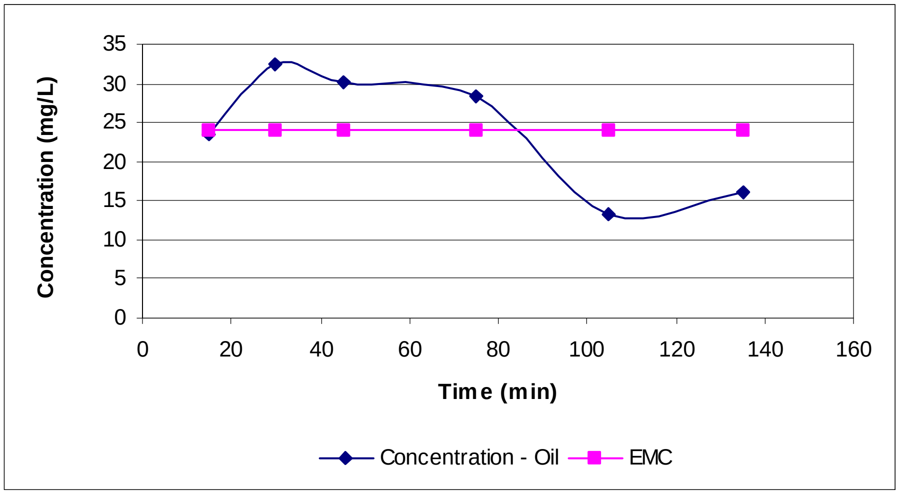

Figure A.25 Pollutograph for Oil obtained from C&M Ecotrihex pavement rig when seven year equivalent pollutants are simulated

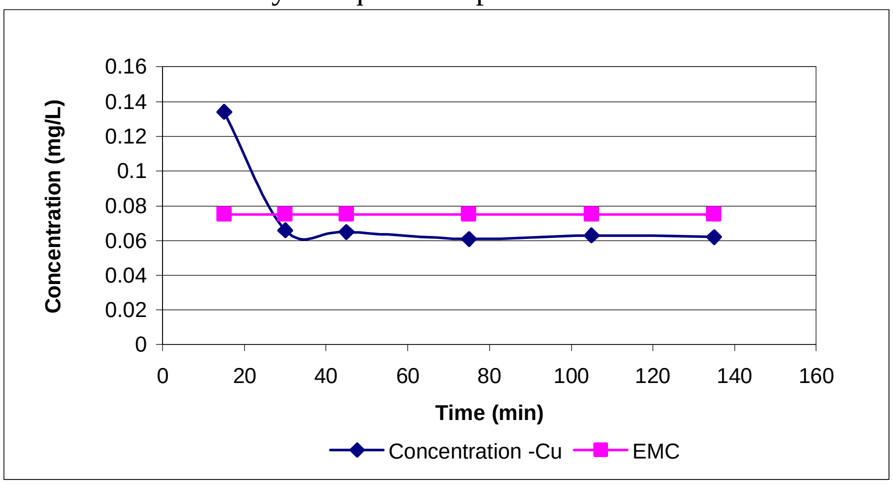

Figure A.26 Pollutograph for Cu obtained from C&M Ecotrihex pavement rig when seven year equivalent pollutants are simulated

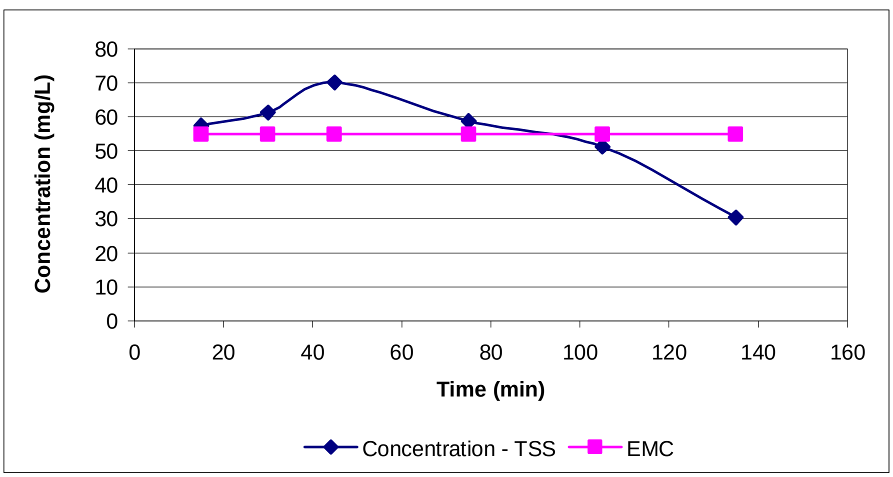

Figure A.27 Pollutograph for TSS obtained from C&M Ecotrihex pavement rig when seven year equivalent pollutants are simulated

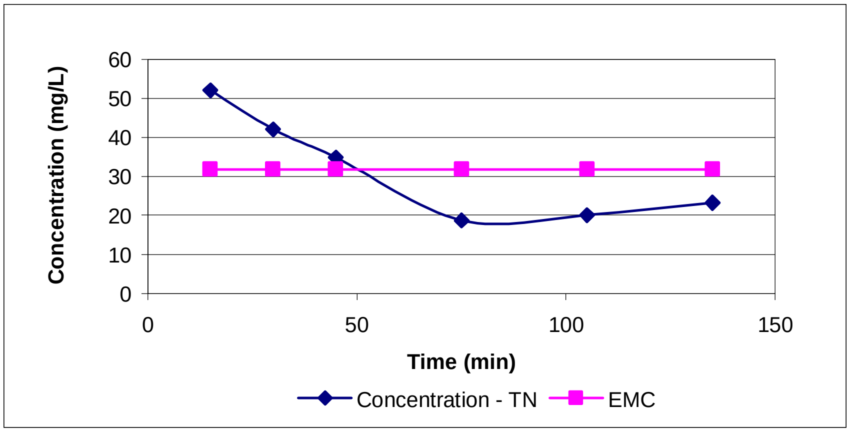

Figure A.28 Pollutograph for TN obtained from C&M Ecotrihex pavement rig when nine year equivalent pollutants are simulated

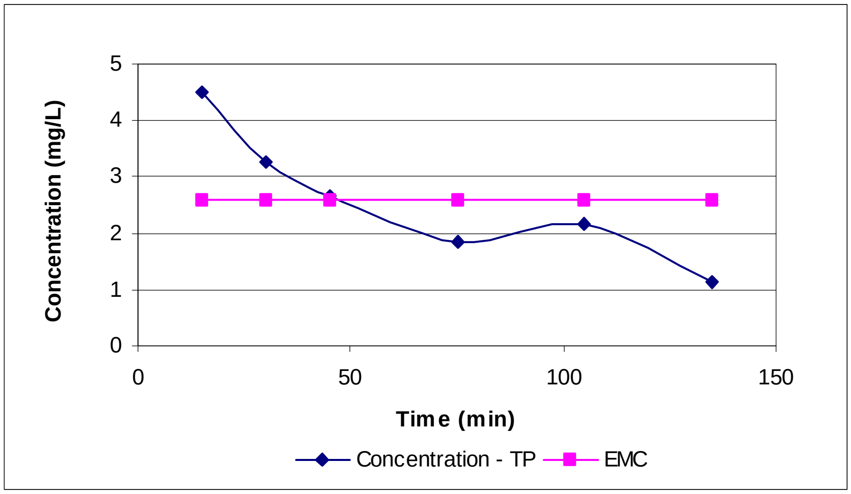

Figure A.29 Pollutograph for TP obtained from C&M Ecotrihex pavement rig when nine year equivalent pollutants are simulated

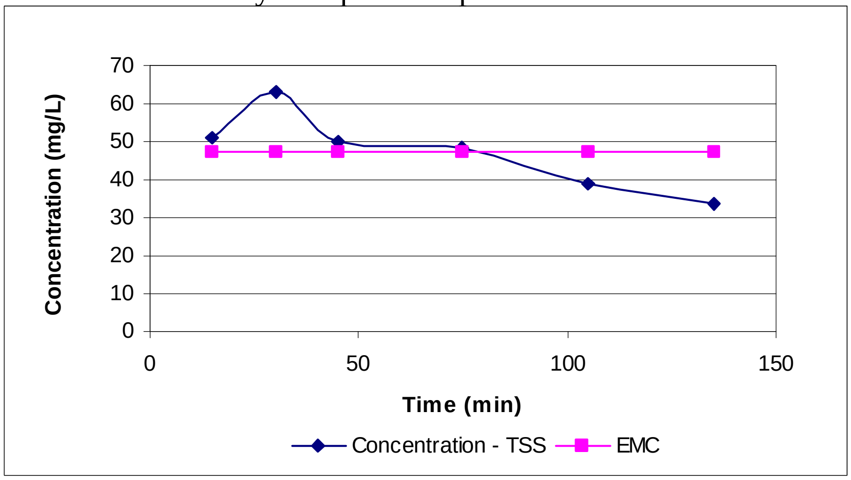

Figure A.30 Pollutograph for TSS obtained from C&M Ecotrihex pavement rig when nine year equivalent pollutants are simulated

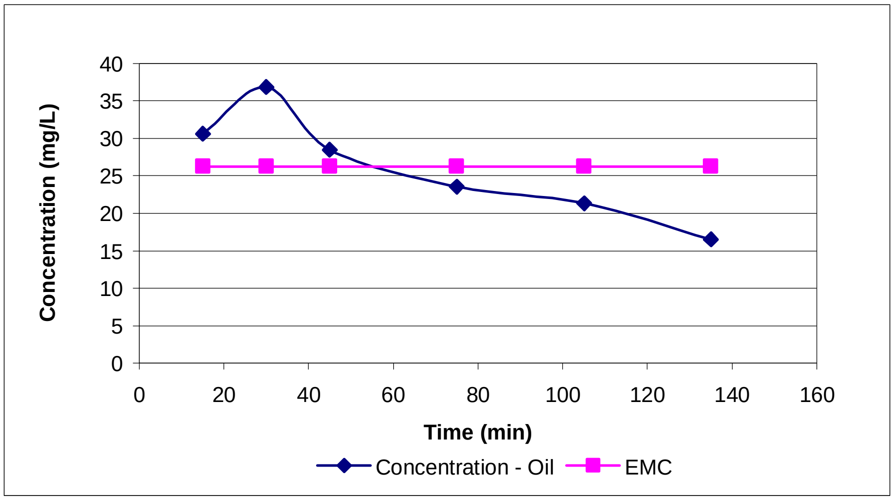

Figure A.31 Pollutograph for Oil obtained from C&M Ecotrihex pavement rig when nine year equivalent pollutants are simulated

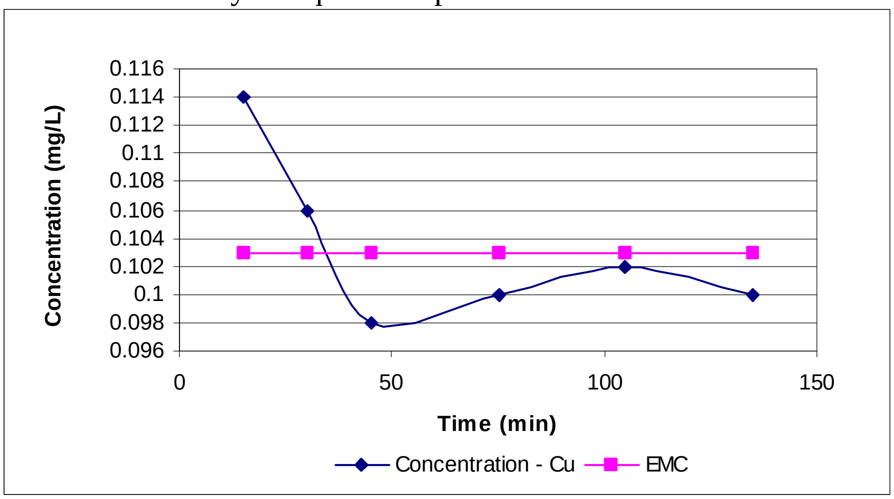

Figure A.32 Pollutograph for Cu obtained from C&M Ecotrihex pavement rig when nine year equivalent pollutants are simulated

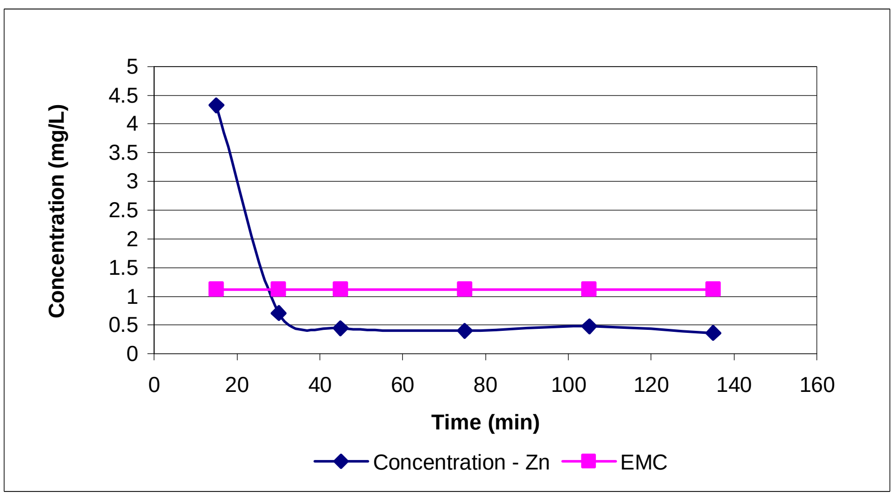

Figure A.33 Pollutograph for Zn obtained from C&M Ecotrihex pavement rig when nine year equivalent pollutants are simulated

