

UNIVERSITY OF CAPE TOWN

Department of Civil Engineering



THE IMPACT OF UNWASHED AGGREGATE ON THE QUALITY OF WATER EMANATING FROM PERMEABLE PAVEMENTS

Prepared by:

Benjamin Biggs

Supervised by:

Dr. Kevin Winter

Prof. Neil Armitage

July 2016

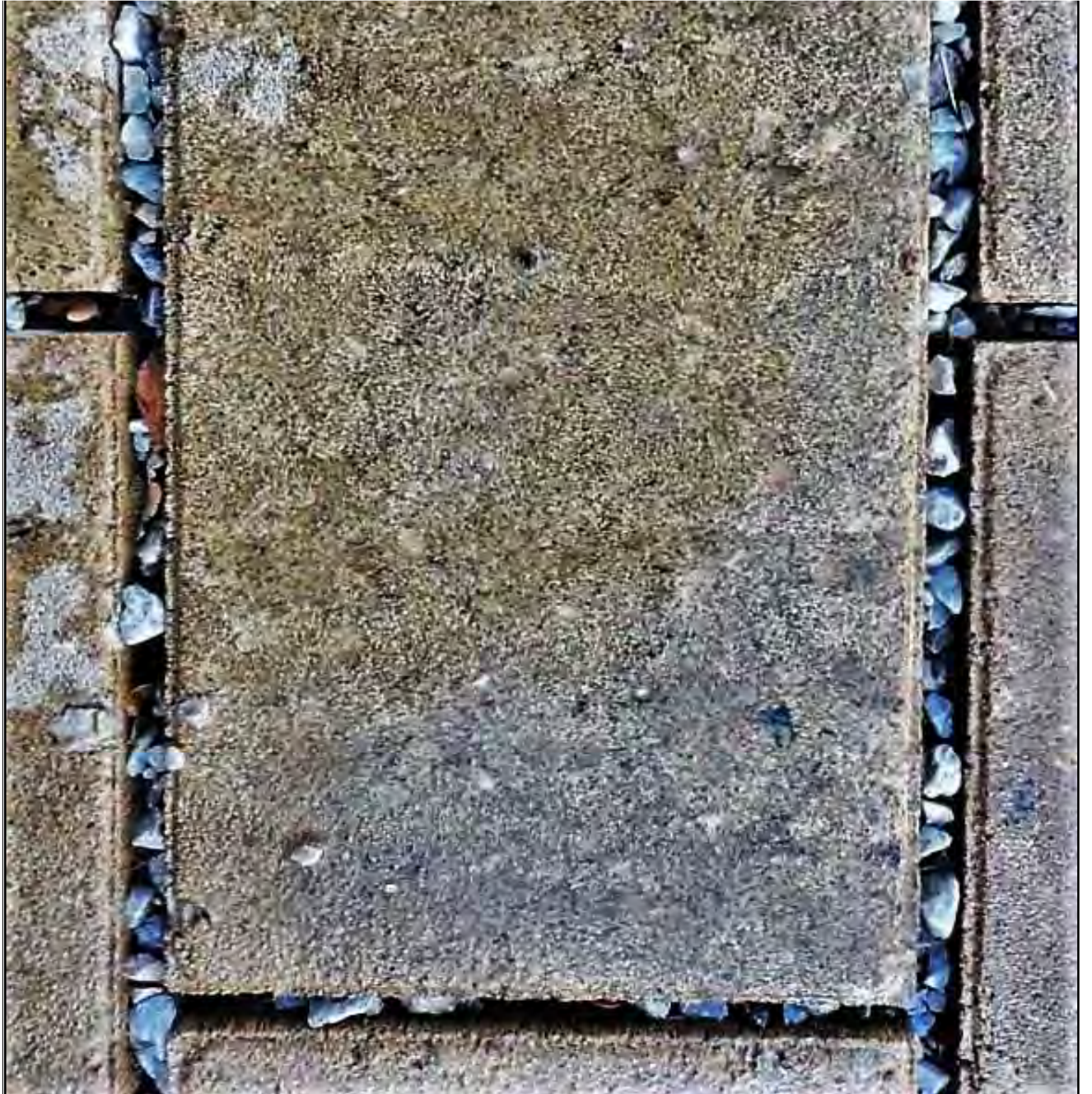
Dissertation submitted in partial fulfilment of the requirements for the degree of Master of Science in
Engineering in Civil Engineering (*MSc. Eng.*)

The copyright of this thesis vests in the author. No quotation from it or information derived from it is to be published without full acknowledgement of the source. The thesis is to be used for private study or non-commercial research purposes only.

Published by the University of Cape Town (UCT) in terms of the non-exclusive license granted to UCT by the author.



PERMEABLE PAVEMENTS



*'Let the wise hear and increase in learning
and the one who understands obtain guidance,
to understand a proverb and a saying,
the words of the wise and their riddles.
The fear of the Lord is the beginning of knowledge;
fools despise wisdom and instruction.'*

~ Proverbs 1:5-7

Declaration

This dissertation is prepared for the faculty of Engineering and Built Environment in partial fulfilment of the requirements for the degree of *Master of Science in Engineering in Civil Engineering*; as described in the Engineering and Built Environment Student Handbook (2016). This dissertation is a product of the Civil Engineering Department of the University of Cape Town.

I, Benjamin Biggs, know the meaning of plagiarism and declare that all the work in this dissertation, barring that which I have properly acknowledged, is my own.

Signed:

Signed by candidate

Date: 07/07/2016

Benjamin Biggs

Acknowledgments

The research project was funded by the **South African Water Research Commission (WRC)**. The **Harry Crossley Foundation Research Fellowship** and the **National Research Fund** funded me personally. I thank these three organisations for their generous and patient financial assistance which gave me financial stability for the duration of my project. I also thankfully acknowledge the following people for input and assistance over the course of this dissertation:

Professor Kevin Winter, my supervisor, provided me with the idea and motivation to commence this journey. I am sincerely grateful for his continued belief, enthusiasm, encouragement and guidance along the way.

Professor Neil Armitage, my supervisor, for his guidance and dedication to excellence over the course of my dissertation. Being a member of the Urban Water Management research group allowed me the opportunity to gain wider experience and to take part in other research projects.

Kirsty Carden, the WRC research leader, overseeing the WRC K5/2409 project: ‘An investigation of the treatment efficacy of permeable pavements with a view to harvesting stormwater for use in South Africa’, for always being warm and positive and for setting aside time to discuss project challenges.

Lloyd Fisher-Jeffes for his helpful insights and willingness to shed light on project challenges.

Peter Wium for his guidance and efforts in providing me with information and guidance. I commend him on his humble disposition and approachability.

My family: My mother **Margie**, my father **Tim**, two brothers, **Sam and Jonathan** and to my sister, **Keetah**, for their emotional, spiritual and moral support throughout my academic career, and also for their endless love, patience, encouragement and prayers. Thank you for helping me with this dissertation, always giving freely of your ideas, your time and skills whenever it was requested.

Nooredien Hassen, Tahir Mukaddam, Hector Mafungwa, Charles May, Charles May and Elvino Witbooi for their assistance in the laboratory and the interesting conversations I enjoyed while working.

Claire Lawrence-Naidoo for allowing me to use the chemistry labs to conduct water quality tests.

Ultimately, I give all the glory to the **Lord God Almighty**.

~

‘Blessed are You, Lord our God, King of the universe, Who has kept us alive, sustained us, and enabled us to reach this season.’

Abstract

Sustainable Drainage System (SuDS) technologies set out to mitigate the adverse effects of urban stormwater runoff, through a multi-objective approach. Permeable pavement systems (PPSs) are one of the most widely-adopted SuDS technologies in South Africa. South Africa is a water scarce country and the sustainable provision of water to its citizens is one of the most significant challenges facing the country. The demand on the potable water supply system could potentially be alleviated by substituting stormwater for potable water in a 'fit for purpose' manner. A Water Research Commission (WRC) pilot study is attempting to provide locally-relevant data on the treatment efficacy of PPS for possible use in stormwater collection, treatment and storage. A laboratory experiment comprising four separate units was set up to determine the capability of various different PPS designs to reduce selected pollutants from stormwater for South African conditions. Permeable concrete block pavers of the type commonly used in the City of Cape Town (CoCT) area were laid over four different layer-work options, one in each unit, using aggregate largely collected from stockpiles used to construct a nearby PPS in a parking area at the University of Cape Town.

In the first phase of the experiment – the 'flushing phase' – clean tap water was applied to each unit over a period of time in quantities roughly representative of a typical rainy season in the CoCT and the discharge was collected and analysed. The measured parameters included: orthophosphate, ammonia, suspended solids, pH and conductivity. After the initial approach proved insufficient for flushing purposes, an accelerated flushing process was then implemented to prepare, as far as reasonably possible, the unwashed in-situ aggregate for the next phase of testing. The second phase examined the pollutant retention capacity of each PPS by comparing the concentrations of various pollutants before and after treatment. However, due to the unforeseen delayed release of the pollutants from the aggregate, the attempted flushing of the in-situ stone again proved insufficient for flushing purposes. The pollutants continued leaching into the effluent showing an excess of the flushing volumes applied and thus the treatment efficacy results after the accelerated flushing were contaminated. Nonetheless, these findings provide useful insights for stormwater practitioners and indicated that failure to adhere to accepted international practice with respect to the washing of the aggregate prior to construction and the prevention of the ingress of dirt into the pavement layers during construction, have an adverse impact on the treatment performance of PPS. Therefore, the selection of base materials, in particular, the use of unwashed aggregate and the variation of the treatment layers and the layer material, affect the treatment performance of the permeable paving system and can pollute storm runoff passing through the PPS substantially for an extended period of time. Further research is needed to: determine suitable flushing methods when PPS are constructed with unwashed aggregate; and conduct additional laboratory testing using pre-washed stone to assess treatment efficacy of design variations. Thereafter, suitable fit-for-purpose applications for the treated effluent can be recommended.

Keywords: Permeable pavement, stormwater harvesting, Sustainable Drainage System (SuDS), treatment efficacy, pollutant retention, fit for purpose, South Africa, unwashed aggregate.

Table of Contents

Declaration	i
Acknowledgments	ii
Abstract	iii
Table of Contents	iv
List of Figures	viii
List of Tables	xii
Glossary of Terms	xiii
Acronyms & Abbreviations	xviii
1. Introduction	1-1
1.1 Background and motivation	1-1
1.2 Problem statement	1-2
1.3 Study aims	1-2
1.4 Method	1-3
1.5 Scope and limitations	1-3
1.6 Chapter Outline	1-4
2. Literature Review	2-1
2.1 Introduction	2-1
2.2 Context within urbanisation and associated water challenges	2-1
2.3 Urban stormwater	2-1
2.3.1 Stormwater pollution	2-2
2.3.2 Characterisation of stormwater	2-3
2.4 Sustainable Drainage Systems (SuDS)	2-4
2.5 Permeable pavement systems (PPSs)	2-8
2.5.1 PPS design	2-10
2.5.2 Costs	2-14
2.5.3 PPS structure and construction	2-16
2.5.4 Assessing performance of PPS	2-18
2.5.5 Hydraulic and hydrological features	2-20
2.5.6 Treatment and pollutant removal	2-22
2.5.7 Clogging	2-28
2.5.8 Maintenance	2-30
2.5.9 Geotextiles	2-32
2.5.10 Observations concerning PPS case studies in South Africa	2-33
2.5.11 Advantages / benefits of PPS	2-34
2.5.12 Disadvantages / costs of PPS	2-34
2.6 Summary and conclusions	2-35

3.	Research method	3-1
3.1	Introduction	3-1
3.2	Laboratory experimental design and methodology	3-1
3.2.1	Experimental apparatus	3-2
3.2.2	Selection of surface wearing course and pavement materials	3-4
3.2.3	Laboratory testing - construction considerations	3-7
3.2.4	Design stormwater	3-8
3.2.5	Assessment of stormwater quality for ‘fit for purpose’ use	3-8
3.2.6	System flushing	3-10
3.2.7	Testing the treatment efficacy of the PPS	3-15
3.2.8	Experimental sampling	3-23
3.2.9	Assessment tools	3-25
3.3	Laboratory pavement disassembly	3-27
3.4	Summary	3-27
4.	Results and analysis	4-1
4.1	Laboratory experiment – pavement flushing process	4-1
4.1.1	Orthophosphate	4-2
4.1.2	Ammonia nitrogen	4-3
4.1.3	Nitrate	4-4
4.1.4	TSS and turbidity	4-5
4.1.5	EC	4-7
4.1.6	Leaching period	4-8
4.2	Laboratory experiment – pollutant addition process	4-10
4.2.1	Orthophosphate	4-11
4.2.2	Ammonia nitrogen	4-12
4.2.3	Nitrate	4-14
4.2.4	TSS and turbidity	4-15
4.3	Laboratory pavement disassembly	4-17
4.3.1	Observations common to each pavement during excavation	4-18
4.3.2	Pavement A – ‘no geotextile’	4-18
4.3.3	Pavement B – ‘standard’, and Pavement C – ‘no small’ stone	4-19
4.3.4	Pavement D – ‘sand’	4-21
4.4	Summary	4-24
5.	Conclusions and recommendations	5-1
5.1	Conclusions	5-1
5.1.1	Observations from laboratory experiment pavement flushing	5-1
5.1.2	Observations from laboratory experiment pollutant addition process	5-2
5.1.3	Overall findings	5-2

5.2	Recommendations	5-2
5.2.1	Recommendations for implementation and management of PPS	5-2
5.2.2	Recommendations for future research	5-3

References **R-1**

Appendix A: Urbanisation and emerging water Challenges

A1.	Urbanisation	A-1
A2.	Emerging urban water challenges	A-2
A2.1	Water demand increases	A-3
A2.2	The quality and quantity of available water supply	A-4
A2.3	Climate variability and future considerations	A-5
A2.4	Alternative water sources	A-5

Appendix B: Stormwater management: past, present and looking forward

B1.	Urban stormwater	B-1
B2.	Stormwater management historically	B-1
B3.	Conventional Separated Drainage Systems	B-2
B4.	The need for alternative stormwater management systems	B-3
B5.	‘Sustainability’ and ‘Sustainable development’ defined	B-8
B6.	Overview of Sustainable Drainage Systems (SuDS)	B-9
B7.	A brief legal context for stormwater management in South Africa	B-12
B8.	Positive impacts of SuDS	B-12

Appendix C: Rainfall data

Appendix D: New Engineering Building parking area

D1.	New Engineering Building (NEB) parking area	D-1
D2.	NEB parking area site description	D-1
D3.	NEB monitoring chamber design and placement	D-4
D4.	Lessons learnt from construction of NEB PPS	D-9
D4.1	Inbitex geotextile	D-9
D4.2	Deposition of dust and fines on pavement	D-9
D4.4	Failed embankment causing pavement failure	D-11
D5.	NEB Site Monitoring	D-12
D5.1	NEB monitoring site preparation and installation	D-12
D5.2	NEB field sampling	D-13
D6.	Data analysis	D-14
D6.1	Rainfall analysis	D-14

D6.2 Observations from NEB site	D-14
D6.3 Water quality monitoring in the field study	D-15
D7. Observations from NEB site	D-15

Appendix E: Assessment of ethics in research projects form

List of Figures

Figure 2-1	The SuDS Stormwater design hierarchy	2-4
Figure 2-2	The SuDS treatment-train	2-6
Figure 2-3	Pervious Concrete	2-9
Figure 2-4	Porous Asphalt	2-9
Figure 2-5	Porous surfaces: (a) Normal and porous asphalt; b) Porous concrete	2-11
Figure 2-6	Permeable interlocking concrete pavers	2-11
Figure 2-7	Alternative PPS designs with differing boundary conditions: (a) partial infiltration, (b) total infiltration and (c) no infiltration	2-13
Figure 2-8	Typical sump and pump layout for water harvesting	2-14
Figure 2-9	PPS underdrain installation in conjunction with an impermeable lining	2-15
Figure 2-10	Example of a typical PPS cross-section	2-17
Figure 2-11	Monitoring stormwater processes	2-19
Figure 2-12	Double-ring infiltrometer (left); Simple infiltration test (right)	2-20
Figure 2-13	Hydrology and hydraulic features of permeable pavements	2-21
Figure 2-14	Treatment process involved with PPS	2-25
Figure 2-15	Concept of pavement clogging	2-29
Figure 2-16	Surface ponding on a section PPS indicating pavement failure	2-29
Figure 2-17	Various street sweeping techniques	2-31
Figure 2-18	Soil embankment located adjacent a PPS causing surface clogging	2-32
Figure 3-1	Typical Aquaflow infiltration system subject to light vehicle activity	3-2
Figure 3-2	Bins positioned on concrete blocks to accommodate drainage tray	3-3
Figure 3-3	The underdrain system for the PPS model	3-3
Figure 3-4	Cross section through a typical permeable pavement testing structure	3-4
Figure 3-5	Aquaflow block® dimensions	3-5
Figure 3-6	Four pavement designs with varying base layers	3-6

Figure 3-7	Permeable demonstration pavement illustrated in plan and elevation	3-11
Figure 3-8	Impermeable demonstration pavement illustrated in plan and elevation	3-11
Figure 3-9	Sample collection intervals throughout the flushing process	3-14
Figure 3-10	Oil application to laboratory pavement surfaces	3-19
Figure 3-11	EMC Sample collection points throughout the pollutant addition process	3-23
Figure 3-12	First flush sample collection points throughout the pollutant addition process	3-23
Figure 4-1	Orthophosphate concentrations in drainage from pavements compared with potable tap water and design storm runoff concentrations	4-2
Figure 4-2	Drained ammonia nitrogen concentrations compared with potable tap water and design storm runoff concentrations	4-3
Figure 4-3	Drained nitrate concentrations compared with potable tap water and design storm runoff concentrations	4-4
Figure 4-4	Drained nitrate concentrations (without Rig A spikes) compared with potable tap water and design storm runoff concentrations	4-5
Figure 4-5	Drained TSS concentrations compared with potable tap water and design storm runoff concentrations	4-6
Figure 4-6	Drained turbidity concentrations compared with potable tap water and design storm runoff concentrations	4-7
Figure 4-7	Drained conductivity levels compared with potable tap water and design storm runoff concentrations	4-8
Figure 4-8	Extrapolated trend lines for TSS concentrations drained from pavement	4-9
Figure 4-9	Extrapolated trend lines for Ammonia concentrations drained from each pavement	4-10
Figure 4-10	Orthophosphate first flush and influent concentrations for each PPS design	4-11
Figure 4-11	Orthophosphate EMCs and influent concentrations for each PPS design	4-12
Figure 4-12	Ammonia first flush and influent concentrations for each PPS design	4-13

Figure 4-13	Ammonia EMCs and influent concentrations for each PPS design	4-13
Figure 4-14	Nitrate first flush and influent concentrations for each PPS design	4-14
Figure 4-15	Nitrate EMCs and influent concentrations for each PPS design	4-15
Figure 4-16	TSS influent, first flush (left) and EMC (right) concentrations for each PPS design	4-16
Figure 4-17	Turbidity influent, first flush (left) and EMC (right) concentrations for each PPS design	4-16
Figure 4-18	Pavement excavation documenting the internal condition of each structure	4-17
Figure 4-19	Oil stain on the bedding layer directly below the pavers	4-18
Figure 4-20	Early stages of the excavation of Pavement A where large amounts of 'dust' were found adhering to the bedding gravel	4-19
Figure 4-21	Sediment observed at different depths within Pavement A: (a) 'upper' base 19-25mm aggregate layer; (b) bottom of the 'lower' base 50-63mm aggregate layer; (c) profile of the excavation	4-20
Figure 4-22	Excavation of Pavement B revealing the condition of the Inbitex ® geotextile	4-21
Figure 4-23	Sediment observed at different depths within Pavement B: (a) profile of the excavation; (b) bottom of the 'lower' base 50-63mm aggregate layer	4-21
Figure 4-24	Sediment observed at different depths within Pavement C: (a) bottom of the 'lower' base 50-63mm aggregate layer	4-22
Figure 4-25	Excavation of the Inbitex ® geotextile below the bedding sand	4-23
	Sediment observed at different depths within Pavement D	4-24
Figure A-1	Second wave of urbanisation	A-1
Figure A-2	Trend in urbanisation in Sub-Saharan Africa	A-2
Figure A-3	South Africa's increasing gap between water demand and supply Second wave of urbanisation	A-3
Figure A-4	Increase in Annual Water Demand (2005 to 2030) Trend in urbanisation in Sub-Saharan Africa	A-4
Figure A-5	Increased Frequency and Impact of Reported Disasters in Africa	A-6
Figure A-6	Increase in Annual Water Demand (2005 to 2030)	A-7

Figure B-1	Typical pre- and post-development scenarios with the conventional approach to stormwater management	B-4
Figure B-2	Typical hydrograph associated with pre- and post-development with the conventional approach to stormwater management	B-5
Figure B-3	Integration of urban water cycle components	B-7
Figure B-4	Urban water management transition framework	B-8
Figure B-5	The Stormwater design hierarchy	B-10
Figure B-6	The SuDS treatment-train	B-11
Figure D-1	Monitoring schematic of the NEB PPSThe SuDS treatment-train	D-2
Figure D-2	NEB permeable pavement layerworks (scale 1:10)	D-2
Figure D-3	NEB permeable pavement underdrain detail (scale 1:10)Monitoring schematic of the NEB PPS	D-3
Figure D-4	Excavation of monitoring chamber B down to the existing stormwater pipeNEB permeable pavement layerworks (scale 1:10)	D-5
Figure D-5	Construction of NEB parking area monitoring chambersNEB permeable pavement underdrain detail (scale 1:10)	D-6
Figure D-6	Diagram showing in section (a) and plan (b) the proposed design for monitoring chamber AExcavation of monitoring chamber B down to the existing stormwater pipe	D-7
Figure D-7	Diagram showing in section (a) and plan (b) the proposed design for the drawpit - labelled as chamber DConstruction of NEB parking area monitoring chambers	D-8
Figure D-8	Clearing of rubble with heavy machinery adjacent to sub-base stone layerDiagram showing in section (a) and plan (b) the proposed design for monitoring chamber A	D-10
Figure D-9	Potential clogging risks are intensified by heavy machinery useDiagram showing in section (a) and plan (b) the proposed design for the drawpit - labelled as chamber D	D-11
Figure D-10	Start of the second stage of constructionClearing of rubble with heavy machinery adjacent to sub-base stone layer	D-11
Figure D-11	Failed embankment on the site causing pollution of the pavement	D-12

List of Tables

Table 2-1	Pollutant concentrations for various land uses	2-5
Table 2-2	SuDS options comprising the ‘treatment train’	2-7
Table 2-3	Capital cost comparison for the Pietermaritzburg Cathedral parking lot	2-16
Table 2-4	Measured pollutant removal capacities of selected local control SuDS options	2-23
Table 2-5	Effect of media characteristics and water chemistry	2-26
Table 3-1	Two iterations measuring the drainage times and volumes for each bin	3-7
Table 3-2	Design stormwater quality	3-9
Table 3-3	Monthly rainfall data (2002) and average monthly rainfall from 1960-2002	3-13
Table 3-4	Proposed laboratory rainfall schedule for ‘flushing’ the system	3-13
Table 3-5	Soluble fertilizer nutrient ratios	3-17
Table 3-6	Design stormwater quality ratios as characterised in Section 3.2.4	3-17
Table 3-7	Conditions of artificial rainfall	3-20
Table 3-8	Sampling regime for each event during the treatment efficacy process	3-22
Table 3-9	SASS5 categories for the river health programme	3-26
Table 3-10	Ecosystem health criteria: categories	3-26
Table 4-1	Predicted rainfall depths (derived from drainage volumes) required by the lab PPS for TSS and ammonia leaching stabilisation	4-9
Table B-1	SuDS options comprising the ‘treatment train’	B-13
Table C-1	Monthly rainfall data for the Cape Town International Airport	C-1
Table C-2	Daily rainfall data in 2002 (mm) recorded at Cape Town International Airport	C-2

Glossary of Terms

This glossary contains stormwater management and engineering related terms that are used throughout the dissertation. Terms used differently from those stipulated in the glossary will be defined specifically in the context in which used. The sources utilised for the compilation of this glossary include: CSIR (2000), Debo & Reese (2003), Roads and Stormwater Department (2009) and Woods-Ballard et al. (2007).