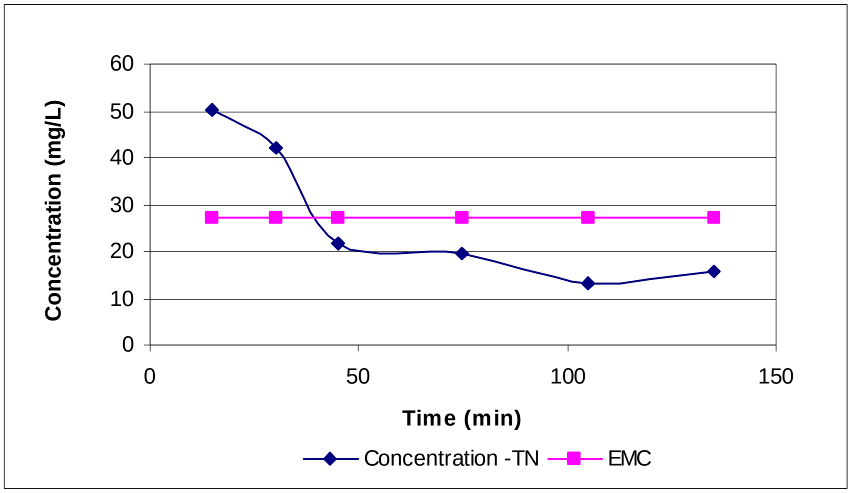

Figure A.34 Pollutograph for TN obtained from C&M Ecotrihex pavement rig when nine year equivalent pollutants are simulated

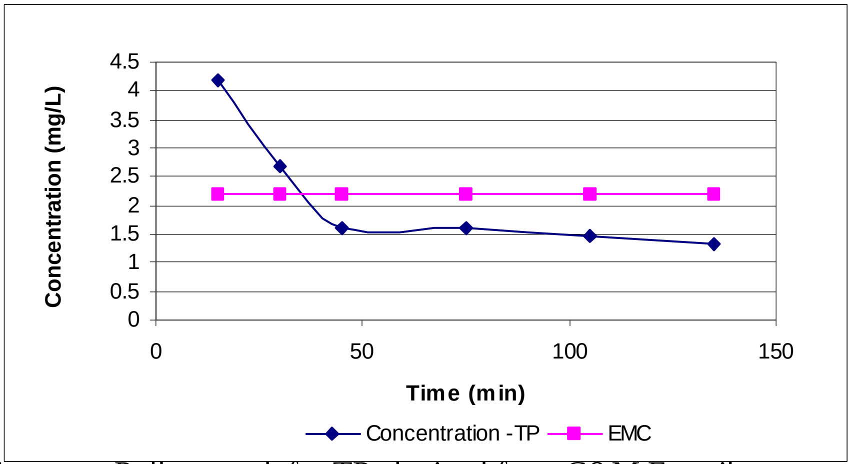

Figure A.35 Pollutograph for TP obtained from C&M Ecotrihex pavement rig when nine year equivalent pollutants are simulated

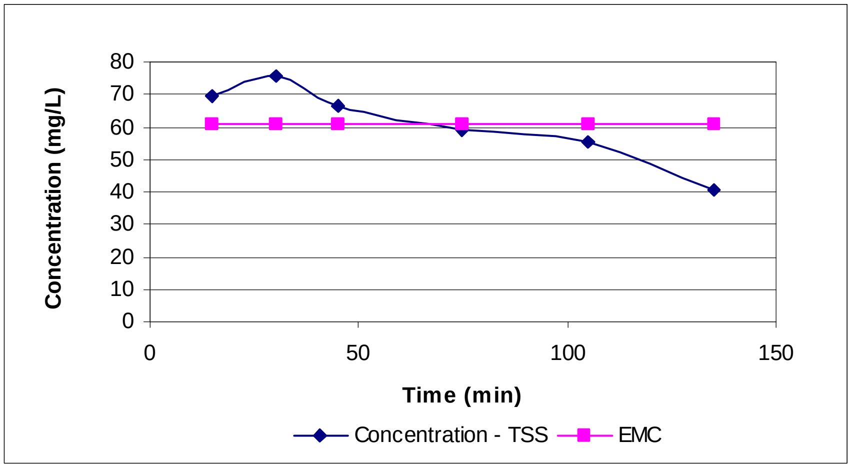

Figure A.36 Pollutograph for TSS obtained from C&M Ecotrihex pavement rig when nine year equivalent pollutants are simulated

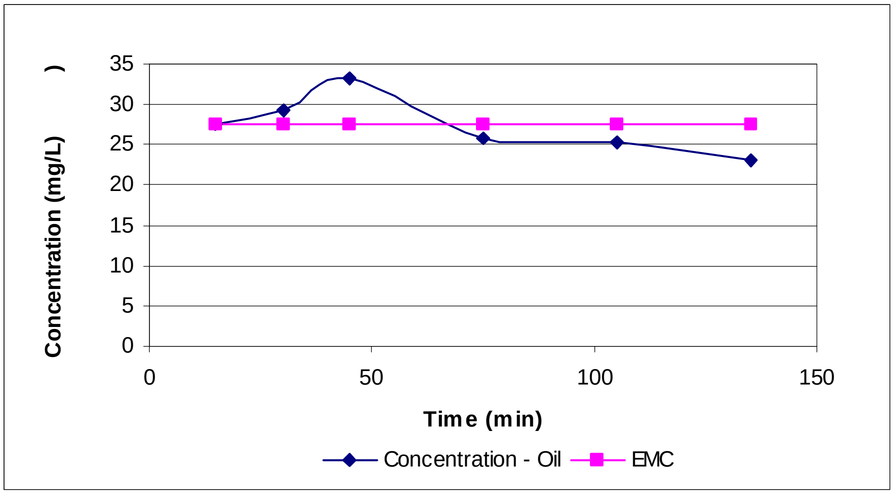

Figure A.37 Pollutograph for Oil obtained from C&M Ecotrihex pavement rig when nine year equivalent pollutants are simulated

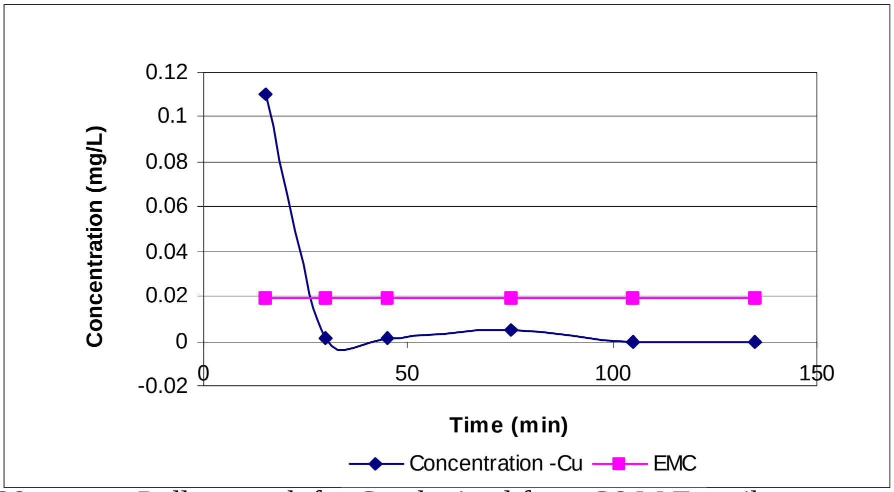

Figure A.38 Pollutograph for Cu obtained from C&M Ecotrihex pavement rig when nine year equivalent pollutants are simulated

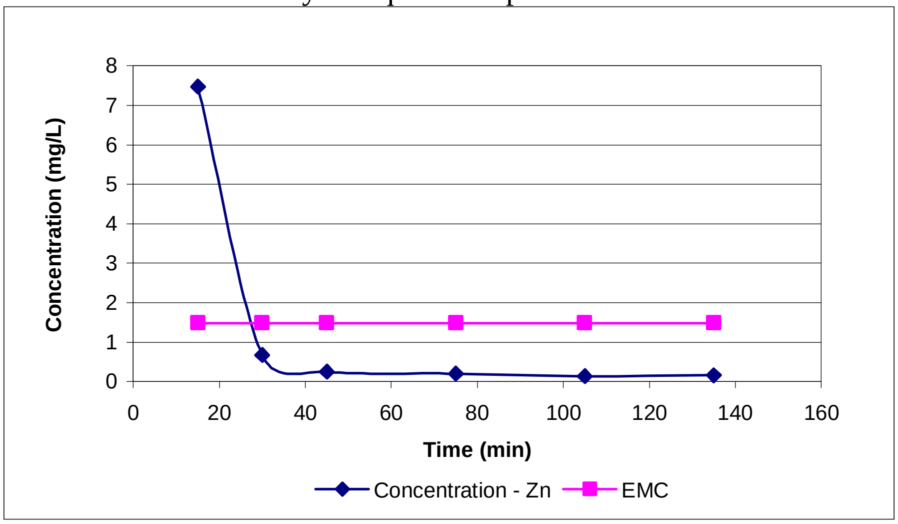

Figure A.39 Pollutograph for Zn obtained from C&M Ecotrihex pavement rig when nine year equivalent pollutants are simulated

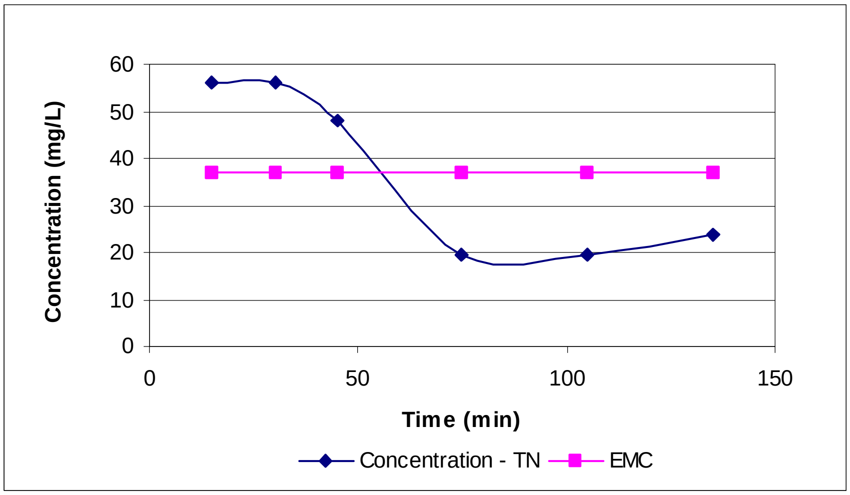

Figure A.40 Pollutograph for TN obtained from C&M Ecotrihex pavement rig when eleven year equivalent pollutants are simulated

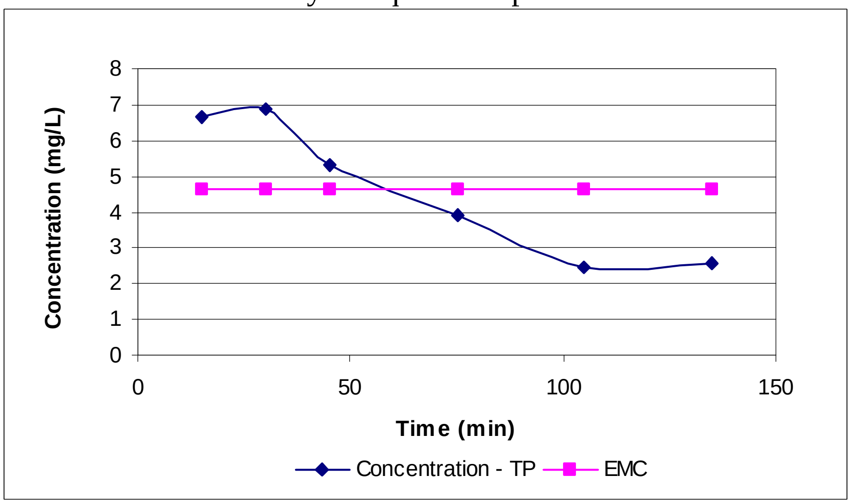

Figure A.41 Pollutograph for TP obtained from C&M Ecotrihex pavement rig when eleven year equivalent pollutants are simulated

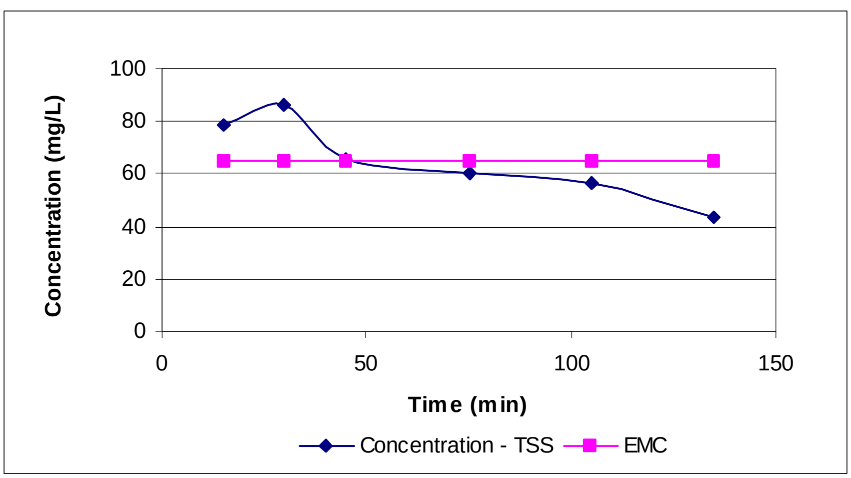

Figure A.42 Pollutograph for TSS obtained from C&M Ecotrihex pavement rig when eleven year equivalent pollutants are simulated

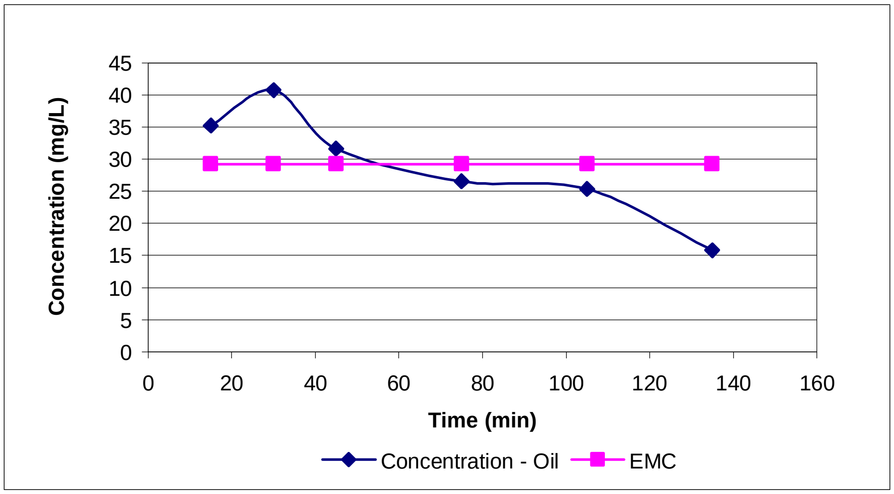

Figure A.43 Pollutograph for Oil obtained from C&M Ecotrihex pavement rig when eleven year equivalent pollutants are simulated