Absorption is the incorporation of a substance in one state into another of a different state and refers to the taking up of one substance into the body of another.

Adsorption is the physical adherence or adhesion or bonding of a chemical species (ion and molecules) onto the surface of particles.

Attenuation is the reduction of peak stormwater flow.

Bioretention area is a depressed landscaping area that collects stormwater runoff resulting in infiltration into the soil below the area into an underdrain, thus initiating pollutant removal.

Block paver is a flexible modular unit the size of a precast concrete or clay brick.

Catchment is the area from which any rainfall will drain into a watercourse or wetland, through surface flow to a common point or common points.

Channel is a natural or artificial watercourse through which a body of water flows periodically or continuously or forms connecting links between other bodies of water.

Climate Change is a continuous phenomenon and refers to the change in global climatic conditions, e.g. as a result of temperature increases due to anthropogenic emissions.

Contamination refers to the introduction of microorganisms, factory produced chemicals, or wastewater in concentrations that render water unsuitable for most human uses.

Degradation refers to the general and progressive lessening of stream or channel profiles, or earth's surface, due to long-term periods of water induced erosion and/or scour.

Depression storage refers to precipitation stored in surface depressions.

Design period is the length of time a structure or asset will be expected to be safely usable, or the period of time for accounting purposes that the structure will depreciated over.

Design storm encompasses the properties of a selected storm, which includes the depth, spread and duration of the rainfall as well as variations in rainfall intensity in space and time over the catchment area during the storm.

Detention pond is a depression that is ordinarily dry, but following larger storm events it will store stormwater temporarily, attenuating flows. It may facilitate infiltration of stormwater into the ground.

Development refers to any man-made change to property, including but not limited to construction, upgrade of structures, paving and municipal infrastructure.

Drainage is commonly referred to as one of the following four: (1) the removal of excess groundwater or surface water by gravity or pumping, (2) the behaviour of water in removal from an area, (3) the area from which water bodies are removed, or (4) the general flow of all liquids under the force of gravity.

Drainage area is that part of a catchment above a specified point that contributes to the runoff to that point.

Drainage system refers to a network of drains, hydraulic control structures, levees, and pumping mechanisms that drain land or protect it from potential flooding.

Effluent is wastewater that flows from a process or storage area that has been partially or completely treated.

Evapotranspiration means the evaporation from all water, soil, snow, ice, vegetation and other surfaces plus transpiration of moisture from the surface membranes of leaves and other plant surfaces.

Event probability is the probability of a particular threshold being equalled or exceeded in any particular rainfall event.

Exfiltration is the process by which infiltrated flow is conveyed from a drainage structure to the surrounding soil, often via an underdrain.

Filtration, means the filtering of stormwater runoff pollutants that are conveyed with sediment by trapping these constituents on vegetative species, in the soil matrix or on geotextiles.

Flood means a temporary rise in water level, including ground water or overflow of water onto land not normally covered by water.

Geotextile is a textile or plastic fabric designed to separate different fill materials, which is normally relatively permeable.

Greenfield means a site or land such as parkland, open space and agricultural land which has previously been undeveloped.

Green roof is roof on which plants and vegetation can grow. The vegetated surface provides a degree of retention, attenuation, temperature insulation and treatment of rainwater.

Hydrograph is a plot of discharge or runoff relative to time.

Hydrology refers to the physical, chemical and physiological sciences of the water bodies of the earth and the interaction to the life thereon, which includes: occurrence, distribution, circulation, precipitation, surface runoff, stream-flow, infiltration, storage and evaporation.

Impervious surface is land where water cannot infiltrate into the subsurface but is conducted by gravity on the surface as overland flow. Roads, parking lots, sidewalks and rooftops are examples of impervious surfaces in urban areas.

Infiltration in the hydrological sense is the downward movement of water into soil. It is a complex process of allowing runoff to penetrate the Earth's surface and flow through the upper soil surface.

Infiltration device is a SuDS element designed to aid infiltration of surface water to the ground.

Infiltration trench is a trench that is usually filled with granular material, designed to promote infiltration of surface water to the ground.

Ion exchange is an exchange of ions between two electrolytes or between an electrolyte solution and a complex.

Long-term storage is the volumetric control of stormwater runoff in a specified infiltrating area that will drain very slowly.

Major drainage system is a stormwater drainage system which caters for severe, infrequent storm events, to prevent fatalities and minimise damage to property.

Minor drainage system is a stormwater drainage system which caters for frequent storms of a minor nature, to minimise inconveniences.

Non-structural measures are planning, institutional and pollution prevention practices designed to prevent or minimise pollutants from entering stormwater runoff and/or reduce the volume of stormwater requiring management.

Peak discharge (also known as 'peak flow') is the maximum rate of flow of water passing a given point during or after a rainfall event.

Percolation is the process of a liquid slowly passing through a filter.

Permeability refers to the ability of a material to allow water to flow through when fully saturated and subjected to an unbalanced pressure.

Permeable pavement system is the collective term comprising porous pavements – pavements with a monolithic surface constructed from porous materials e.g. porous asphalt or porous concrete, and pervious pavements – pavements with modular paving blocks (MPBs) that allow water through gaps, usually a concrete paver or cellular grid that is filled with dirt, sand, or gravel

Porous asphalt is an asphalt surface that is used to make pavement layers pervious, with open voids to allow water to pass through.

Porous concrete is a concrete surface that is used to make pavement layers pervious, with open voids to allow water to pass through.

Precipitation is the water received from atmospheric moisture as rainfall, hail, snow or sleet, normally measured in millimetres according to depth.

Rainwater harvesting is the direct capture of stormwater runoff, typically off rooftops, for supplementary water uses onsite.

Receiving waters are natural or man-made aquatic systems which receive stormwater runoff e.g. watercourses, wetlands, canals, estuaries, groundwater and coastal areas.

Responsible person means the person whose act or omission caused, or contributed to, an emergency incident and, if the incident occurred in the course of that person's employment, his or her employer.

Retention pond is a pond-like structure where runoff is detained for a sufficient time to allow settlement and possibly biological treatment of some pollutants.

Retrofitting means the process of modification or installation of additional or alternative stormwater management devices or approaches in an existing developed area in order to achieve best management of stormwater.

Return period is the average time interval of hydrological event occurrences of a given or greater magnitude. The interval is normally expressed in years.

Runoff generally refers to the excess water that flows after precipitation.

Sedimentation is the deposition of soil particles that have been carried by flowing waters, typically during flood peaks, as a consequence of a decrease in the velocity of flow below the minimum transportation velocity.

Soakaway is a subsurface structure that is designed to promote infiltration into the ground.

Sorption, a general term that includes absorption, adsorption and ion exchange, is a physical and chemical process by which one substance becomes attached to another.

Source controls are non-structural or structural best management practices to minimise the generation of excessive stormwater runoff and/or pollution of stormwater at or near the source.

Stormwater is water resulting from natural precipitation and/or accumulation and includes rainwater, groundwater and spring water.

Stormwater attenuation pond is a facility which temporarily stores excess stormwater runoff with the intention of reducing the flood peak.

Stormwater outfall is the point at which runoff discharges from a conduit.

Stormwater runoff refers to the portion of rainfall which flows to the surface drainage system.

Stormwater system is constituted by both the constructed and natural facilities, including stormwater pipes, canals, culverts, overland escape routes, 'vleis', wetlands, dams, lakes, and other watercourses, whether over or under public or privately owned land, used or required for the management, collection, conveyance, temporary storage, control, monitoring, treatment, use and disposal of stormwater.

Structural measures/controls are permanent, engineered devices implemented to control, treat or prevent stormwater pollution and/or reduce the volume of stormwater that requires management.

Subdrain or underdrain is generally a drain-type structure that is implemented beneath lined conduits such as sewers, stormwater networks, canals, or roadways, to manage groundwater flows in order to mitigate potential damage to property.

Subsurface runoff is the flow derived from water infiltrating the soil and flowing laterally in the upper soil strata. It usually reaches the receiving streams or bodies of water fairly soon after a rainfall event without joining the main body of groundwater (referred to as 'interflow').

SuDS is the abbreviation for sustainable drainage systems or sustainable (urban) drainage systems, which are individual or sequential management practices and/or control structures or technologies designed to drain surface water in a more sustainable manner than conventional techniques.

Surface runoff is that part of the runoff that travels over the ground surface and in channels to reach the receiving streams or bodies of water.

Sustainable development means development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Swale is a shallow vegetated channel designed to conduct and retain water, but may also permit infiltration. The vegetation assists in filtering particulate matter.

Treatment train is a combination of different methods implemented in sequence or concurrently to achieve best management of stormwater. These methods include source control, non-structural and structural measures.

Watercourse means a river, stream, channel, canal or other visible topographic feature, whether natural or constructed, in which water flows regularly or intermittently and includes any associated storage and/or stormwater attenuation dams, natural vleis or wetland areas.

Watershed is the upper boundary of a specified catchment area for rainfall that contributes to a given drainage area.

Wetland means land transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil. This includes water bodies such as lakes, salt marshes, coastal lakes, estuaries, marshes, swamps, 'vleis', pools, ponds, pans and artificial impoundments.

Acronyms & Abbreviations

AASHTO American Association of State Highway Transportation Officials

BMP Best Management Practice

CBP Concrete Block Paver

CoCT City of Cape Town

DWAF Department of Water Affairs and Forestry

EBE Engineering and the Built Environment

EPA Environmental Protection Agency

HDPE High Density Polyethylene

IUWM Integrated Urban Water Management

LCCA Life Cycle Cost Analysis

LID Low-Impact Development

LOS Level of Service

MPBs Modular Paving Blocks

NH₃ Ammonia Nitrogen

PCBP Permeable Concrete Block Paving

PO₄³⁻ Orthophosphate

PPS Permeable Pavement System

SS Settleable Solids

SuDS Sustainable Drainage Systems

TN Total Nitrogen

TP Total Phosphorous

TSS Total Suspended Solids

UK United Kingdom

UNEP United Nations Environmental Programme

UNESCO United Nations Educational, Scientific and Cultural Organization

USA United States of America

USEPA United States Environmental Protection Agency

UWM Urban Water Management

WRC Water Research Commission

WSUD Water Sensitive Urban Design

1. Introduction

1.1 Background and motivation

South Africa is a water scarce country and the sustainable provision of water to its citizens is one of the most significant challenges facing the country. If a water crisis is to be averted, existing systems will need to be managed effectively – including the conjunctive use of potable water and alternate sources, such as stormwater. However, the viability of stormwater as a resource requires active management of the associated risks, (Hatt *et al.*, 2006) and in order to manage these risks the treatment efficacy of stormwater management technologies must be understood.

The vision of a Water Sensitive Settlement (WSS) is one where the management of the urban water cycle in its entirety (*inter alia*, water supply, sanitation, stormwater and groundwater) is undertaken in a manner that is sensitive towards water sustainability and environmental protection (Brown *et al.*, 2008). WSSs aim to use the water in different areas of the urban water cycle in a ‘fit-for-purpose’ manner. For this to be possible it is necessary to develop a clear understanding of each of the systems that make up the urban water cycle, as well as the quality of water in each system and the suitable purposes for which the water will be used. ‘Water Sensitive Urban Design’ (WSUD) – Water Sensitive Design (WSD) in South Africa – encompasses design considerations for all aspects of the urban water cycle. In South Africa, the component of WSD relating to stormwater specifically is referred to as ‘Sustainable Drainage Systems’ (SuDS). SuDS as an urban drainage concept considers the ideals of sustainable development holistically (Wilson *et al.*, 2003; Woods-Ballard *et al.*, 2007).

The publication of ‘The South African Guidelines for Sustainable Drainage Systems’, as part of WRC Project K5/1826 (Armitage *et al.*, 2013b), has contributed to improving the management of stormwater, but the use of harvested stormwater as a resource in South Africa is under-exploited. One of the principal recommendations for further research from Project K5/1826 was the need to undertake long-term monitoring of SuDS to test their efficacy in South African conditions. This will require the identification, instrumentation and ongoing monitoring of typical examples across South Africa (Armitage *et al.*, 2013b).

Permeable Pavement Systems (PPSs) are one of the SuDS source control technologies that have found relatively widespread acceptance in practice in South Africa. PPSs are SuDS control devices (Pratt *et al.*, 1989, 2002a; Pratt, 1999) that reduce stormwater runoff and/or pollution of stormwater at or near the source. PPSs allow stormwater to infiltrate into their porous sub-structures thereby reducing drainage volumes (Pratt *et al.*, 1989, 1999); attenuating peak stormwater flows (Pratt *et al.*, 1989) and potentially trapping pollutants (Pratt *et al.*, 1989; Brattebo & Booth, 2003; Tota-Maharaj *et al.*, 2012). Additional benefits of PPSs include the capture of stormwater for subsequent reuse or increased groundwater recharge (Tota-Maharaj & Scholz, 2010). Furthermore, they are easily constructed by engineering companies and do not usually take up any additional plan area. Consequently, PPSs are now widely considered as

sustainable substitutes for conventional impervious surfaces (Andersen *et al.*, 1999; Beecham *et al.*, 2012).

1.2 Problem statement

While there have been a number of international studies investigating the treatment efficacy of permeable pavements with a view to harvesting stormwater for use, little or no studies have been conducted in a South African context. This study, therefore, intended to address the literature ‘gap’ by investigating the treatment efficacy of permeable pavements with a view to harvesting stormwater for use in South Africa. It was also noted that stormwater practitioners in South Africa commonly failed to adhere to accepted international practice with respect to the washing of the aggregate prior to construction (Wium, 2015), which could have adverse impacts on the treatment performance of PPS. In this regard, it was important to determine whether there is potential for the harvested stormwater to meet the SuDS quality guidelines being enforced in municipal policies such as the City of Cape Town’s (CoCT’s) ‘Management of Urban Stormwater Impacts Policy’ (CoCT, 2009) – particularly if it is to be used in an effort to reduce demand for potable water. The outcomes of this study are geared towards contributing to the broader understanding of treatment efficacy, water storage and harvesting potential of PPS in a South African context as well as supplementing the South African SuDS Guidelines (Armitage *et al.*, 2013b) for the design and maintenance of permeable pavements in South Africa. It set out to answer the following question: ‘What impact does unwashed aggregate stone have on water quality emanating from permeable pavements, and thus the associated stormwater harvesting potential in South Africa?’

The pavement designs and construction methods adopted in this study were informed by the design and construction methods used for the New Engineering Building (NEB) permeable paving parking area on the University of Cape Town’s Upper Campus, adjacent to the laboratory building. This NEB site was adapted for long-term quality and quantity monitoring. Research was carried out by an independent MSc. student in a separate study that allowed for comparison of different sub-structure designs to assess suitability for harvesting ‘fit for purpose’ stormwater and was completed during the early phases of the dissertation.

1.3 Study aims

The study provides one of the first locally-relevant insights into the functioning and treatment efficacy of permeable pavements in South Africa, and into the contexts under which permeable pavements can be adapted to store stormwater and potentially harvest it for use in fit-for-purpose applications. At the outset, the primary aim of the study was to provide substantial data in the laboratory to understand pollutant throughput and potential for harvesting water from permeable pavements. Various designs were tested using the same unwashed aggregate currently used for the construction of permeable pavements in South Africa. However, as the study progressed, it

became apparent that the use of unwashed aggregate compromised the treatment potential of the system. After considerable volumes of clean tap water were passed through each test pavement to clean the unwashed stone, the effluent continued to be contaminated. The issue of unwashed aggregate stone had to be addressed before the pollutant throughput and potential for harvesting water from permeable pavements could be investigated. Therefore, although it was not the original intention to look at the impact of unwashed stone – literature (Pratt *et al.*, 1989, 1995; Pratt, 1999; Myers *et al.*, 2011) indicates that it can be problematic – the primary aim of the study shifted to examine the impact of unwashed aggregate on water quality emanating from permeable pavements.

1.4 Method

The following intermediate tasks were completed to address the study aims:

- i) Four separate laboratory units were designed and constructed to determine the capability of various PPSs to retain selected pollutants;
- ii) An experimental methodology for three investigation phases in the laboratory was developed:
 - a) In the first phase, clean tap water was applied to each unit over a period of time in quantities roughly representative of the rainfall volumes during a typical rainy season in CoCT, and the discharge was collected and analysed. This was done to determine the effect unwashed aggregate had on each system and to facilitate effluent quality stabilisation in each system.
 - b) The second phase tested the treatment efficacy after the aggregate stone was flushed. Pollutants were applied to each pavement and water quality of effluent was examined.
 - c) Lastly, the pavements were stripped and examined for the presence of sediment.

1.5 Scope and limitations

The research approach focused on setting up a laboratory simulation experiment (for both short- and long-term monitoring) in the Department of Civil Engineering laboratory at UCT. Budgetary constraints limited the number of laboratory water quality tests that could be conducted on collected samples. The work was carried out between 10th February 2014 to the 30th June 2016.

1.6 Chapter Outline

The subsequent chapters of this dissertation include the following:

Chapter 2 provides a broad overview of the literature relating to permeable pavement systems, reviewing aspects of design, construction, quality of performance and quantity of performance with a view to harvesting stormwater for reuse.

Chapter 3 denotes the investigation method employed to undertake the research in the laboratory.

Chapter 4 presents the results from the two laboratory phases of the study as well as the interpretation and analysis of these findings.

Chapter 5 presents a summary of the findings, draws conclusions from the research and provides recommendations for future research work.

The various **Appendices** provide the supporting documentation for the dissertation including; additional literature on the effects of urbanisation on stormwater management and how harvested stormwater can be used to address the emerging urban water challenges facing South Africa and rainfall data used in the study. Furthermore, a section on the NEB permeable parking area has been included for reference, detailing, *inter alia*, the design and construction and quality monitoring results.

2. Literature Review

‘We forget that the water cycle and the life cycle are one.’ ~ Jacques Cousteau

2.1 Introduction

The literature review will provide a brief context for the study within urbanisation and the associated water challenges, as well as an overview of stormwater and how it relates to SuDS. SuDS are an adopted paradigm in South Africa and are the stormwater component of the WSD framework. Thereafter, the current state of knowledge pertaining to permeable pavements, which is the focus of the study, will be provided commenting on aspects of design, construction, performance (both quantity and quality), clogging, maintenance and the incorporation of geotextiles.

2.2 Context within urbanisation and associated water challenges

With half the world's population already living in urban areas (United Nations, 2005; Pieterse, 2008), the issue of sustainable cities is high on the international agenda; and water plays a critical role in ensuring their sustainability. Urbanisation, particularly in the developing world, is characterised by ‘intense social and political struggles over water’ (Pieterse, 2008). The 2006 Human Development Report (UNDP, 2006) noted that the world may be approaching a ‘global water crisis’, not only in terms of water shortages, but also as a result of inequity in distribution of water, power struggles and poverty.

There are various critical challenges facing the urban water sector both in South Africa and worldwide, particularly the security of water resources. There is a growing realisation that conventional water management strategies are inadequate to address emerging water challenges and consequently, the water sector is beginning to look to alternative management approaches, principally integrated water resources management strategies. These alternative approaches aim to mitigate negative impacts associated with conventional urban water management, *inter alia*, protecting water resources, promoting environmental and human security and facilitating sustainable urban development. More detail on urbanisation and emerging water challenges in South Africa is provided in Appendix A.

2.3 Urban stormwater

Stormwater management in the urban areas of South Africa has, and continues to, predominantly focus on collecting runoff and channelling it to the nearest watercourse (Armitage *et al.*, 2013a). This means that stormwater drainage currently prioritises quantity (flow) management with little or no emphasis on the preservation of the environment. The result has been a significant impact

on the environment, particularly the receiving waters, through the resulting erosion, siltation and pollution. (Fletcher *et al.*, 2014a) and Armitage *et al.* (2014) stress that stormwater forms one part of the urban water cycle and therefore, should be integrated with other urban services, such as water supply and groundwater systems. This will aid the transformation of stormwater into a protected asset used for harvesting rather than a waste product that is disposed of as quickly as possible. Consequently, the urban environment may be enhanced, water security could be increased and an interdisciplinary environment to address stormwater management can be fostered.

An alternative approach is to consider urban design with a holistic view of all components of the urban water cycle in the context of the wider watershed; integrating stormwater management with water supply, sanitation and groundwater (Jacobsen *et al.*, 2013). This strategy is being increasingly known as Water Sensitive Urban Design (WSUD) – this term is reduced to ‘Water Sensitive Design’ (WSD) in South Africa to avoid alienating rural communities. It describes an overarching paradigm with aims and objectives related to the sustainable use and management of water resources in the urban context. Other equivalent terms to WSD are used internationally including, *inter alia*, ‘Integrated Urban Water Management’ (IUWM) – a term historically used in South Africa – ‘Total Water Cycle Management’ (TWCW) and ‘Integrated Water Resource Management’ (IWRM). Fletcher *et al.* (2014) covers the evolution of these terminologies and others such as ‘Low Impact Development’ (LID), SuDS and ‘Best Management Practices’ (BMP).

More detail on conventional stormwater management – past, present and looking forward – in South Africa is provided in Appendix B.

2.3.1 Stormwater pollution

Increases in the number of impervious surfaces have reduced natural infiltration, increased run-off volumes and pollution and have often distorted the natural ecology of receiving rivers and streams (Walsh, 2000; Paul & Meyer, 2001). Hydraulically efficient drainage can introduce non-point source pollutants to downstream aquatic ecosystems, which may provide a more significant pollutant ‘shock’ than secondary treated wastewater (Taebi & Droste, 2004; Goonetilleke *et al.*, 2005).

The list of pollution sources in urban areas is extensive and includes dry and wet atmospheric deposition (from local and remote sources), catchment land use activities (residential, commercial and industrial sources, pets, parks, road maintenance, spills, traffic), and surface attrition/weathering which includes road wear and tear, corrosion of structures, and elution of chemicals from construction materials, sediment deposits and soils (Marsalek, 2000).

Probably the most universal source of potential pollutants is what is termed ‘dry atmospheric deposition’ (Collins *et al.*, 2010) which, includes atmospheric deposition of dust, aerosols and gases, that forms a layer on surfaces to be washed away by rainfall. Deposition varies according to the atmospheric composition but local wind patterns may create distinct

spatial variation (Göbel *et al.*, 2007). Paved areas and roads act as a significant source of urban runoff pollution as they are generally highly impervious and accumulated pollutants are readily washed off. As well as being a source for pollutions to be wash-off during storm events, pavements themselves may contribute to stormwater pollutant loadings by leaching chemicals (Bernot *et al.*, 2011).