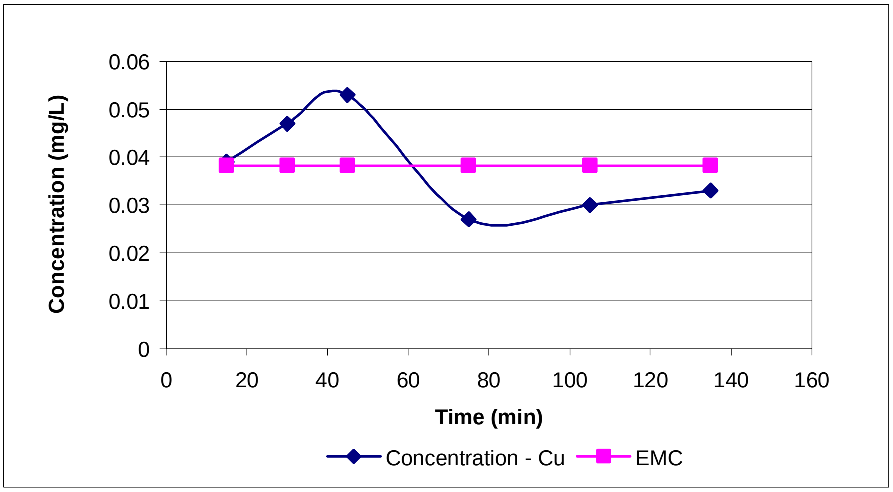

Figure A.44 Pollutograph for Cu obtained from C&M Ecotrihex pavement rig when eleven year equivalent pollutants are simulated

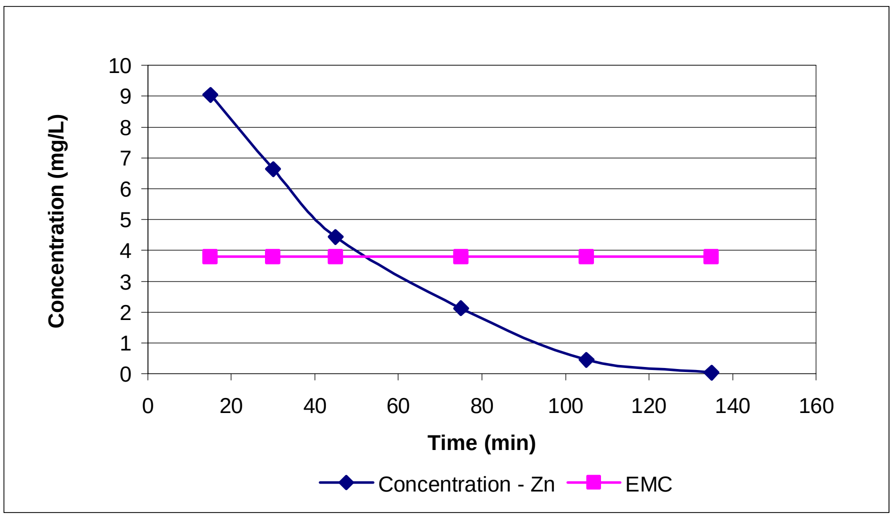

Figure A.45 Pollutograph for Zn obtained from C&M Ecotrihex pavement rig when eleven year equivalent pollutants are simulated

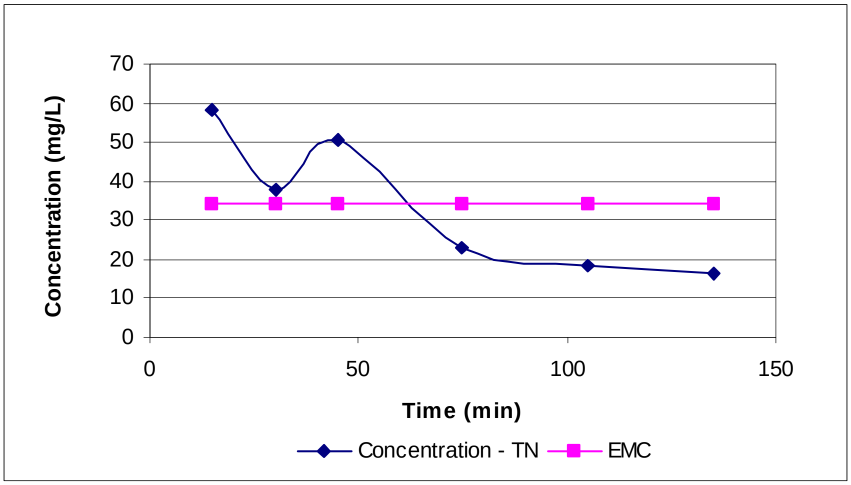

Figure 6.46 Pollutograph for TN obtained from C&M Ecotrihex pavement rig when thirteen years equivalent pollutants are simulated

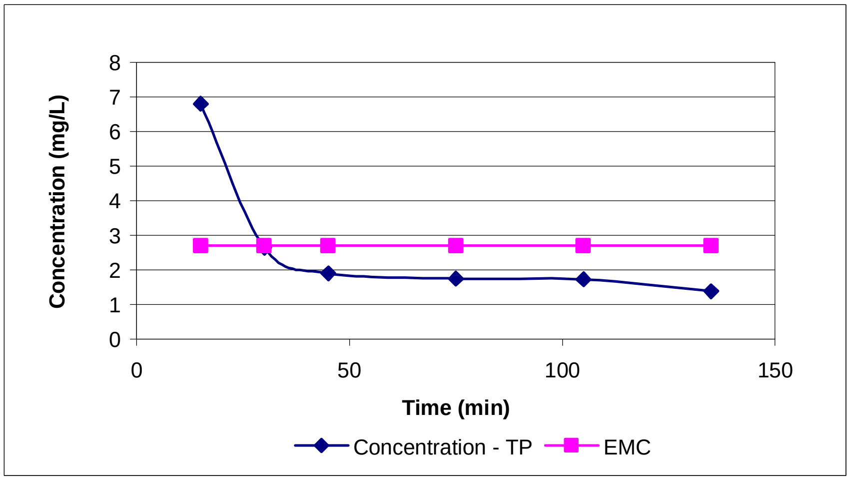

Figure A.47 Pollutograph for TP obtained from C&M Ecotrihex pavement rig when thirteen years equivalent pollutants are simulated

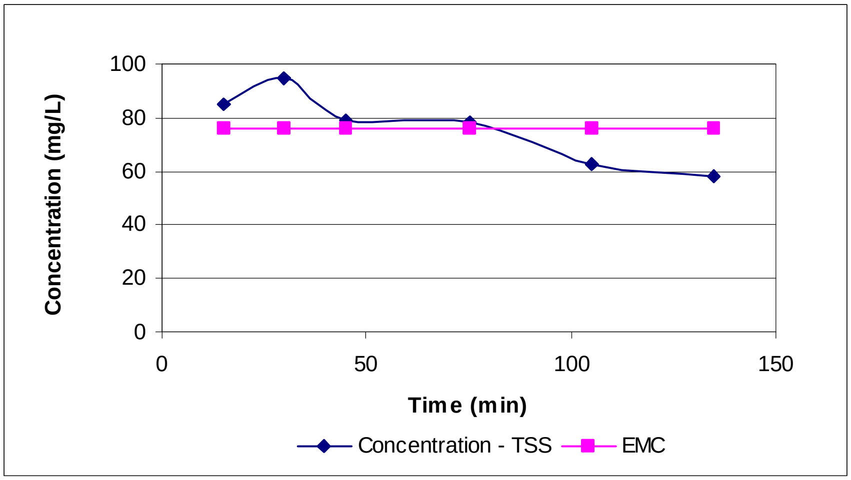

Figure A.48 Pollutograph for TSS obtained from C&M Ecotrihex pavement rig when thirteen years equivalent pollutants are simulated

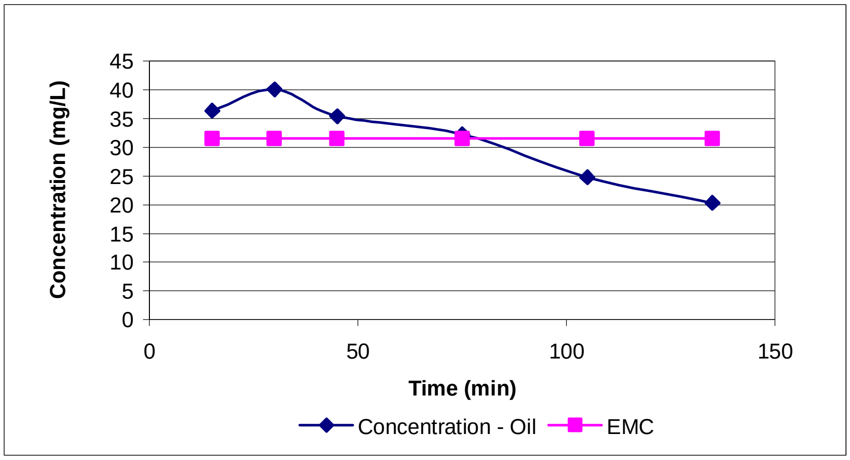

Figure A.49 Pollutograph for Oil obtained from C&M Ecotrihex pavement rig when thirteen years equivalent pollutants are simulated

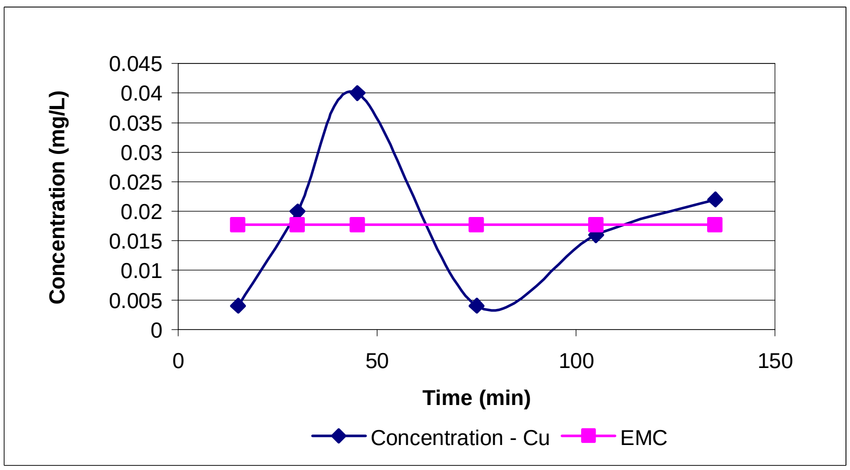

Figure A.50 Pollutograph for Cu obtained from C&M Ecotrihex pavement rig when thirteen years equivalent pollutants are simulated

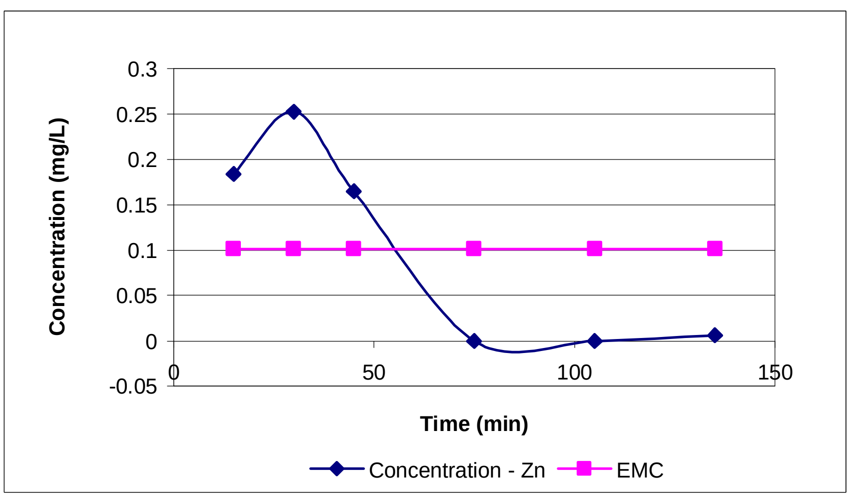

Figure A.51 Pollutograph for Zn obtained from C&M Ecotrihex pavement rig when thirteen years equivalent pollutants are simulated

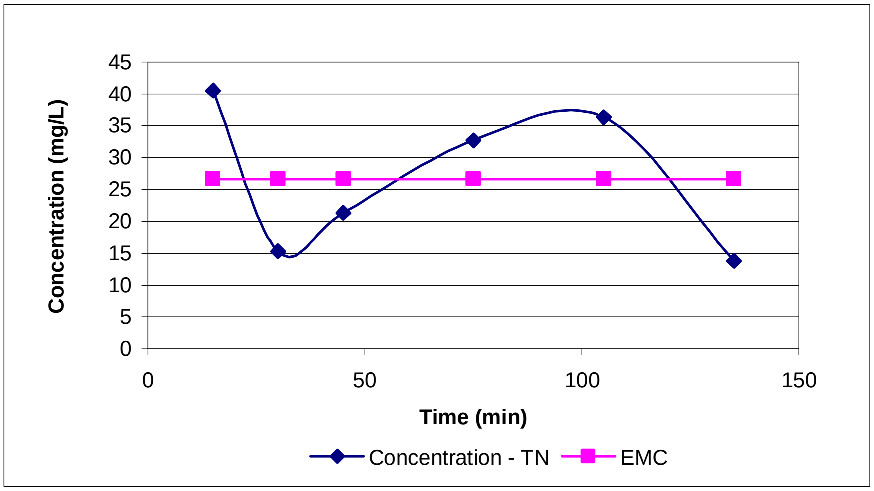

Figure A.52 Pollutograph for TN obtained from C&M Ecotrihex pavement rig when fifteen years equivalent pollutants are simulated