Initial runoff, termed the ‘first flush’, may carry pollutants that accumulate on the urban surfaces during the dry period before the storm (Kim *et al.*, 2007). The ‘first flush’ seems to exhibit significantly different characteristics depending on the system under observation (Deletic, 1998).

Urban runoff carries a considerable load of chemical pollutants – these include heavy metals, hydrocarbons & polyaromatic hydrocarbons (PAH), nutrients, oil, grease, salt and sediment (Pitt *et al.*, 1995; Goonetilleke *et al.*, 2005; Rossi *et al.*, 2005). The final pollutant makeup, which can originate from a variety of sources, depends largely on the type and intensity of land use.

High vehicular activity also results in the deposition of pollutants such as heavy metals, oil, grease, particulates and others. These are caused by road surface abrasion, brake pad abrasion, tyre abrasion, and drip loss and corrosion; and they vary with the type and intensity of vehicle activity, traffic technology and rainfall and deposition characteristics (Göbel *et al.*, 2007; Kim *et al.*, 2007; Berndtsson, 2014; Brown & Peake, 2006). The sediment and chemicals which accumulate on urban surfaces are transported by storm runoff during rainfall events and make their way into the drainage system and then the receiving waters if left untreated (Vaze & Chiew, 2002).

Urban runoff has also been found to have an elevated level of faecal coliform indicators, which has significant risks to human health, to the point that it may be the primary source of bacterial contamination in surface waters (Salmore *et al.*, 2006; O’Neill *et al.*, 2013). Sources for bacterial contamination include septic seepage and animal waste, as well as combined sewer overflow (CSO) discharges (O’Neill *et al.*, 2013). The latter are insignificant in regions with separate systems – such as South Africa.

2.3.2 Characterisation of stormwater

Stormwater quality is difficult to characterise due to its complex, highly variable nature – not only within storms, but among different storms at one site, as well as among sites. In an attempt to represent this variability, Debo & Reese (2003) suggest using the event mean concentration (EMC) as a baseline. The EMC is a measure of the magnitude of urban runoff pollution and is defined as the total constituent mass discharge divided by the total runoff volume for a given storm event. Marsalek (2000) reported mean values for the quality of urban runoff and combined sewer overflows in three other studies. These studies are combined in Table 2–1 to indicate pollutant concentrations for various land uses.

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

2.4 Sustainable Drainage Systems (SuDS)

Armitage *et al.* (2013a) defines Sustainable Drainage Systems (SuDS) as follows:

‘SuDS attempt to manage surface water drainage systems holistically in line with the ideals of sustainable development by mimicking the natural hydrological cycle, often through a number of sequential interventions in the form of a “treatment train”.’

SuDS promote the natural drainage processes to effectively manage stormwater runoff quantity (flow and volume); water quality; and the associated amenity and biodiversity of the urban drainage system (Figure 2-1) (Armitage *et al.*, 2013a). SuDS are technological solutions designed for more sustainable drainage solutions which can be arranged to form a ‘treatment train’ as illustrated in Figure 2-2. The efficacy and resilience of a treatment train is typically dependent on the number of SuDS options used throughout, and is likely to result in the appropriation of useful ‘ecosystem services’ (Vice, 2011). While these solutions have a myriad of forms such as bio-swales, constructed wetlands, rain gardens and permeable pavements (Table 2-2) identifies the different SuDS intervention devices) they can be broadly categorised into four scales of intervention, namely ‘good housekeeping’ – as a preventative measure, source control, local control and regional control (Heal *et al.*, 2004; Armitage *et al.*, 2013b). The categorization of SuDS into the respective scale of treatment highlights the intention of these measures to be utilised in conjunction with each other – as it is common to utilise more than one option (unit input) per site and arrange options sequentially – from source to sink.

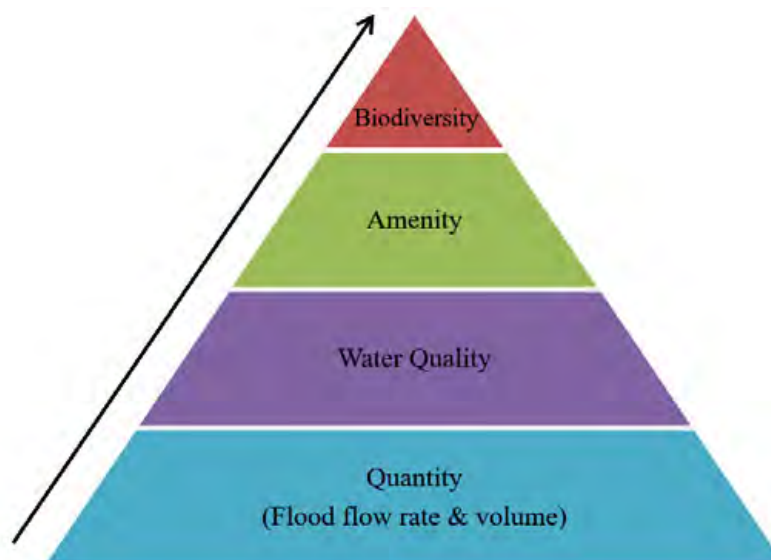


Figure 2-1: The Stormwater design hierarchy
(Armitage *et al.*, 2013b)

In South Africa the national legislative context concerning stormwater strongly favours conventional drainage practices, as well as being extensively supported by building codes and

Table 2-1: Pollutant concentrations for various land uses

Contaminant	Units	Pollutant concentrations for different land uses			
		Residential	Commercial / Industrial	Urban stormwater	
Source		Debo & Rees (2002)		Duncan (1999)	U.S. EPA (1983)
BOD	mg/ℓ	10	9.3	14	9
COD	mg/ℓ	73	57	80	65
TSS	mg/ℓ	101	69	150	100
Total Lead (Pb)	μg/l	144	104	140	144
Total Copper (Cu)	μg/l	33	29	50	34
Total Zinc (Zn)	μg/l	135	226	240	160
Total Nitrogen	mg/ℓ	-	-	2.6	-
TKN	mg/ℓ	1.9	1.18	-	-
NO ₂ + NO ₃	mg/ℓ	0.736	0.572	-	-
Total Phosphorus	mg/ℓ	0.383	0.201	0.35	0.33
Soluble Phosphorus	mg/ℓ	0.143	0.08	-	-
Oil and Grease	mg/ℓ	-	-	8.7	-
Faecal Coliforms	FCU/100m ℓ	-	-	8000	-

Chapter 2 : Literature Review

The impact of unwashed aggregate on water quality emanating from permeable pavements

guidelines. However, in 2009 the CoCT issued arguably the most progressive stormwater management policy in the country – Management of Urban Stormwater Impacts Policy (CoCT, 2009) – that supports of the notion of WSD; recognising the potential of SuDS in the urban landscape. Furthermore, it was the first policy to place value on stormwater in the context of the national water crisis and ‘climate change’.

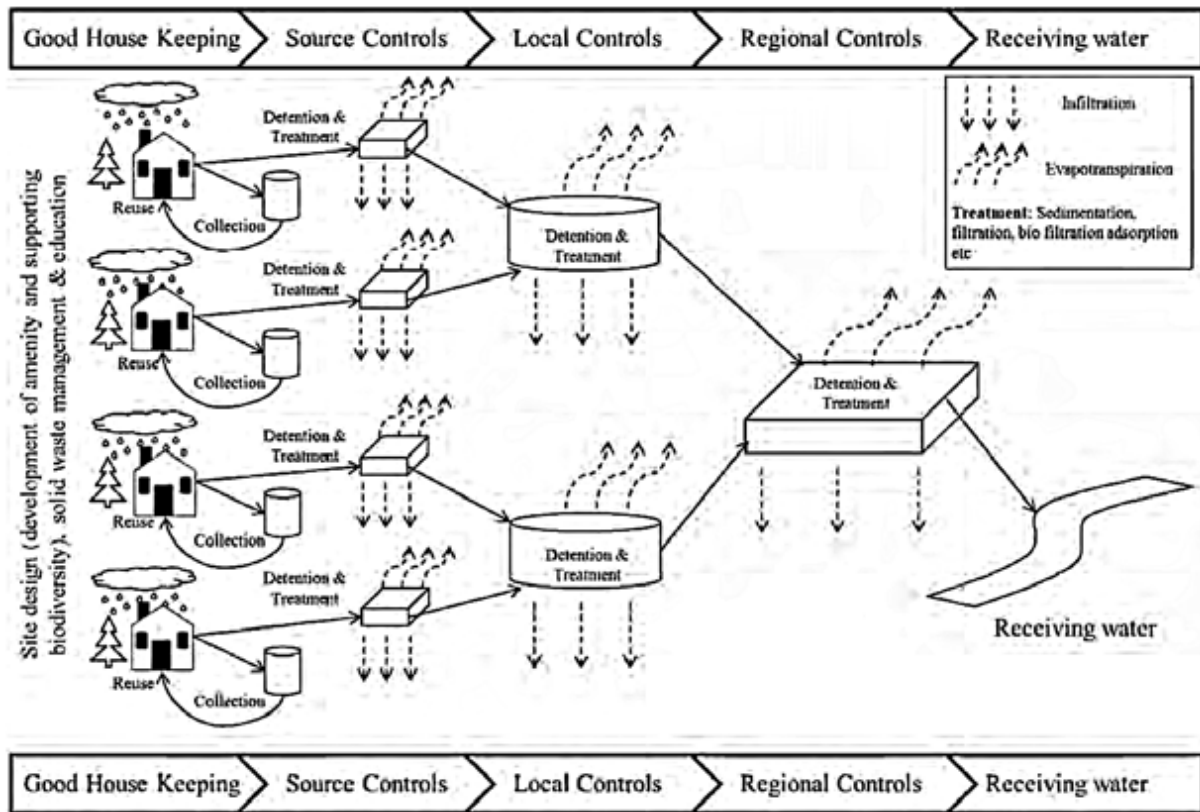


Figure 2-2: The SuDS treatment-train
(Fisher-Jeffes, 2011)

The implementation of SuDS in cities, if carried out carefully, should positively impact all four objectives in the stormwater design hierarchy: stormwater runoff quantity (flow and volume); quality; associated amenity and biodiversity. Armitage *et al.* (2013a and 2013b) mention a number of additional SuDS ‘greening’ sustainability benefits over conventional stormwater management approaches. These include carbon capture, reduced heat island effects as well as contributing towards addressing the challenges of climate change. An important practical benefit which further promotes use of SuDS is its ability to be installed incrementally with innate adaptability and flexibility to combat climate change knowledge advances (Armitage *et al.*, 2013b). Conventional drainage systems have worked well in the past to preserve public safety but do not generally provide the other benefits now expected.

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

Table 2-2: SuDS options comprising the ‘treatment train’
(Armitage *et al.*, 2013b)

	Example	Description
Source Control	Rainwater Harvesting	Temporary storage and reuse of rooftop and/or surface runoff
	Green Roofs	Vegetated roofs
	Permeable Pavements	Load-bearing, durable and pervious surfaces such as concrete block pavers (CBPs) laid on top of granular or stone base that can treat and temporarily store stormwater runoff.
	Soakaways	Excavated pits that are packed with coarse aggregate and other porous media and are used to detain and infiltrate stormwater runoff from a single source.
	Filter strips	Vegetated areas of land that are used to manage shallow overland stormwater runoff through filtration (Debo & Reese, 2003).
Local Control	Swales	Shallow grass-lined channels with flat and sloped sides that are used to convey stormwater from one place to another. They typically remain dry between rainfall events
	Infiltration	Trenches are excavated trenches which are lined with a geotextile and backfilled with rock or other relatively large granular material. They are typically designed to receive stormwater runoff from residential properties.
	Bio-retention areas	Landscaped depressions used to manage stormwater runoff through several natural processes such as filtration, adsorption, biological uptake and sedimentation (Debo & Reese, 2003).
	Sand filters	Underground sedimentation chamber connected to a filtration chamber in which stormwater runoff is temporarily stored before being filtered through a sand filter (Woods-Ballard <i>et al.</i> , 2007).
Regional Controls	Detention ponds	Relatively large depressions that temporarily store stormwater runoff in order to reduce the downstream flood peak (Woods-Ballard <i>et al.</i> , 2007).
	Retention ponds	Also known as ‘retention basins’ – are formed by excavating below the natural ground water level and/or lining the base to retain stormwater runoff (Debo & Reese, 2003).
	Constructed wetlands	Attempt to mimic the characteristics of natural wetlands through the use of marshy areas and aquatic-resilient plants (Woods-Ballard <i>et al.</i> , 2007).

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

2.5 Permeable pavement systems (PPSs)

Permeable pavement systems (PPSs) have become one of the most widely adopted SuDS technologies in developed countries such as the UK, Australia, North America, Canada, signifying the growing global acceptance of this approach (Hatt *et al.*, 2007; Scholz & Grabowiecki, 2007; Nnadi, 2009; Coupe *et al.*, 2010; Drake *et al.*, 2013).

While some researchers (Scholz & Grabowiecki, 2007; Beecham *et al.*, 2010; Drake *et al.*, 2013; Walker, 2013) have drawn a distinction, the terms permeable, porous and pervious are frequently used interchangeably by professionals without regard to their unique characteristics. However, there are certain physical and aesthetic differences between pervious, porous and permeable pavements which need to be considered prior to project design and installation.

Nine different permeable surface categories have been identified by Ferguson, (2006), namely: open-celled paving grids; open-graded aggregate; open-jointed paving blocks; plastic geocells, porous asphalt; pervious concrete; decks; porous turf and soft paving. Similarly, Beecham *et al.*, (2010) identified five broad types of permeable pavements, namely porous pavers, pavers with apertures, pavers with wide joints and porous asphalt and pavers with grass-filled wide joints. Three of these types are usually manufactured as blocks. The fourth type, porous asphalt is often seen as problematic because of its tendency to clog rapidly and because of environmental concerns associated with hydrocarbon leaching. The fifth category, pavers with grass-filled wide joints is generally used in cooler climates. However, in areas with the long dry spells and hot weather, for example in many parts of Australia, combined with the fact that such paving systems can only handle light vehicular loads, have meant that such systems are rarely used. Yong *et al.*, (2008) simplified this categorisation by grouping these paving surfaces into either monolithic (porous asphalt and porous concrete) surfaces – see Figure 2-3 and 2-4 – or modular (open jointed paving blocks) surfaces - see Figure 2-5. Monolithic PPS comprise granular material which is bound, excluding finer aggregate particle sizes, while modular PPS utilise individual block pavers which has a gap between pavers. In this study, monolithic (or pervious) and modular (or porous) paving systems are collectively referred to ‘permeable pavement systems’ (PPS). Selecting paver type is important not only for water quality treatment, but also for appropriate structural application purposes. Because of structural considerations, interlocking permeable pavers have become popular, particularly in the UK.

PPSs are increasingly being included in SuDS/WSUD/LID approaches due to their effective source control capabilities as drainage mechanisms (Hatt *et al.*, 2007; Tota-Maharaj & Scholz, 2010). This has resulted largely owing to their ability to infiltrate stormwater into ‘hard’ surfaces (i.e. where impermeable roads and parking areas have been replaced with permeable alternatives) thereby: reducing drainage volumes (Pratt *et al.*, 1989; Pratt, 1999); attenuating peak stormwater flows (Pratt *et al.*, 1989); and improving water quality of storm runoff into the soil or drain outlets by retaining stormwater pollutants within their structure (Pratt *et al.*, 1989; Brattebo & Booth, 2003; Tota-Maharaj *et al.*, 2012). Additional benefits of PPSs include the retention of stormwater for potential reuse, increased groundwater recharge and an overall

reduction in the urban heat island effect (Scholz & Grabowiecki, 2007). Consequently, PPSs are now widely considered as sustainable substitutes for conventional impervious surfaces (Beecham *et al.*, 2012).

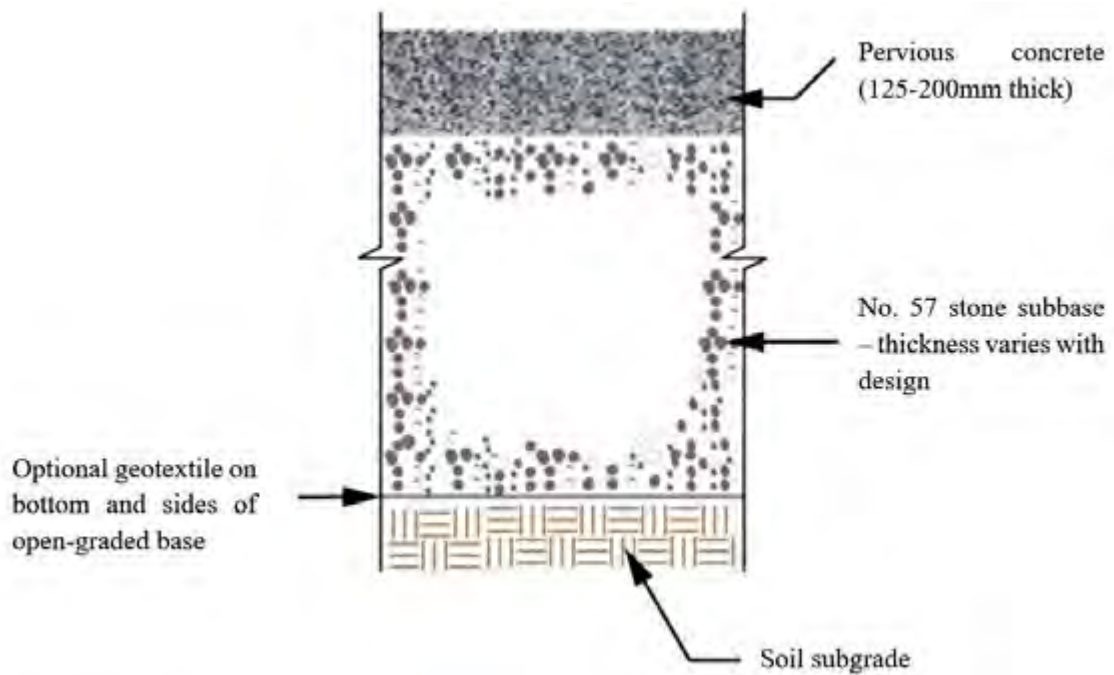


Figure 2-3: Pervious Concrete
(Minnesota Highway Department, 2014)

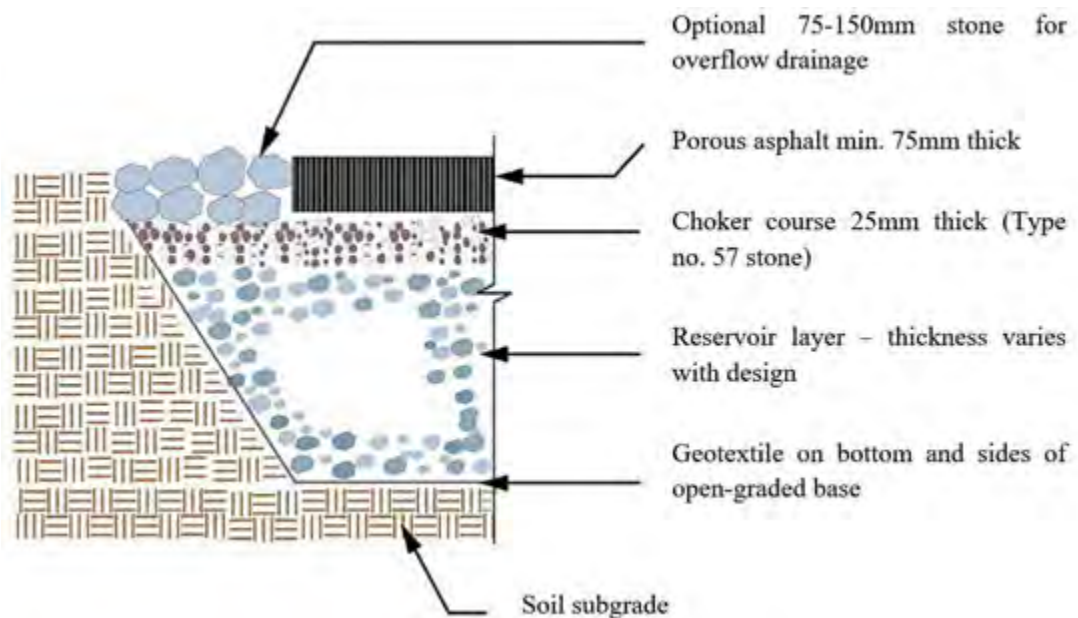


Figure 2-4: Porous Asphalt
(Minnesota Highway Department, 2014)

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

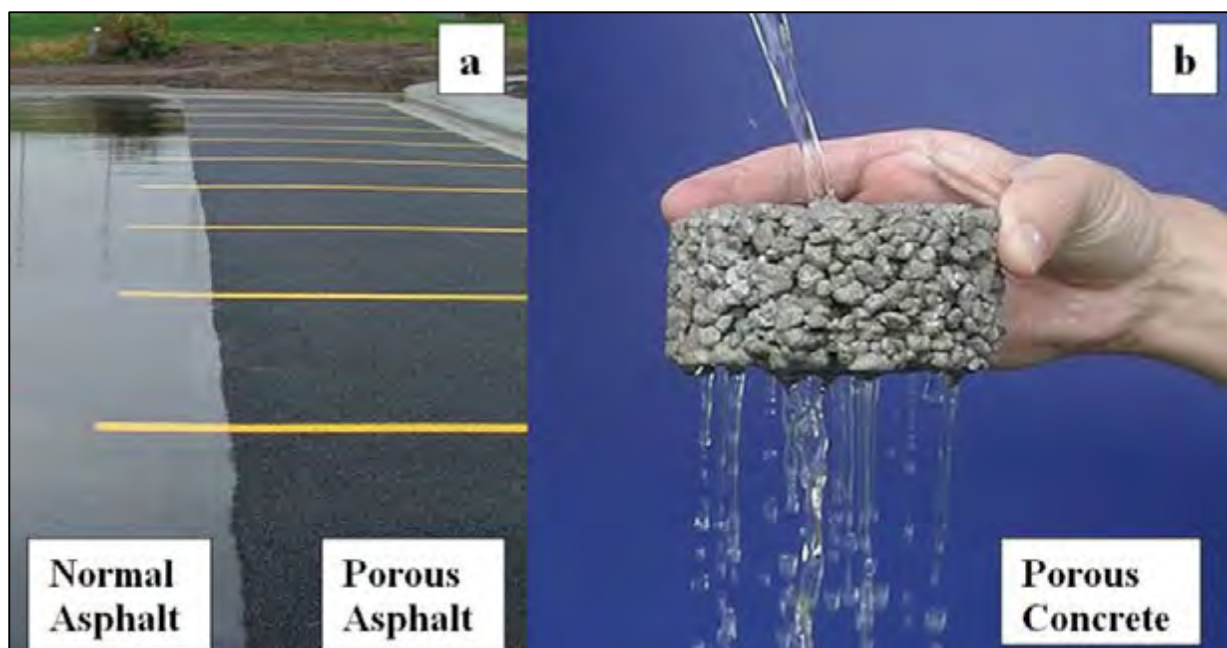


Figure 2-5: Porous surfaces: (a) Normal and porous asphalt; (b) Porous concrete
(Lucke *et al.*, 2013)

2.5.1 PPS design

Permeable pavements operate by allowing water to infiltrate through the surface layer and into the aggregate beneath. Pavers are laid onto a fine-grain bedding medium, which in some cases is separated from the base-course aggregate by a geotextile layer. The base-course consists of coarse gravel with a high voids ratio (e.g. 30%). Either joints between the pavers act as voids to allow water to seep through the surface, or the concrete pavers are designed to contain void spaces to allow infiltration. The paver design will depend on a number of factors, including whether or not the pavement is designed to be vegetated (Beecham *et al.*, 2010).