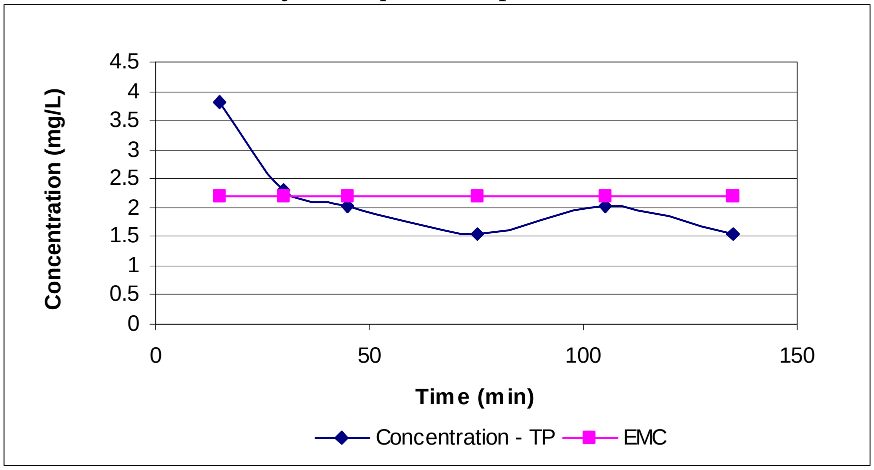

Figure A.53 Pollutograph for TP obtained from C&M Ecotrihex pavement rig when fifteen years equivalent pollutants are simulated

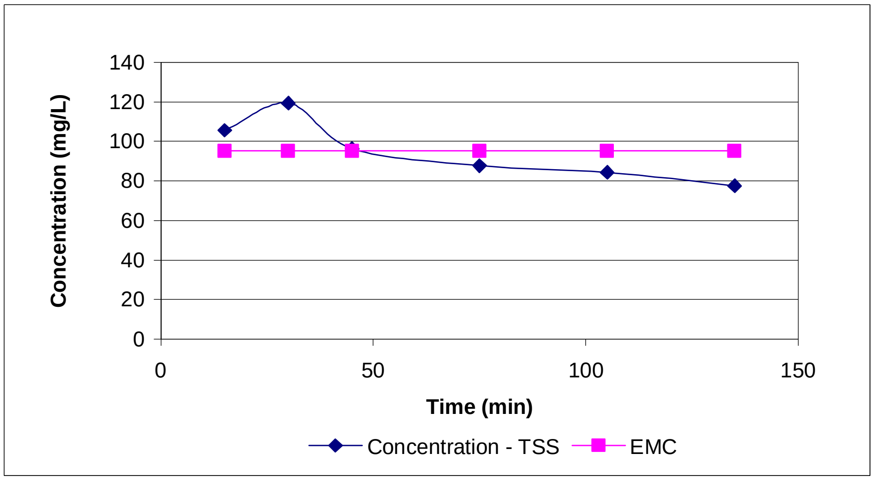

Figure A.54 Pollutograph for TSS obtained from C&M Ecotrihex pavement rig when fifteen years equivalent pollutants are simulated

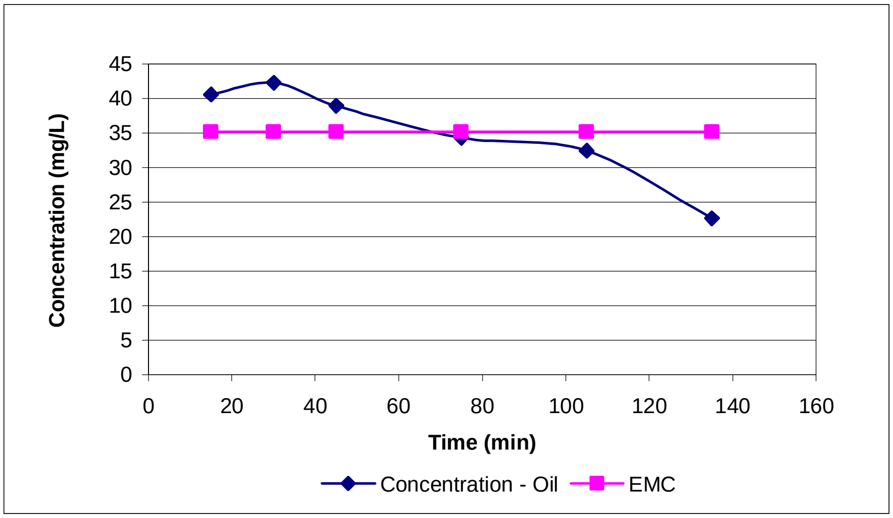

Figure A.55 Pollutograph for Oil obtained from C&M Ecotrihex pavement rig when fifteen years equivalent pollutants are simulated

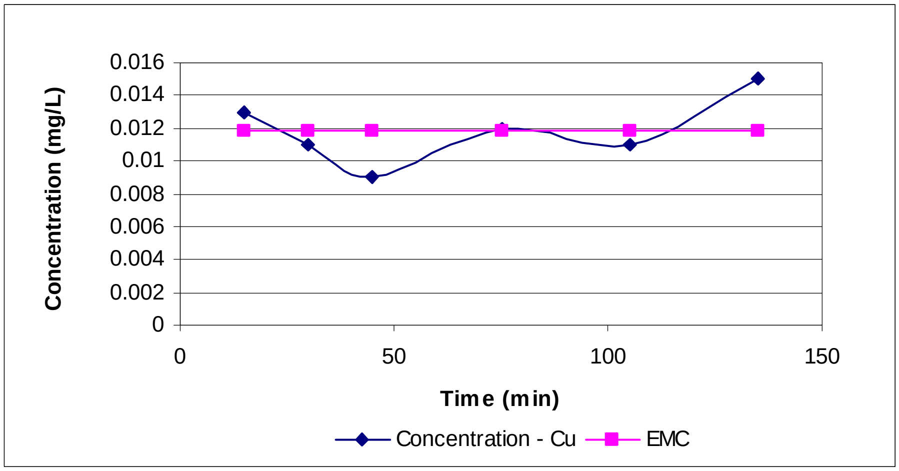

Figure A.56 Pollutograph for Cu obtained from C&M Ecotrihex pavement rig when fifteen years equivalent pollutants are simulated

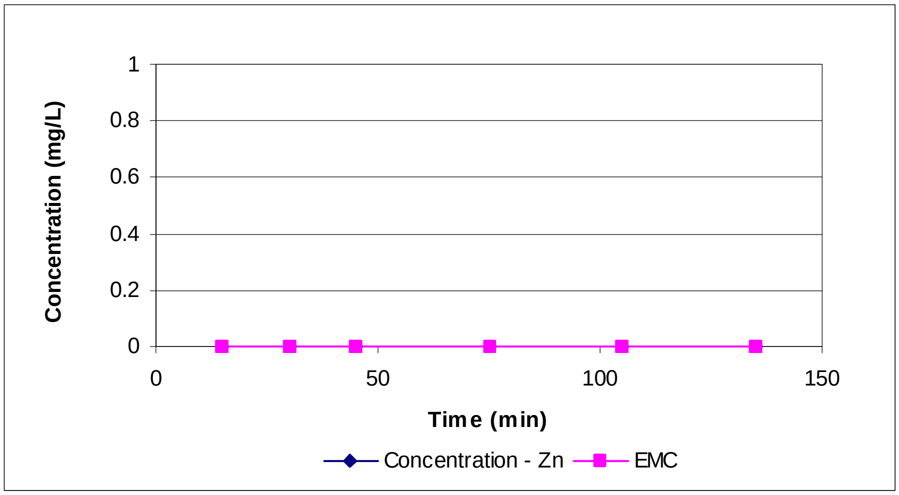

Figure A.57 Pollutograph for Zn obtained from C&M Ecotrihex pavement rig when fifteen years equivalent pollutants are simulated

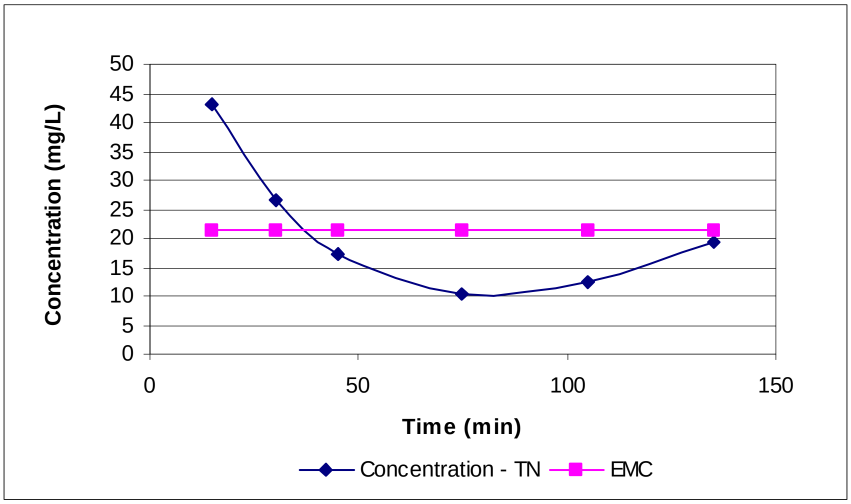

Figure A.58 Pollutograph for TN obtained from C&M Ecotrihex pavement rig when seventeen years equivalent pollutants are simulated

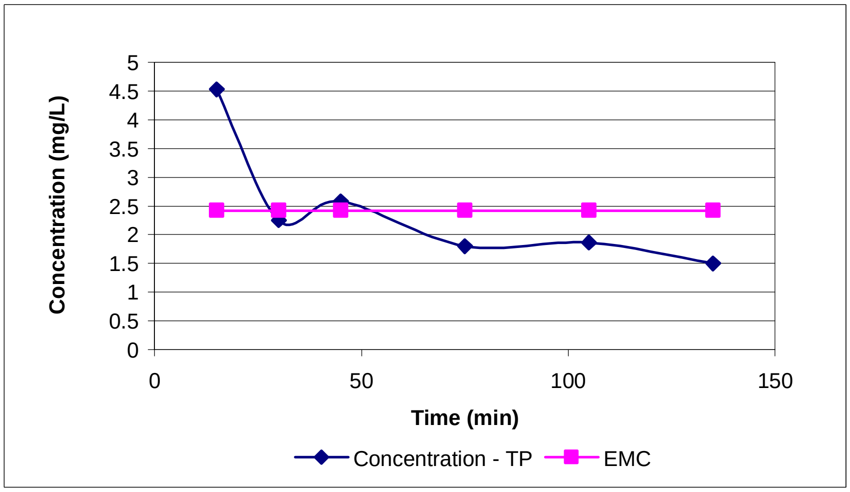

Figure A.59 Pollutograph for TP obtained from C&M Ecotrihex pavement rig when seventeen years equivalent pollutants are simulated

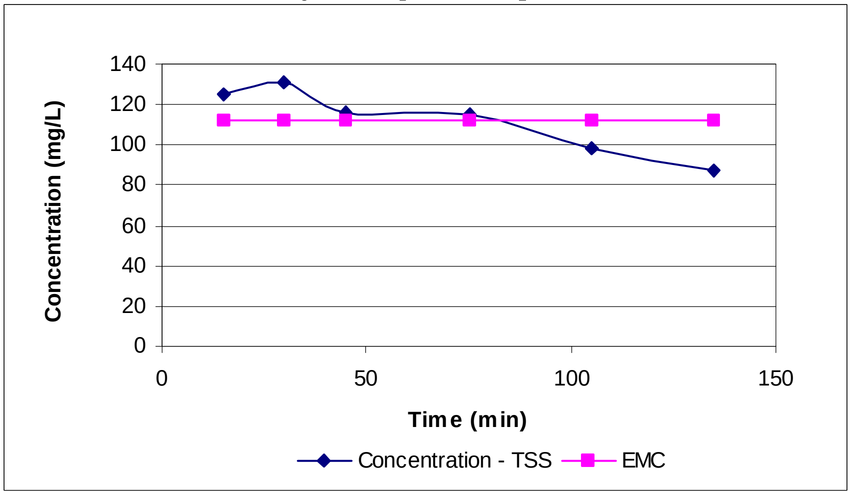

Figure A.60 Pollutograph for TSS obtained from C&M Ecotrihex pavement rig when seventeen years equivalent pollutants are simulated

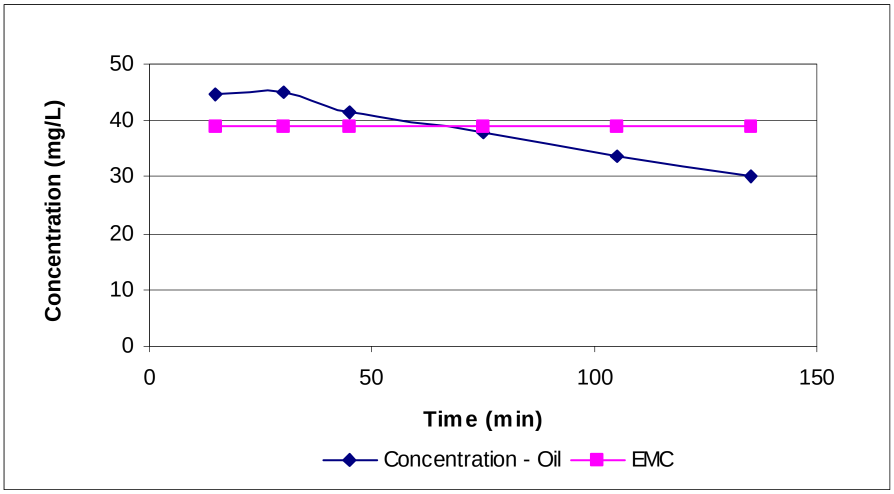

Figure A.61 Pollutograph for Oil obtained from C&M Ecotrihex pavement rig when seventeen years equivalent pollutants are simulated

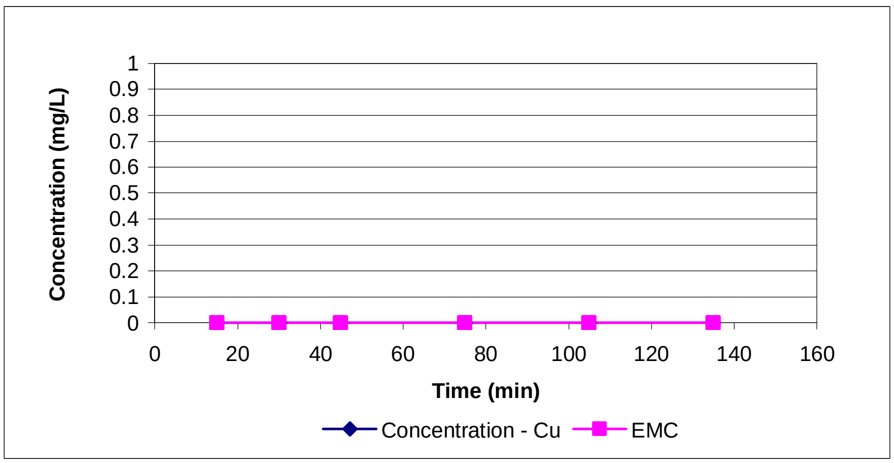

Figure A.62 Pollutograph for Cu obtained from C&M Ecotrihex pavement rig when seventeen years equivalent pollutants are simulated

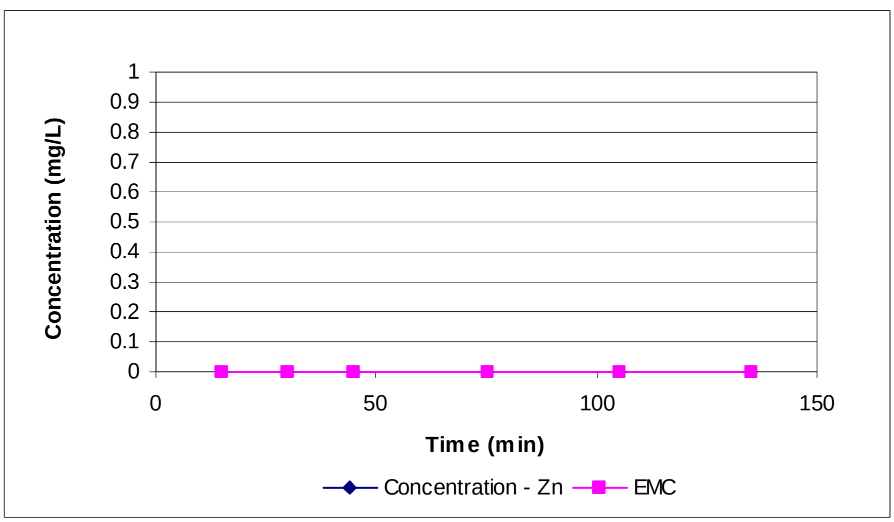

Figure A.63 Pollutograph for Oil obtained from C&M Ecotrihex pavement rig when seventeen years equivalent pollutants are simulated

APPENDIX B RESULTS OBTAIND FROM FIELD STUDIES

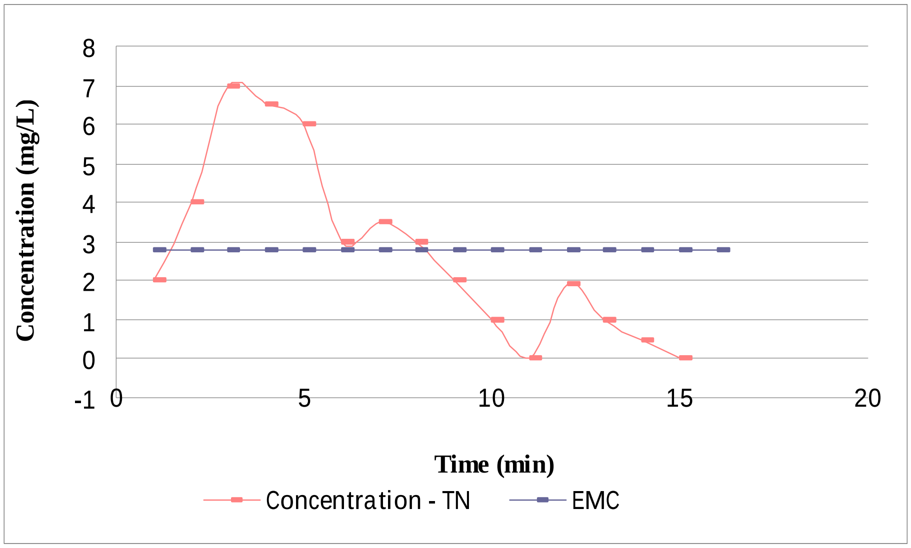

Figure B.01 Pollutograph for TN – Asphalt (Natural rain event 27/06/07)

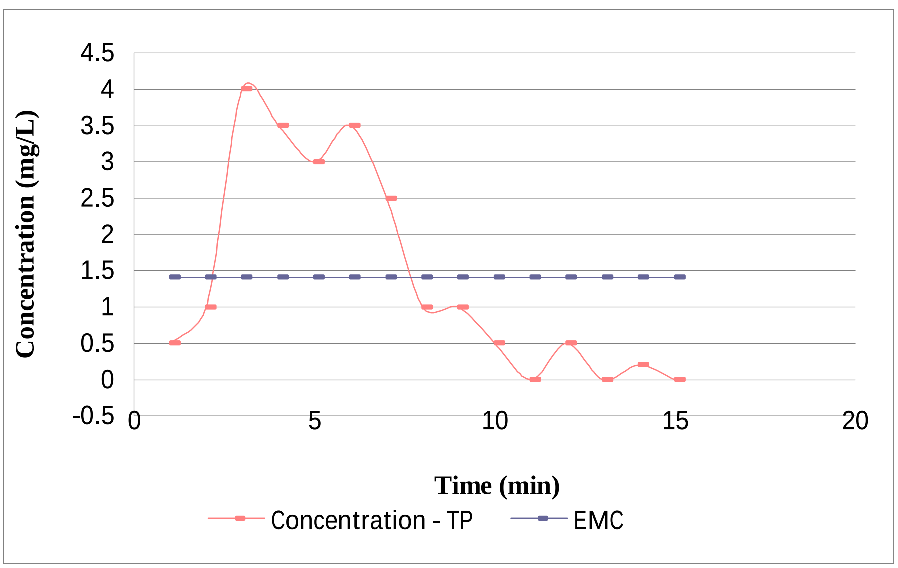

Figure B.02 Pollutograph for TP – Asphalt (Natural rain event 27/06/07)

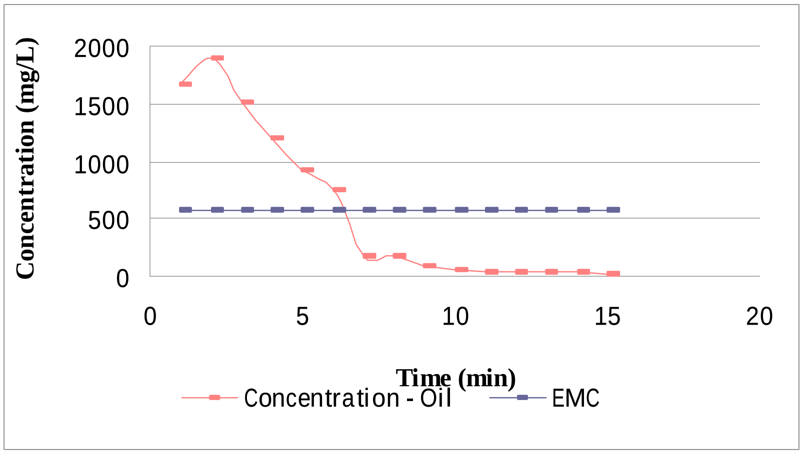

Figure B.03 Pollutograph for Oil – Asphalt (Natural rain event 27/06/07)

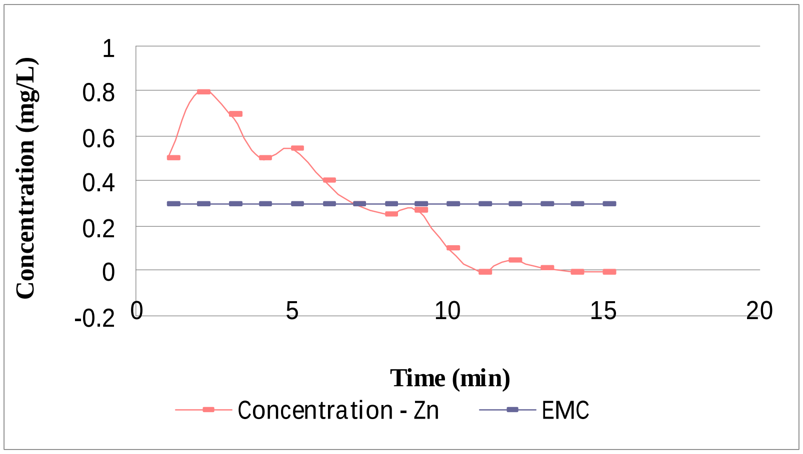

Figure 6.04 Pollutograph for Zn – Asphalt (Natural rain event 27/06/07)

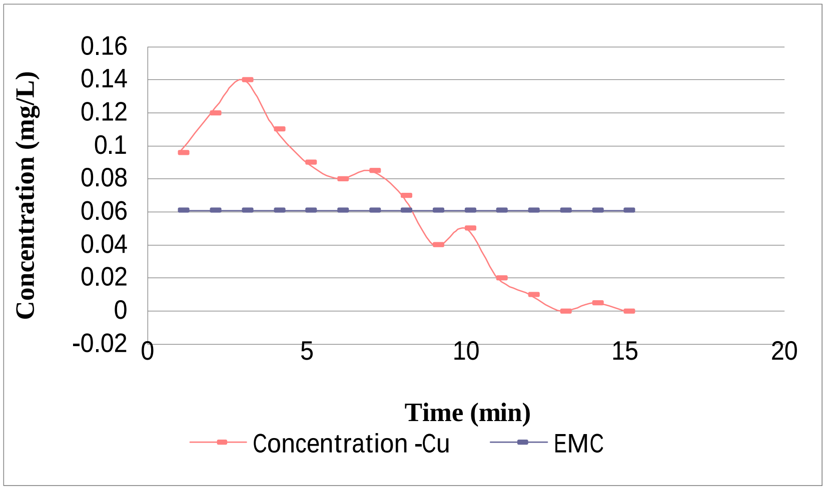

Figure B.05 Pollutograph for Cu – Asphalt (Natural rain event 27/06/07)

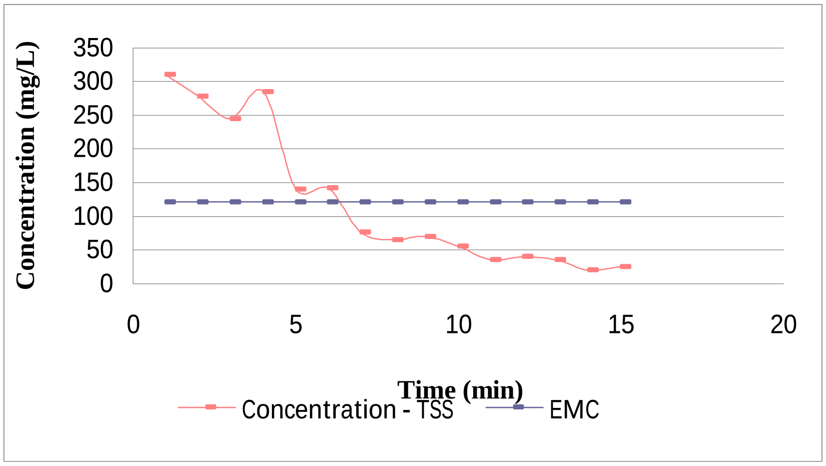

Figure B.06 Pollutograph for TSS – Asphalt (Natural rain event 27/06/07)

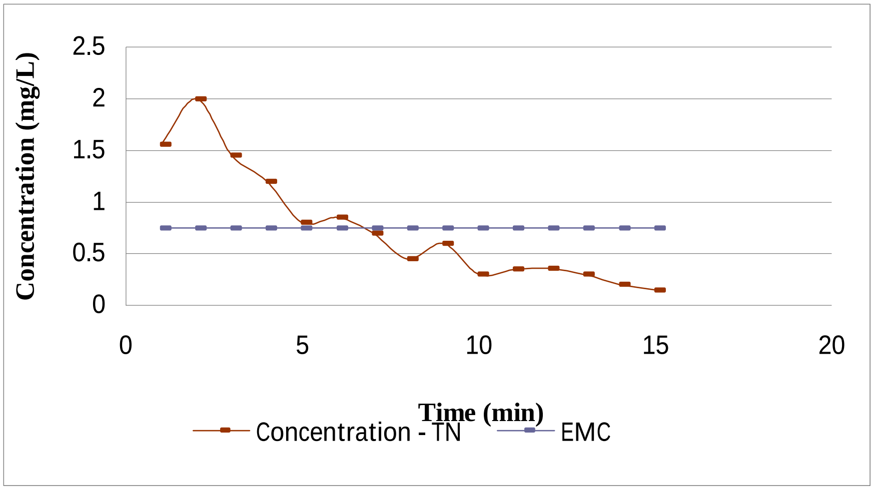

Figure B.07 Pollutograph for TN – C&M Ecotrihex (Natural rain event 27/06/07)