Armitage *et al.* (2013), as adapted from Woods-Ballard *et al.* (2007), state that the most important design considerations for PPSs are to ensure:

- The entire minor design storm – which includes the specified Water Quality Volume (*WQV*) – is captured. Additional flow should be discharged into a specified drainage system or outfall in a controlled manner; and
- The provision of adequate structural support to withstand the expected loadings from pedestrian, vehicles, plant or other machinery.

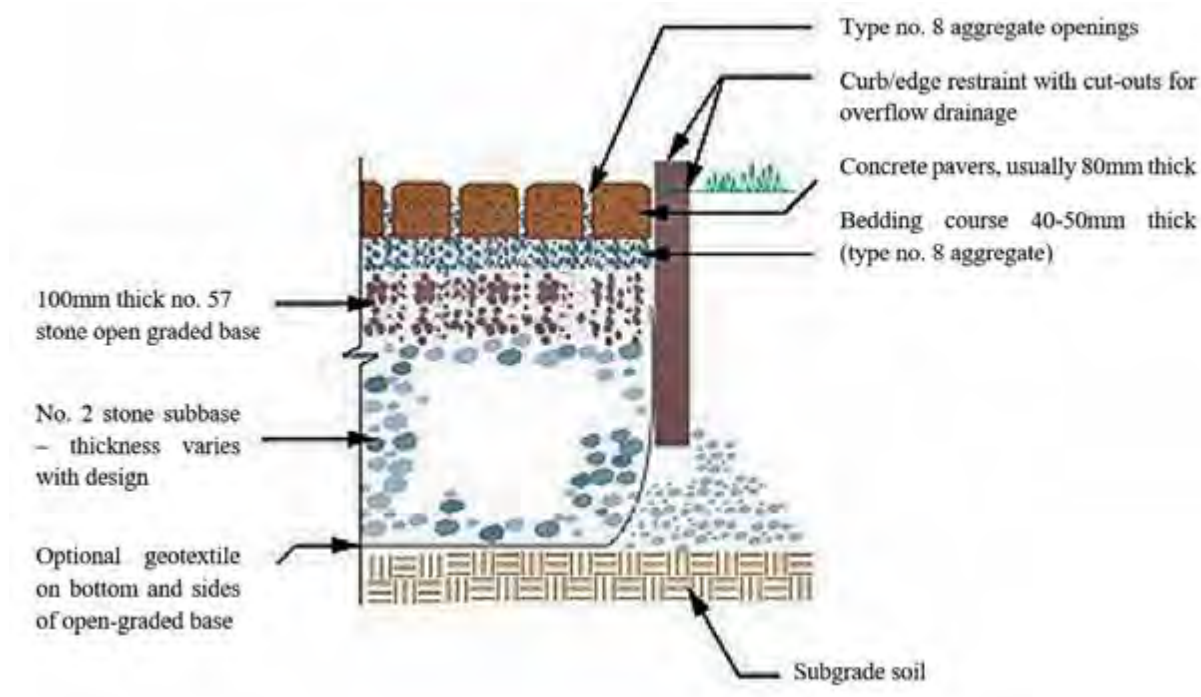


Figure 2-6: Permeable interlocking concrete pavers
(Minnesota Highway Department, 2014)

Generally, PPSs are installed for their ability to manage stormwater runoff quantity at source in a more effective way than impermeable roadways. PPS design is usually aimed at limiting the retention of water on the road by infiltrating the runoff into the road base layers for temporary storage and/or soil infiltration, thereby reducing peak flows in urban environments and limiting the possible damage occurring to the surface of the roadways in the process (Pratt, 1999; Brattebo & Booth, 2003; Ball & Rankin, 2010).

In some applications, PPSs are installed to reduce spray, aquaplaning and traffic noise, rather than infiltrate water to the underlying layers, as they can be used to form a permeable frictional course overlay on highways (Drake *et al.*, 2013). An interesting highway construction application for PPS has been developed that has promising prospects. The philosophy of highway construction has developed internationally to make use of porous asphalt for the purpose of increasing surface friction thereby reducing aquaplaning risk for vehicles in wet conditions. In South Africa, the South African National Roads Agency (SANRAL) is trialling porous asphalt for this purpose. This process involves laying an impermeable bitumen bound sub layer, overlain by a bitumen bound open graded layer to provide a water-absorbing, friction-providing surface. Although this application has great potential, one of the major concerns has been around the understanding of how clogging of these surfaces when exposed to fine sand – a particular concern in the CoCT where there are large amounts of Cape Flats windblown sand – effects the system performance. A typical maintenance procedure includes vacuum sweeping and/or high pressure jet-washing of the surface every three months or four times per year (Field & Sullivan, 2002;

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

Donovan & Naji, 2003; Armitage *et al.*, 2013b). In many cases this is anticipated to maintain the characteristics. However, Ferguson (2006) noted that in the event sedimentary clogging occurs, the essential step in most pavement restoration is vacuuming, because vacuuming pulls sedimentary particles back out of the pores. Low-pressure washing may help to mobilize sediment before it is removed by vacuuming. High-pressure washing only drives sediment deeper into the pores. Sweeping is worthwhile only when combined with immediate vacuuming.

If runoff is infiltrated into the subgrade soil, the drainage volumes are also reduced. When designing a PPS it is critically important to enable and sustain adequate surface infiltration capacity surface infiltration and storage capacity to allow sufficient stormwater volumes to be intercepted and temporarily stored within the system until drained for infiltrated to the subgrade. Adequate infiltration can be sustained up to 90% reduction in infiltration capacity (Dhalla & Zimmer, 2010).

In addition, many studies have shown significant quality improvements to storm runoff infiltrating the PPS which has led to the investigation of PPSs being used as storage and stormwater harvesting devices (Pratt *et al.*, 1995; Pratt, 1999; Beecham *et al.*, 2010; Nnadi *et al.*, 2014). However, other studies (Pratt *et al.*, 1989, 1995, 2002a; Pratt, 1999; Myers *et al.*, 2011) have shown that the design and condition of the pavement materials impact on the quality of the drainage from PPSs e.g. conductivity, alkalinity and pH of stored stormwater. In particular, the total suspended solids (TSS) exiting the structure can show considerable variability deriving from the condition of the internal construction materials themselves (Pratt *et al.*, 1995). Reservoirs may be filled with a range of base aggregate materials that provide structural support to the pavement. The materials have the potential to affect the quality of water being stored or passing through the structure. Myers *et al.*, (2011) noted initially significant increases in the levels of TSS and turbidity when water came in contact with the reservoir base course aggregate. Consequently, the material selection and associated condition in PPS design should be considered carefully according to the design objectives. Design objectives can include: infiltration into the subsoils, temporary attenuation before release into the receiving waters and/or storage within the structure for reuse.

Kazemi & Hill (2015) identified some key findings relating to stored water quality in PPS: firstly, it showed that stormwater can be harvested and stored under base course aggregates of permeable pavements. It also indicated that stored stormwater quality was impacted by not only different base course aggregates but also different periods of time of storage. Lastly, the quality of such stored water was generally adequate for reuse for irrigation of green spaces.

PPSs are generally compatible with roads with low traffic volumes, driveways, car parks, and pedestrian paths but can be used on high speed freeways if appropriately designed. Small slopes and permeable sub-grade soils are also preferable if stormwater harvesting and groundwater recharge are design objectives (Pitt *et al.*, 1990; Sansalone & Teng, 2004; Fassman & Blackburn, 2010).

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

Permeable pavements can be installed with different boundary components for full, partial or no soil infiltration depending on the design requirements and site conditions as shown in Figure 2-7. Many PPSs worldwide are installed with an impermeable underlining as a result of poor soil infiltration characteristics or when no exfiltration is desired. Hence, unless harvested, runoff volume is not always significantly reduced.

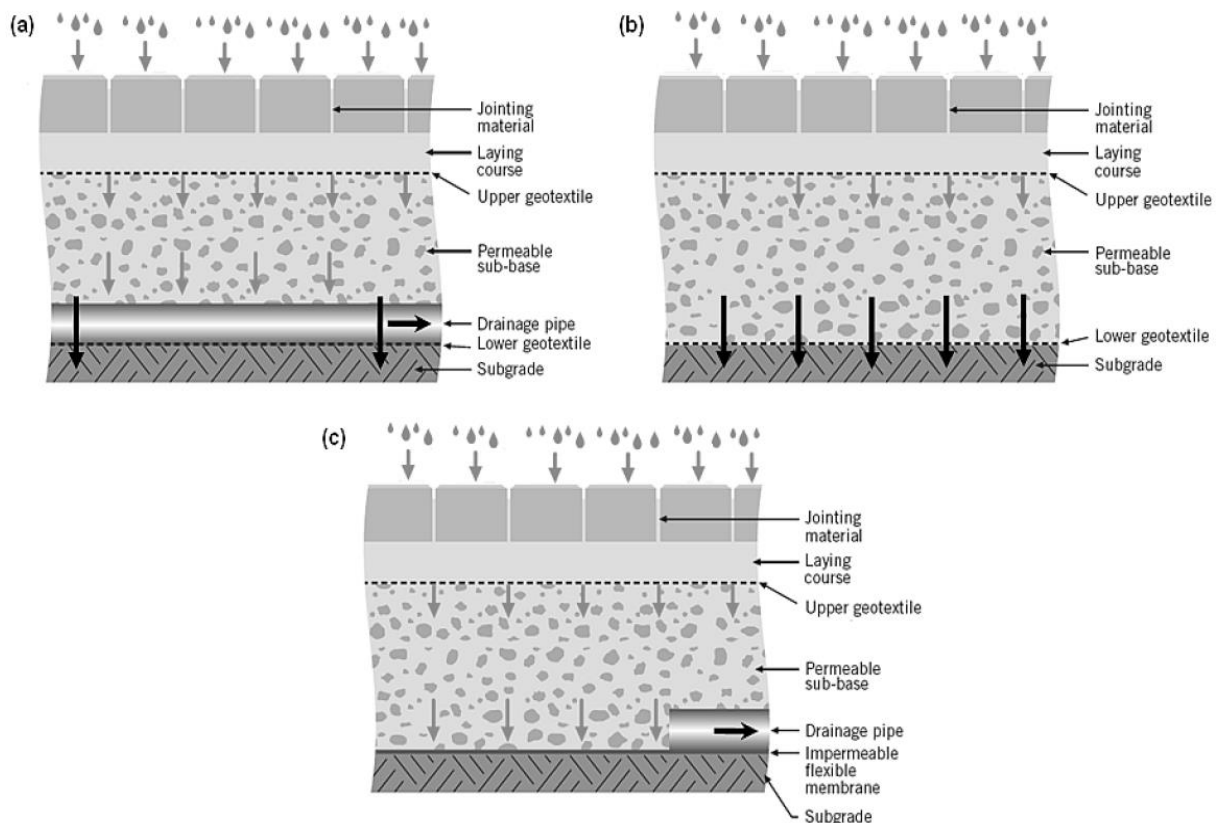


Figure 2-7: Alternative PPS designs with differing boundary conditions: (a) partial infiltration, (b) total infiltration and (c) no infiltration (Tota-Maharaj, 2010)

When an impermeable underlining is installed there is an opportunity for storing stormwater within their structure for subsequent reuse (Pratt *et al.*, 1995). A sub-surface tank/sump can be installed in conjunction with an impermeable underlying to increase the harvesting potential of the system (see Figure 2-8). PPS fitted with impermeable lining must be provided with underdrains, usually perforated pipes, which are placed along or near the base of the stone reservoir to collect and transport the stormwater which has infiltrated the system to a nearby storm drain or the receiving waters (see Figure 2-9). The positioning of the underdrain is also important; if the level of the underdrains are elevated such that they are positioned above the bottom of the stone aggregate layer there can be improved quality treatment as any sediment migrating through the pavement layers toward the bottom settle below the level of the underdrain and are not transported into the drainage system. Additionally, if there is no impermeable

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

underlining, the permeability rates into the underlying soil can be improved as the level of water is required to rise to the invert level of the underdrain before the stored storm runoff can escape as effluent through the pipes.