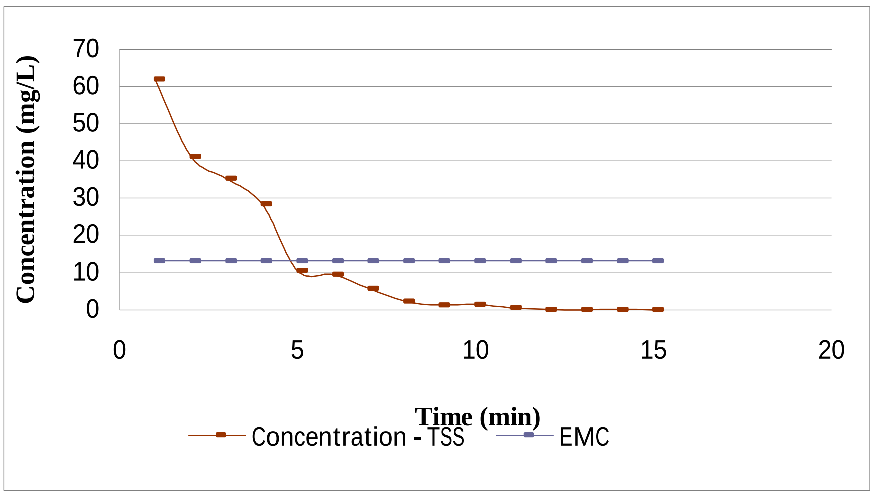

Figure B.08 Pollutograph for TSS – C&M Ecotrihex (Natural rain event 27/06/07)

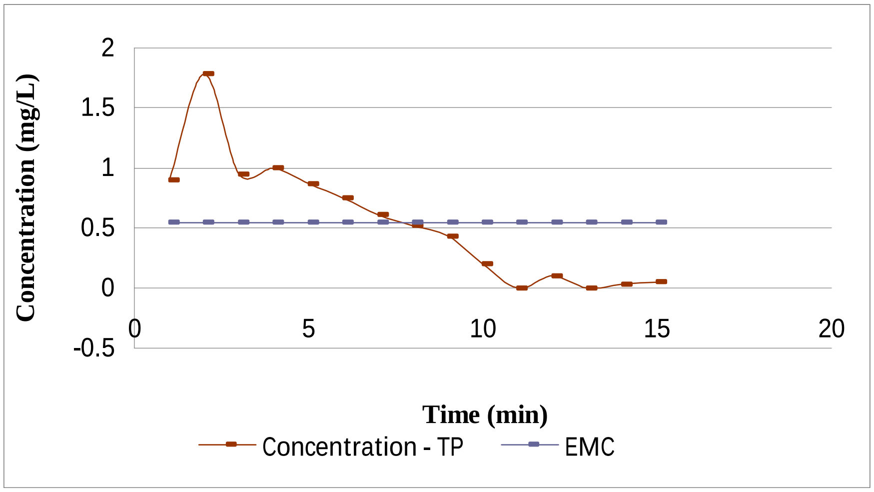

Figure B.09 Pollutograph for TP – C&M Ecotrihex (Natural rain event 27/06/07)

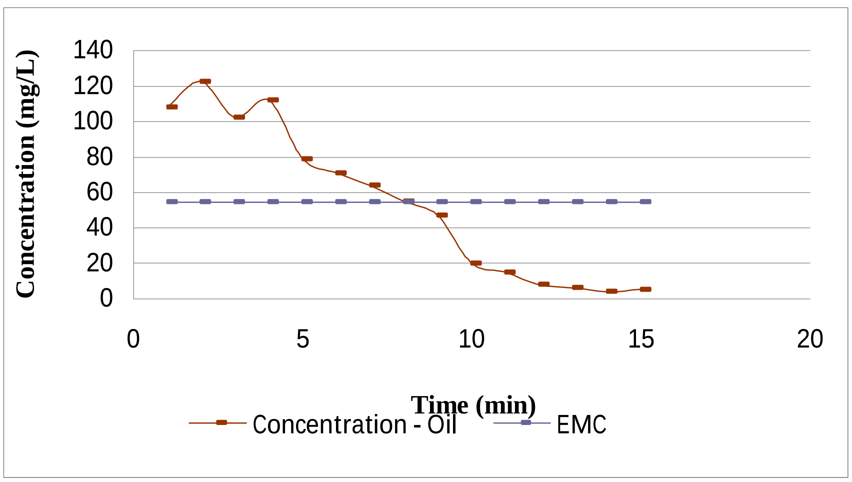

Figure B.64 Pollutograph for Oil – C&M Ecotrihex (Natural rain event 27/06/07)

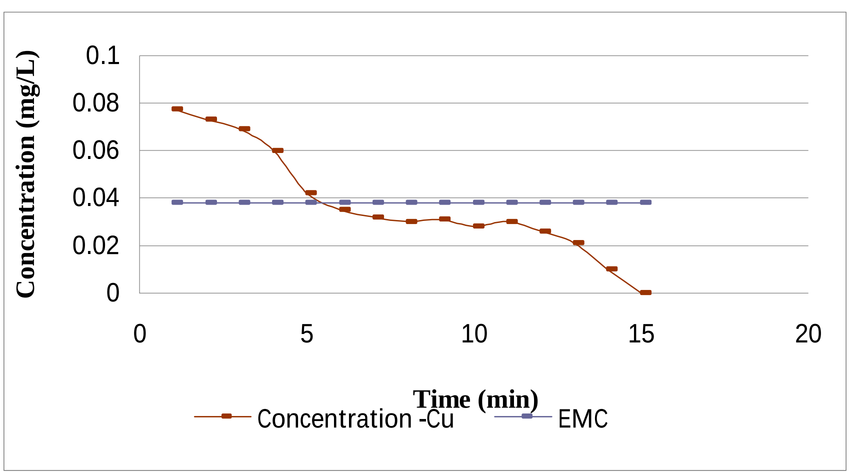

Figure B.11 Pollutograph for Cu– C&M Ecotrihex

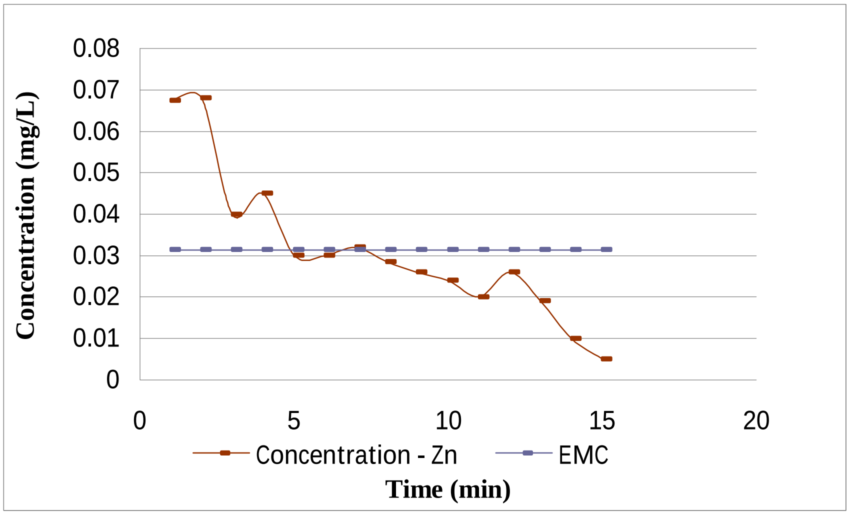

Figure B.12 Pollutograph for Zn – C&M Ecotrihex (Natural rain event 27/06/07)

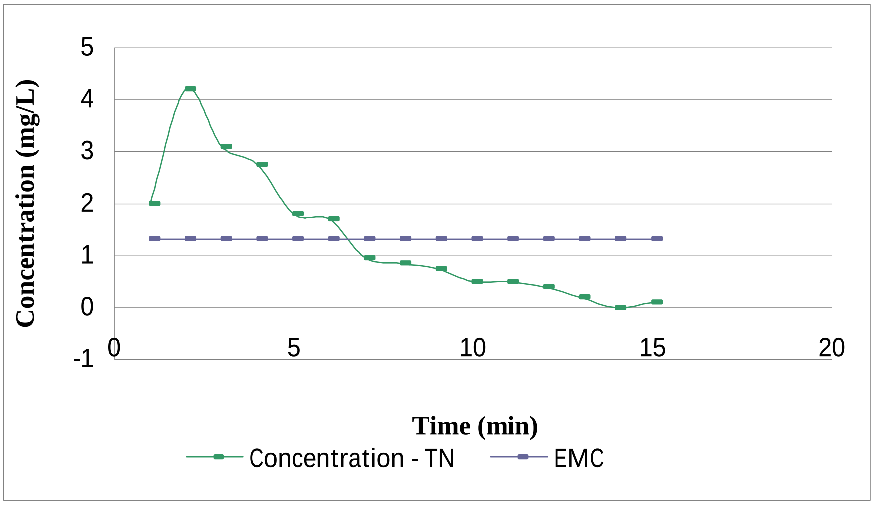

Figure B.13 Pollutograph for TN – Atlantis (Natural rain event 27/06/07)

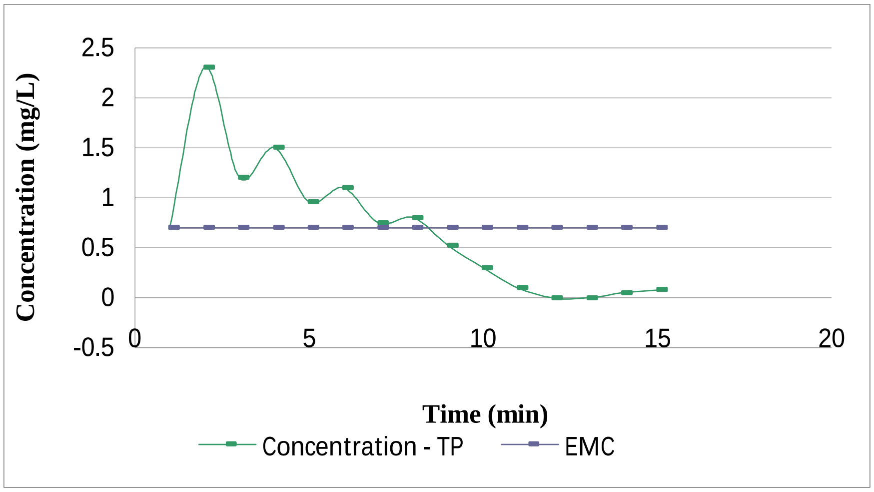

Figure B.14 Pollutograph for TP – Atlantis (Natural rain event 27/06/07)

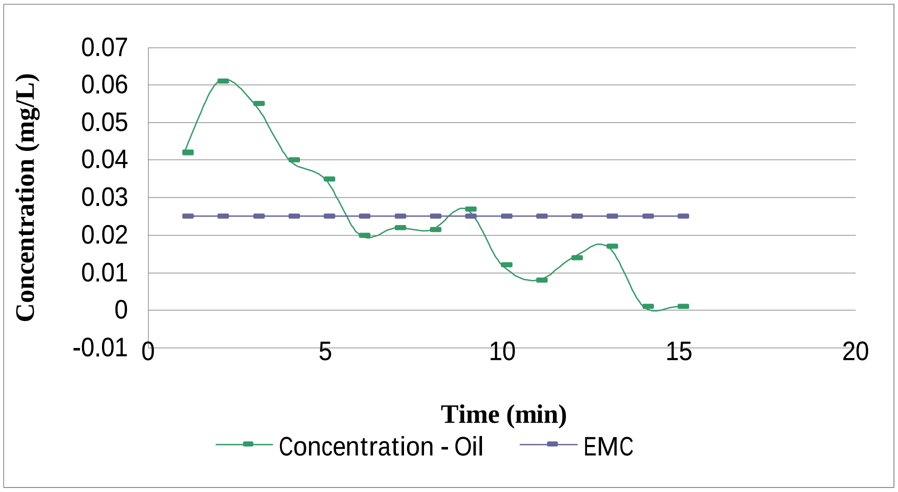

Figure B.15 Pollutograph for oil – Atlantis (Natural rain event 27/06/07)

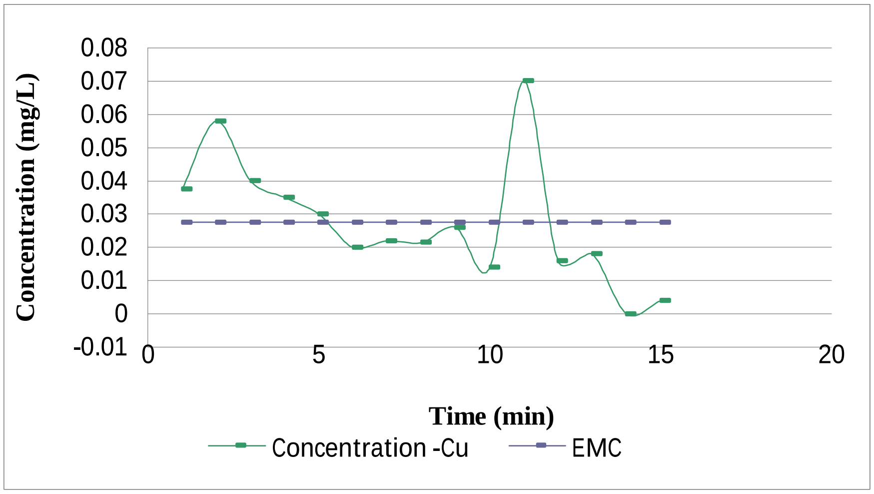

Figure B.16 Pollutograph for Cu – Atlantis (Natural rain event 27/06/07)

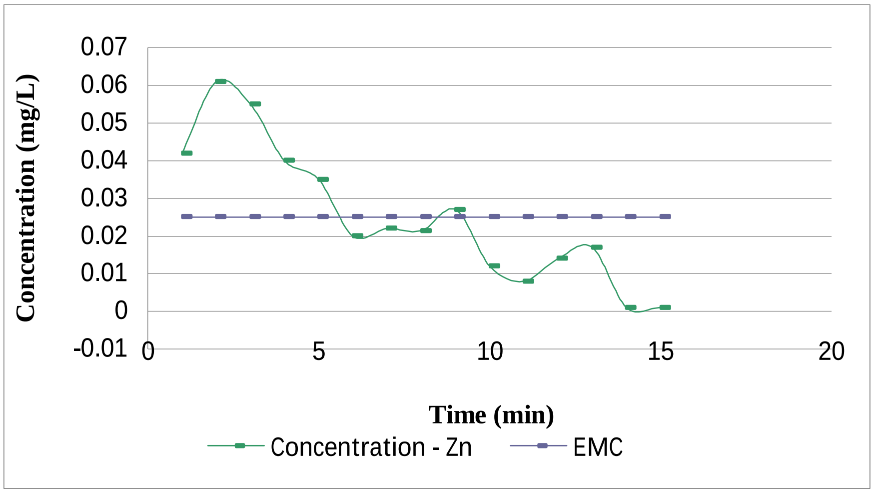

Figure B.17 Pollutograph for Zn – Atlantis (Natural rain event 27/06/07)

Table B.1 Summary of EMCs and Loads obtained from natural rain events for asphalt pavement

Date	Runoff (L)	Zn		Cu		TN		TP		Oil		TSS	
		EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)
2/11/06	647.2	0.000	0.000	0.000	0.0	0.0	0.0	0.0	12.9	540.0	349488.0	218.1	141128.4
24/03/07	698.5	0.010	6.810	0.027	18.9	1.0	663.6	0.4	305.9	588.6	411102.2	104.2	72783.7
18/05/07	732.7	0.008	5.605	0.024	17.5	2.4	1758.5	0.5	388.3	649.6	475961.9	117.1	85799.2
27/06/07	867.8	0.295	256.001	0.061	52.9	2.8	2395.1	1.4	1223.6	573.0	497249.4	121.4	105350.9
13/07/07	903.4	0.076	68.658	0.059	53.2	7.1	6414.1	0.9	845.6	624.0	563721.6	134.3	121326.6
4/11/07	1200.3	0.090	108.027	0.060	72.0	9.1	10922.7	1.0	1212.3	702.0	842610.6	142.3	170802.7
21/12/07	1256.4	0.110	138.204	0.074	93.0	11.4	14323.0	1.2	1520.2	762.0	957376.8	132.7	166724.3

Table B.2 Summary of EMCs and Loads obtained from natural rain events for C&M Ecotrihex pavement

Date	Runoff (L)	Zn		Cu		TN		TP		Oil		TSS	
		EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)
2/11/06	317.1	0.000	0.000	0.000	0.0	1.7	539.1	0.0	3.2	62.3	19757.1	43.0	13636.5
24/03/07	405.1	0.002	0.952	0.017	6.8	1.2	465.9	0.2	80.0	43.5	17615.1	12.8	5197.8
18/05/07	411.3	0.001	0.281	0.014	5.9	1.1	452.4	0.2	96.2	69.2	28462.0	13.2	5429.2
27/06/07	461.8	0.031	14.501	0.038	17.5	0.8	346.4	0.5	252.1	54.6	25214.3	13.2	6095.8
13/07/07	501.3	0.005	2.557	0.035	17.6	1.9	974.0	0.4	178.5	61.6	30880.1	10.3	5163.4
4/11/07	559.5	0.009	5.036	0.034	19.0	2.4	1342.8	0.4	241.7	39.7	22212.2	12.3	6881.9
21/12/07	675.3	0.009	6.078	0.042	28.4	4.2	2836.3	0.5	359.3	43.5	29375.6	11.4	7698.4

Table B.3 Summary of EMCs and Loads obtained from natural rain events for Atlantis Turf Cell pavement

Date	Runoff (L)	Zn		Cu		TN		TP		Oil		TSS	
		EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)
2/11/06	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24/03/07	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
18/05/07	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
27/06/07	391.4	0.025	9.824	0.028	10.8	1.3	516.6	0.7	274.0	33.2	12994.5	10.0	3906.2
13/07/07	428.6	0.006	2.572	0.024	10.2	2.8	1212.9	0.4	175.7	42.4	18172.6	13.2	5657.5
4/11/07	485	0.008	3.880	0.029	14.1	3.1	1513.2	0.4	182.4	49.3	23910.5	14.8	7178.0
21/12/07	525	0.009	4.725	0.039	20.5	3.5	1858.5	0.5	253.1	39.8	20895.0	12.3	6457.5

Table B.4 Summary of EMCs and Loads obtained from simulated rain events for Asphalt pavement

Date	Runoff(L)	Zn		Cu		TN		TP		Oil		TSS	
		EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)
20/03/07	727.69	0.0005	0.364	0.085	61.9	0.4	312.9	0.3	181.9	599.0	435886.3	51.5	37483.3
22/03/07	692.8	0.002767	1.917	0.129	89.6	0.5	325.6	0.2	159.3	590.0	408752.0	102.2	70783.4
26/03/07	695.6	0.00675	4.695	0.023	15.7	1.8	1217.3	0.5	373.9	567.1	394474.8	108.0	75152.6
31/03/07	713.94	0.00875	6.247	0.030	21.4	0.7	499.8	0.6	419.4	602.2	429899.0	102.2	72936.1
2/04/07	624.37	0.04207	26.267	0.040	24.7	1.6	999.0	0.5	296.6	541.8	338252.4	135.0	84258.7
4/04/07	620.95	0.0588	36.512	0.075	46.6	3.1	1924.9	0.4	271.7	573.1	355866.4	103.8	64423.6
6/04/07	558.72	0.1337	74.701	0.053	29.6	5.2	2922.1	2.0	1124.7	648.8	362497.5	95.0	53078.4
11/04/07	454.16	0.0309	14.034	0.032	14.3	10.4	4723.3	1.1	514.3	612.3	278082.2	111.5	50638.8
13/04/07	531.96	0.1637	87.082	0.047	25.0	6.3	3367.3	1.6	872.4	589.2	313430.8	107.2	57026.1
16/04/07	530.04	0.42	222.617	0.033	17.5	1.5	811.0	0.4	215.7	519.6	275408.8	105.7	56025.2
18/04/07	500.97	0.35	175.340	0.070	35.1	1.6	801.6	0.4	190.4	605.2	303187.0	89.6	44886.9
23/04/07	473.07	0.48	227.074	0.056	26.5	3.6	1703.1	0.8	354.8	615.0	290938.1	98.6	46644.7
26/04/07	475.49	0.29	137.892	0.061	29.0	2.5	1188.7	1.2	570.6	563.0	267700.9	100.4	47739.2
30/04/07	465.32	0.375	174.495	0.049	22.8	6.0	2791.9	0.9	400.2	578.0	268955.0	104.3	48532.9

Table B.5 Summary of EMCs and Loads obtained from simulated rain events for C&M Ecotrihex pavement

Date	Runoff (L)	Zn		Cu		TN		TP		Oil		TSS	
		EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)
20/03/07	352.5	0.0002	0.071	0.066	23.3	0.6	211.5	0.3	103.3	43.9	15481.8	7.0	2460.5
22/03/07	287.8	0.00025	0.072	0.116	33.3	0.6	165.5	0.2	45.3	61.7	17742.9	8.9	2572.9
26/03/07	290.2	0.000802	0.233	0.015	4.4	2.4	696.5	0.2	48.6	52.5	15235.5	10.2	2965.8
31/03/07	348.4	0.00183	0.638	0.021	7.1	1.2	400.7	0.4	131.5	53.9	18771.8	11.8	4121.6
2/04/07	352	0.00235	0.827	0.027	9.4	0.9	325.6	0.4	124.1	58.0	20426.6	8.8	3097.6
4/04/07	350	0.00385	1.348	0.047	16.6	1.6	551.3	0.3	88.4	48.5	16985.5	10.5	3668.0
6/04/07	267	0.00497	1.327	0.036	9.6	2.0	542.8	0.7	198.4	58.6	15646.2	8.7	2320.2
11/04/07	212	0.003	0.636	0.020	4.2	4.2	883.4	0.7	150.0	54.3	11511.6	11.3	2395.6
13/04/07	269.5	0.0085	2.291	0.030	8.1	2.6	691.8	0.6	150.1	49.4	13313.3	9.6	2576.4
16/04/07	255.8	0.067	17.139	0.023	5.8	0.4	114.3	0.2	46.0	43.5	11127.3	11.5	2951.9
18/04/07	240.1	0.033	7.923	0.045	10.8	0.3	78.0	0.2	36.0	55.9	13421.6	8.2	1968.8
23/04/07	243	0.042	10.206	0.037	9.0	1.2	279.5	0.3	78.0	61.2	14871.6	10.2	2481.0
26/04/07	216.1	0.028	6.051	0.038	8.2	0.8	162.1	0.5	98.5	55.3	11950.3	8.2	1772.0
30/04/07	272.5	0.029	7.903	0.031	8.4	1.7	450.2	0.3	84.5	58.9	16050.3	8.3	2261.8

Table B.6 Summary of EMCs and Loads obtained from simulated rain events for Atlantis Turf Cell pavement

Date	Runoff (L)	Zn		Cu		TN		TP		Oil		TSS	
		EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)	EMC (mg/L)	Load (mg)
20/03/07	289	0.00065	0.1879	0.0440	12.7	1.3	388.1	0.3	89.6	31.2	9025.5	4.9	1424.8
22/03/07	260	0.0005	0.1300	0.0130	3.4	2.1	552.5	0.2	39.7	27.3	7085.0	7.5	1950.0
26/03/07	255	0.0011	0.2805	0.0120	3.1	2.5	637.5	0.3	72.7	23.2	5903.3	10.8	2764.2
31/03/07	300	0.001	0.3000	0.0154	4.6	0.7	219.0	0.4	117.8	25.6	7692.0	12.2	3651.0
2/04/07	255	0.0054	1.3770	0.0210	5.4	1.3	331.5	0.2	60.6	24.4	6209.3	7.2	1830.9
4/04/07	232	0.0015	0.3480	0.0370	8.6	3.0	696.0	0.3	70.2	27.2	6310.4	14.1	3259.6
6/04/07	245.4	0.00657	1.6123	0.0277	6.8	3.7	908.0	1.0	242.9	32.5	7975.5	10.6	2608.6
11/04/07	216	0.001386	0.2994	0.0150	3.2	5.9	1267.3	0.5	115.6	40.2	8683.2	13.7	2957.0
13/04/07	196.4	0.0128	2.5139	0.0200	3.9	3.8	746.3	1.0	192.5	28.7	5626.9	11.5	2258.6
16/04/07	194.8	0.0523	10.1880	0.0150	2.9	0.8	155.8	0.2	35.1	39.6	7714.1	13.3	2590.8
18/04/07	191.5	0.04	7.6600	0.0340	6.5	0.8	143.6	0.2	42.1	29.6	5668.4	9.6	1838.4
23/04/07	229.3	0.0578	13.2535	0.0290	6.6	1.5	348.5	0.4	96.3	24.3	5572.0	9.0	2054.5
26/04/07	175.5	0.021	3.6855	0.0250	4.4	1.0	179.0	0.7	114.1	31.2	5475.6	8.8	1535.6
30/04/07	219.4	0.04	8.7760	0.0240	5.3	2.5	555.1	0.4	92.1	35.4	7766.8	11.2	2457.3

APPENDIX C TRANSFER FUNCTIONS FOR MUSIC MODELS

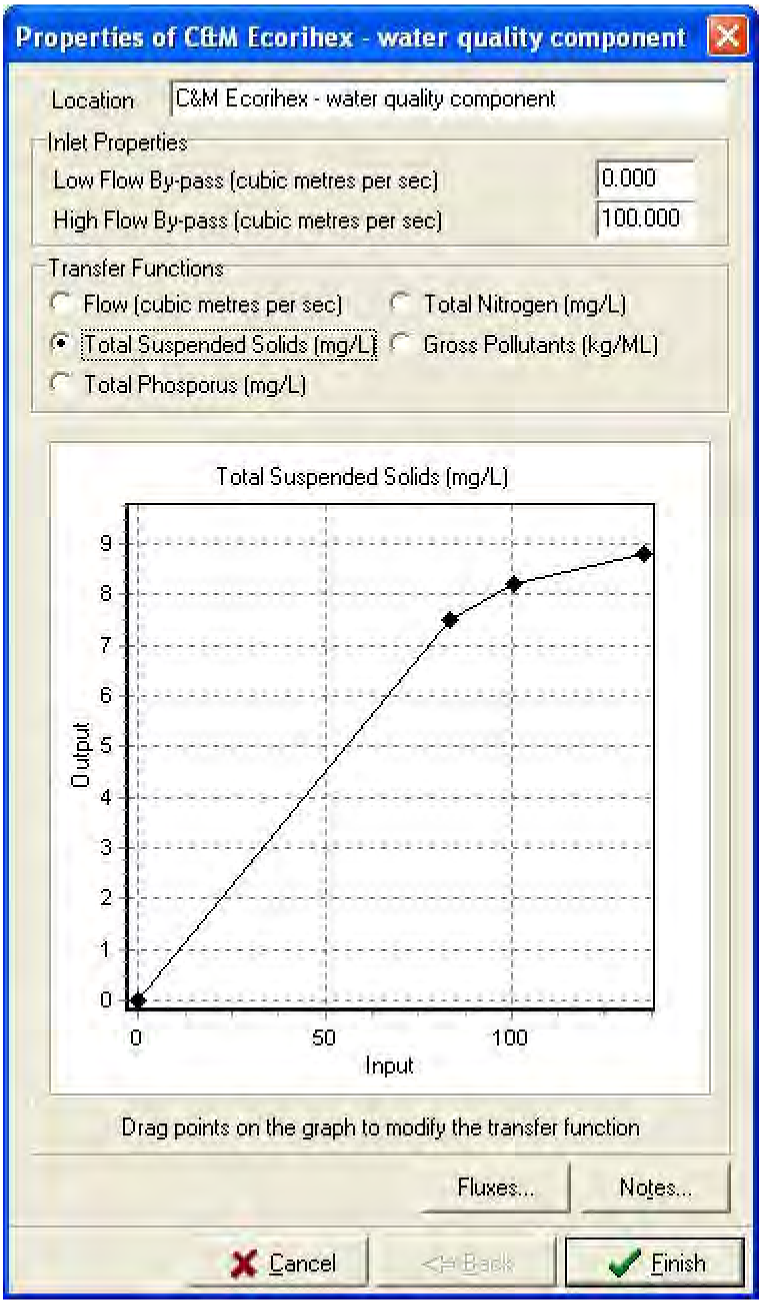

Figure C.1 Developed transfer function for TSS to be applied for a lined C&M Ecotrihex pavement system with an underdrain (FORMAT)

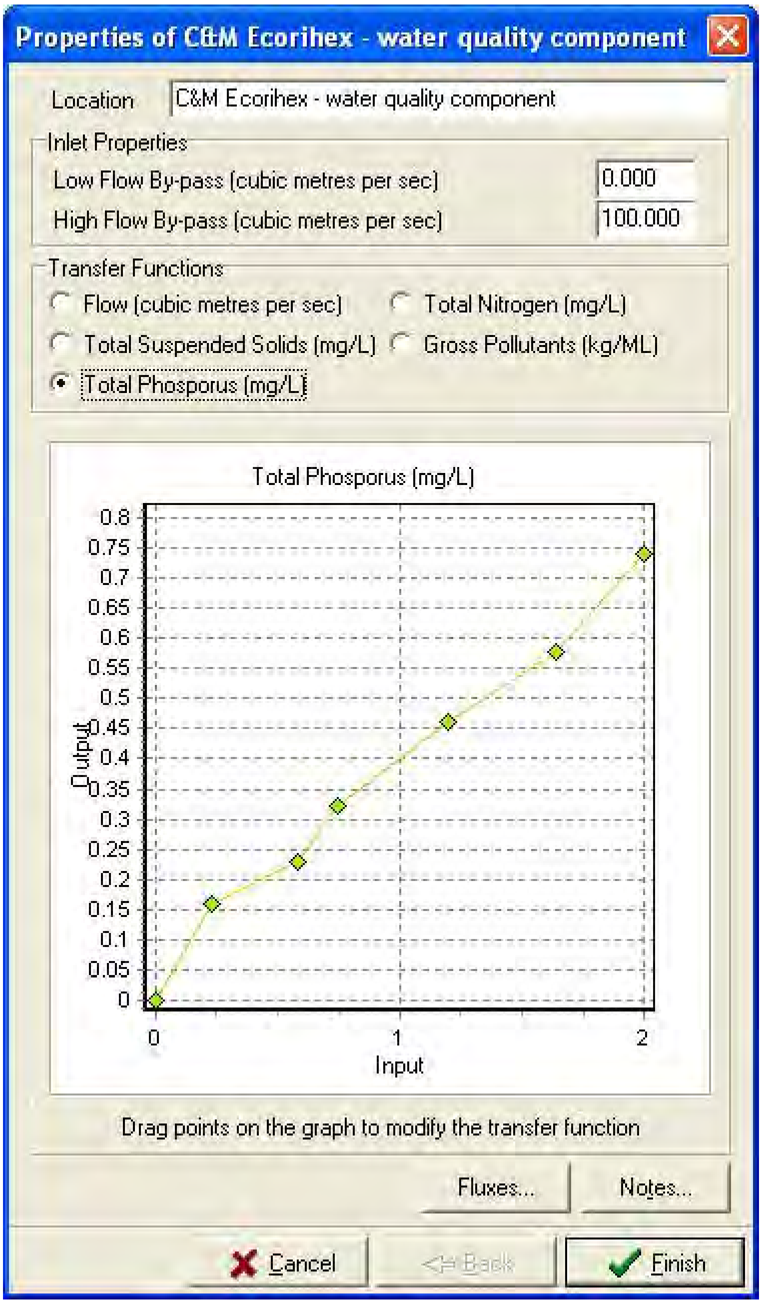

Figure C.2 Developed transfer function for TP to be applied for a lined C&M Ecotrihex pavement system with an underdrain

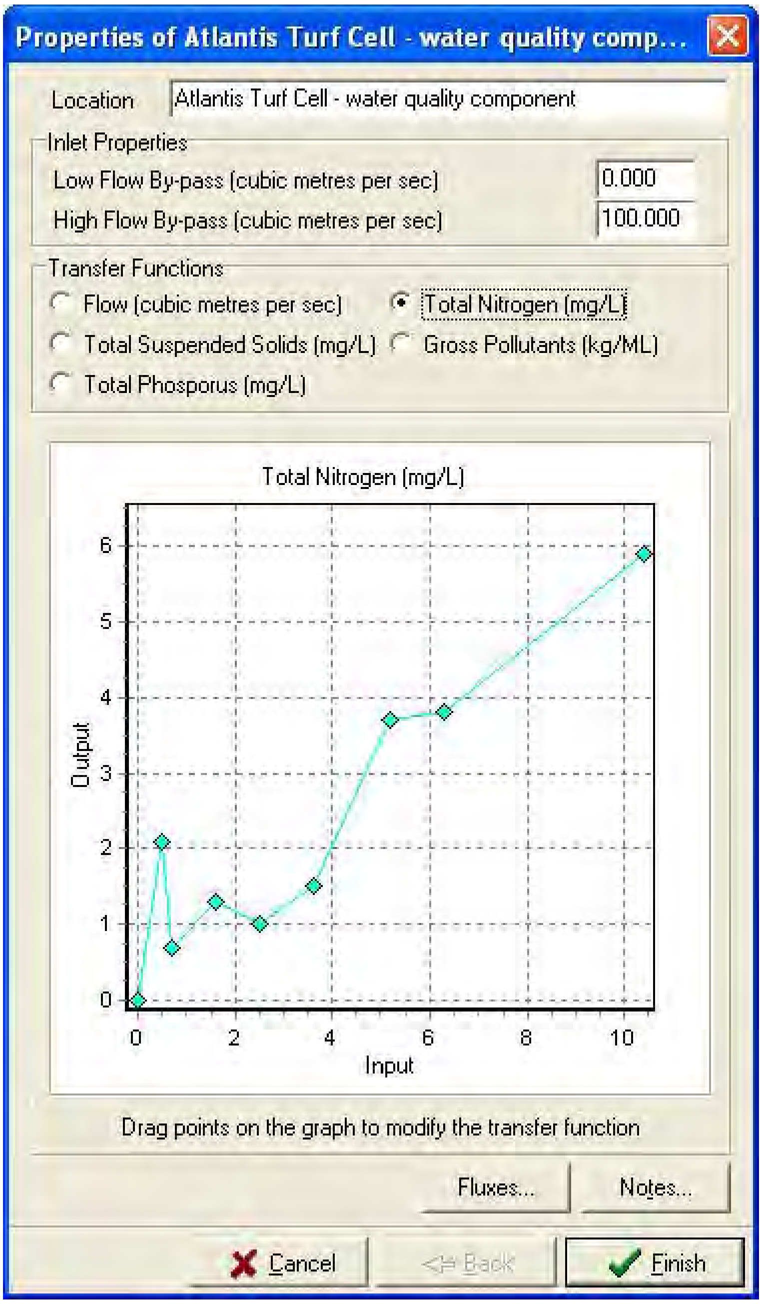

Figure C.3 Developed transfer function for TN to be applied for a lined Atlantis Turf Cell pavement system with an underdrain (format title. Can you get this as a smooth curve)

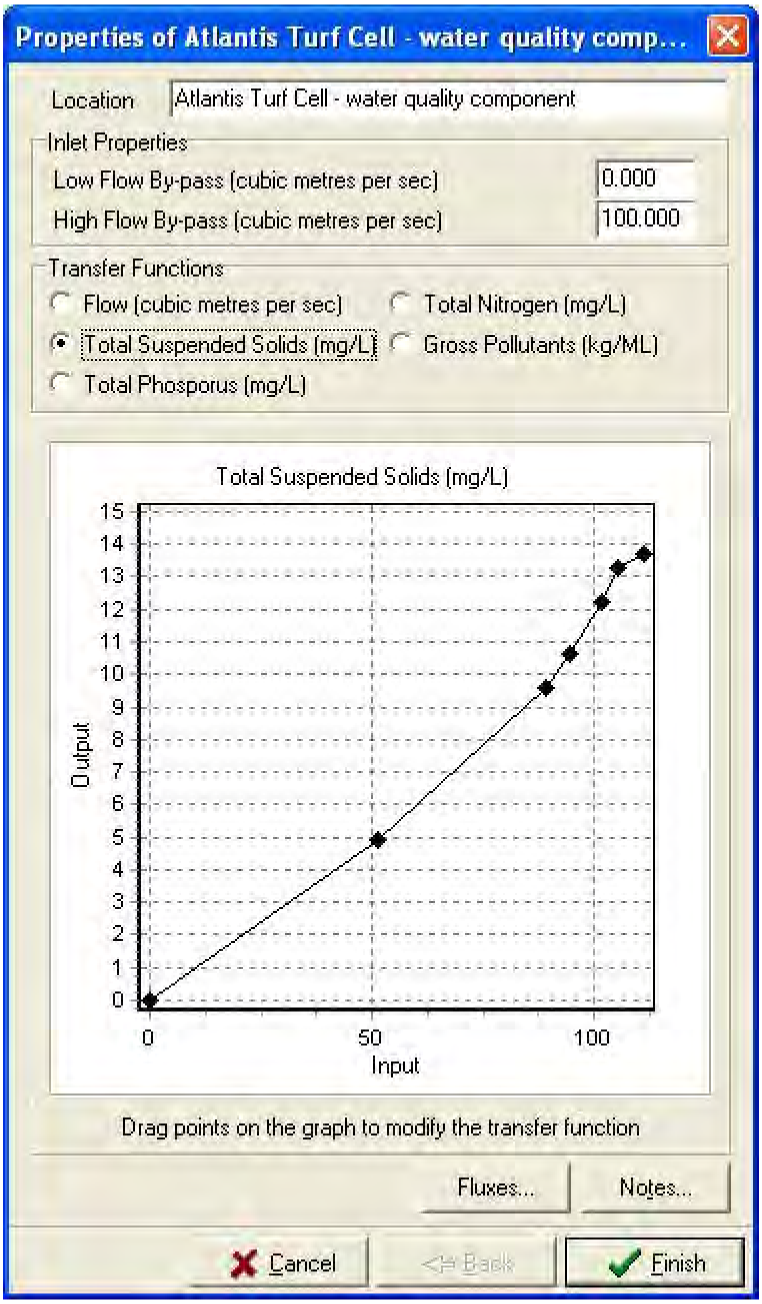

Figure C.4 Developed transfer function for TSS to be applied for a lined Atlantis Turf Cell pavement system with an underdrain

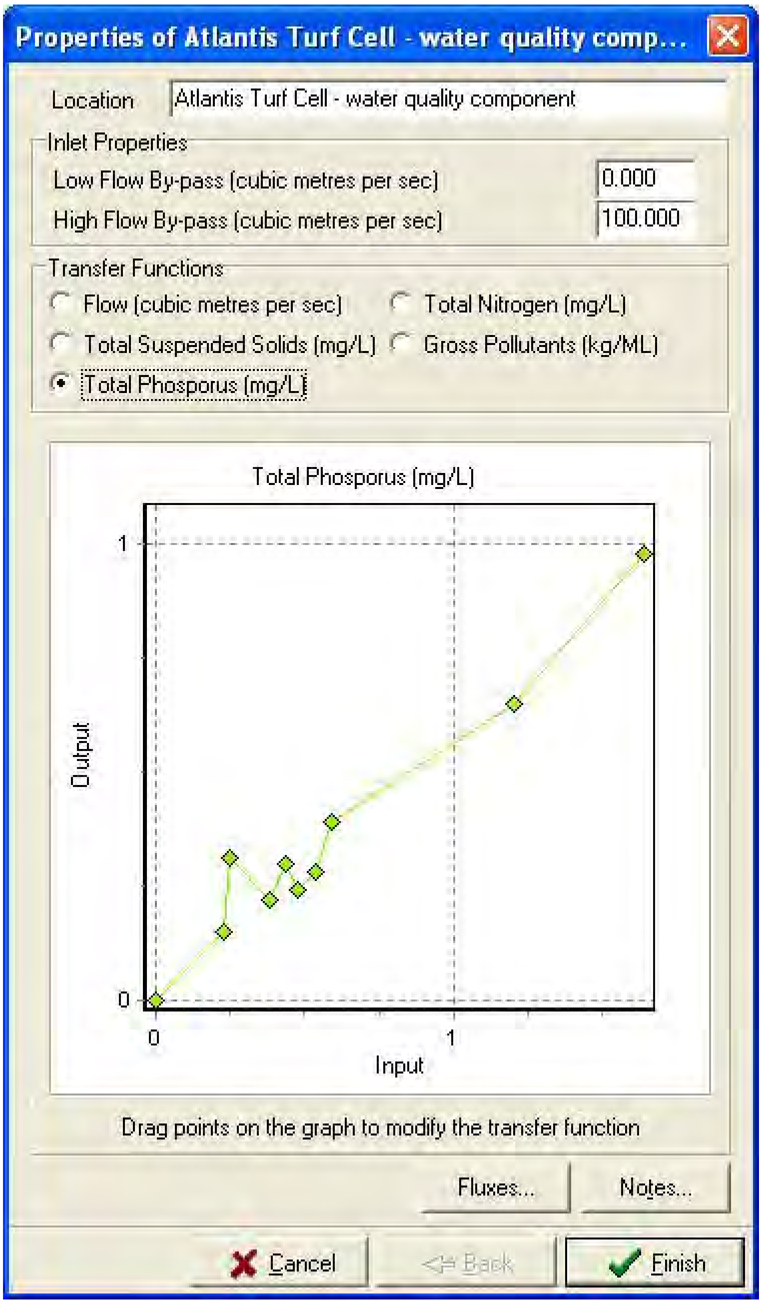

Figure C.5 Developed transfer function for TP to be applied for a lined Atlantis Turf Cell pavement system with an underdrain Same comment as in C3

APPENDIX D PUBLICATIONS

Jayasuriya N., Kadurupokune N., Othman M., Jesse K., (2007), 'Contributing to the sustainable use of stormwater: the role of pervious pavements'. Water Science & Technology Vol 56 No 12 pp 69–75 © IWA Publishing 2007.

Jayasuriya N., Kadurupokune N., Othman M., Jesse K., (2007), 'Managing Stormwater Productively Using Pervious Pavements', Proceedings of NOVATECH 2007 6th international conference on sustainable techniques and strategies in urban water management Lyon, France, June 25-28

Kadurupokune N., Jayasuriya N., (2007), **'**Field testing the effectiveness of pervious pavements as a water sensitive urban design initiative' Proceedings of Rainwater and Urban Design 2007, Sydney, Australia 21-23 August 2007