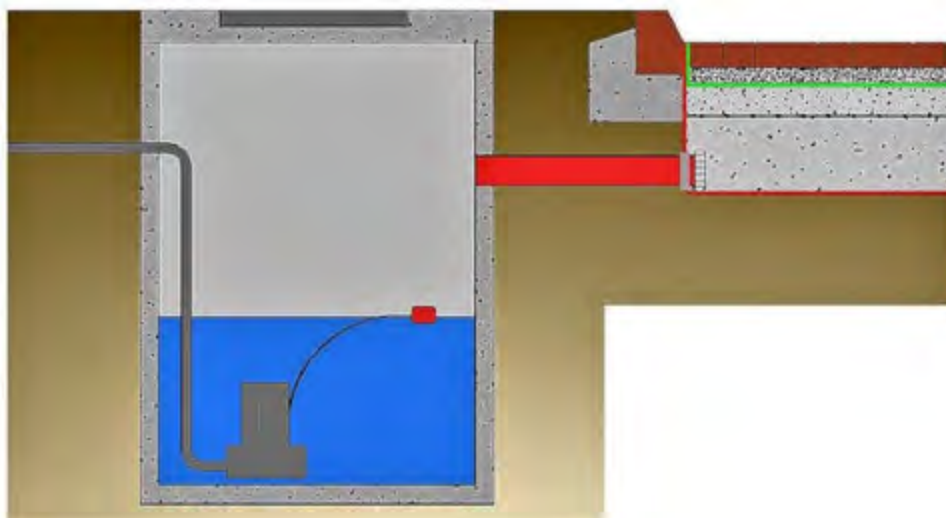


Figure 2-8: Typical sump and pump layout for water harvesting
(Formpave & Hanson, 2010)

If the PPS is to be used for harvesting, an impermeable membrane needs to be incorporated outside the storage layers to prevent the lateral and vertical drainage into the subgrade soil. Suitable membranes – typically HDPE but there are others – have a high resistance to puncture, restrict water entering the subgrade thereby preserve the sub-grade structural integrity and are tape or weld jointed. Impermeable membranes can deteriorate when left exposed to the elements and should therefore be stored until installation and covered as soon as possible after installation. The membranes should also be washed before being laid to prevent the addition of fines to the system.

2.5.2 Costs

SuDS are relatively new to South Africa. As with many new technologies of this nature there is a degree of scepticism about local applicability (Armitage *et al.*, 2013b). This is possibly due to a concern about maintenance and associated costs for which there is a general lack of data worldwide (Taylor & Fletcher, 2007) and, furthermore, local conditions will influence costs. Conversely, there are also ‘hidden’ externalised costs associated with conventional drainage systems which should be considered but are generally not. Armitage *et al.*, (2013a) commented on the economics of stormwater management as follows:



Figure 2-9: PPS underdrain installation in conjunction with an impermeable lining
(Voogt, 2011)

‘SuDS are usually, but not always, 5-25% more economical than conventional systems on the basis of Life Cycle Cost Analysis (LCCA). In some cases, conventional systems potentially cost twice that of the SuDS equivalent over the lifetime of the project. It is however important to identify “who pays for what”. SuDS require on-going, regular maintenance so a relatively higher proportion of the LCCA cost is contained within this activity... Consequently, there is uncertainty in some of the contingency values which could make a difference of 10-30% either way’.

Furthermore, the economics of the design are affected by both the designer and the contractor. This is particularly relevant to South Africa where there is not much experience with SuDS and possibly more significantly, there is a cartel in operation controlling the price. The fairness of the comparison between conventional and SuDS technologies is therefore a significant issue which is difficult to resolve.

A cost comparison was conducted for a parking lot in Pietermaritzburg, South Africa as shown in Table 2-3. In this comparison it can be seen that the conventional system has a lower capital cost than the sustainable system (permeable paving) with the biggest difference being in the cost of the paving surfacing materials. However, the costing for the conventional asphalt solution ignores the potential increase in municipal stormwater pipes and the impact of poorer quality water downstream. The cost of the potential ecological destruction as a result of the conventional system – an aspect that lies outside the scope of this study – is difficult to quantify but nonetheless an important issue which is considered in greater detail in Armitage *et al.*, (2013a).

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

2.5.3 PPS structure and construction

PPS usually comprise a wearing course overlaying a gravel bedding layer and free draining base stone aggregate layers which may be separated from the bedding layer and sub-grade by the inclusion of a geotextile. The wearing course enables stormwater infiltration, while the purpose of the aggregate base layer, constructed from various types of crushed stone, is threefold: firstly it acts as a load bearing structure; secondly, it allows a section of nearly limitless infiltration potential (when new) for temporary storage of rain and storm flow (James & Langsdorff, 2003). Lastly, it acts as a pollutant filter and trap (James & Langsdorff, 2003). The geotextile membrane prevents, *inter alia*, the migration of fines between base and sub-grade layers (Yong *et al.*, 2008) and has been shown to improve the pollutant removal efficacy of the system in some studies (Newman & Pratt, 2002; Tota-Maharaj *et al.*, 2012; Nnadi *et al.*, 2014). A typical PPS design is illustrated in Figure 2-10.

Table 2-3: Capital cost comparison for the Pietermaritzburg Cathedral parking lot
(Partners in Development 2009)

Capital costs	Conventional (R)	Permeable paving (R)
Preliminary and General	44 500.00	54 500.00
Parking Area	208 837.50	255 865.00
Outfall drain	12 050.00	12 050.00
Contingencies (5%)	13 269.38	16 120.75
Subtotal	278 656.88	338 535.75
VAT (14%)	39 011.96	47 395.01
Total Cost (R)	317 668.84	385 930.76

Suitability of the sub-grade in PPS is important to determine boundary conditions. The sub-grade is the native material underneath a constructed road, pavement or railway. The sub-grade needs to be excavated to the required depth according to the design drawings. A minimum fall of roughly 1:1000 is usually stipulated when a fin drain is incorporated to allow drainage to the drainage point (Woods-Ballard *et al.*, 2007). Where the system is designed to exfiltrate into the sub-grade no fall is necessary. Areas which have insufficient bearing capacities should be excavated and replaced with suitable sub-grade material. The sub-grade material is usually vibro-compacted according to the various road design guidelines. However, excessive compaction reduces the infiltration capacity of the soil and therefore can affect the performance of the system where exfiltration is required. Where the PPS is to be used by heavy vehicles, the California Bearing Ratio (CBR) should be improved to no less than 15% (Formpave & Hanson, 2010).

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

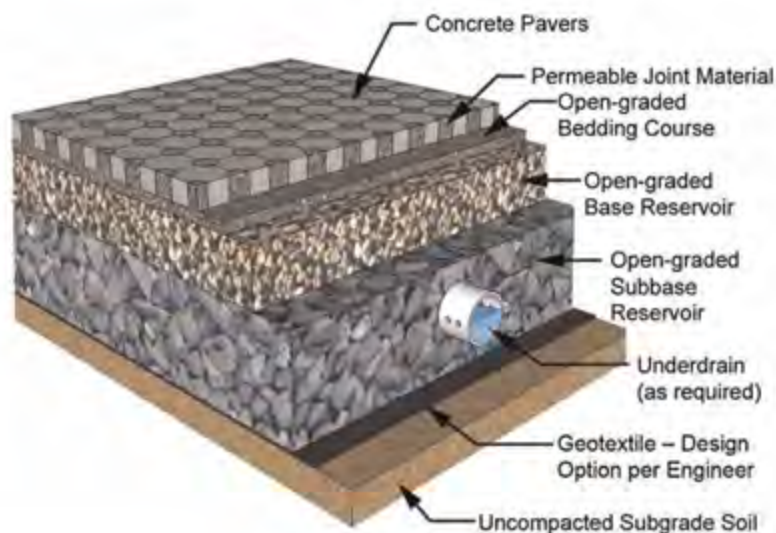


Figure 2-10: Example of a typical PPS cross-section
(Drake *et al.*, 2013)

The operation of permeable pavements is highly dependent on good workmanship – particularly with the laying of pavers (Woods-Ballard *et al.*, 2007; Armitage *et al.*, 2013b). Internationally, the aggregate used in PPS installations is required to be washed, clean stone to prevent the leaching of sediments and other pollutants from the base layers.

There are commonly two or more types of aggregate used in the base layers which should be sized for both the storm event to be treated and the structural requirements of the expected traffic loading. The lower base layers generally comprise larger stone sizes (10-70mm) and the upper layer smaller stone sizes (5-20mm) (Woods-Ballard *et al.*, 2007). The role of these layers is to provide storage space and a suitable bear capacity to handle traffic loads. The thickness of this base layer is usually approximately 300mm thick but it can be varied according to storage requirements. Where separate layers are used, guidelines often stipulate to place them separately and vibrate each layer to compaction with a vibrating roller or vibrating plate.

A fin drain, when included in the design, enables the rapid removal of water from the base layers. It usually comprises a perforated pipe which is wrapped in clog resistant geotextile to ensure that the pipe stays sediment free. Care needs to be taken not to crush the pipe during construction as this will compromise the drainage capacity of the system.

Some designs incorporate an upper geotextile to separate the upper base layer from the bedding layer. As with the impermeable layer, care should be taken to overlap joints by a reasonable amount to ensure that the infiltrate passes through the membrane. The membrane should be stored until installation where after it should be covered as soon as possible to prevent construction sediment clogging the pores as well as weather damage. The use of an upper geotextile layer between the bedding and base course layers used to be common practice in both

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

the UK and Australian systems but such a layer is rarely used today in these countries for a number of reasons. Firstly, it facilitates increased slippage tenancies (including ripping) and because of clogging issues.

A bedding or laying course is placed underneath the pavers (and on top of the upper geotextile if it is included). The bedding layer usually comprises 2-6mm crushed stone laid to a depth of 50-100mm (Woods-Ballard *et al.*, 2007; Formpave & Hanson, 2010). This stone should be washed to prevent the migration of fines into the geotextiles or base layers. Concrete brick pavers are placed on top of the bedding gravel to form the wearing course. The average compressive strength of permeable concrete brick pavers is approximately 30-40 N/mm², with a minimum strength of 30 N/mm² (Woods-Ballard *et al.*, 2007). These pavers are usually designed with impact resistance that is sufficient to avoid cracking of the pavers during the handling and laying. Lastly, 2-4mm quartzite/gritstone or pea gravel is applied to the surface of the PICPs and swept or vibrated between the pavers.

2.5.4 Assessing performance of PPS

Terms like ‘performance’, ‘effectiveness’ and ‘efficiency’ are often used interchangeably, but may have significantly differing meanings. For SuDS, ‘performance’ is defined as a measure of how well the system meets the SuDS objectives relating to the management of stormwater quantity (flow and volume), quality and the associated amenity and biodiversity which can be arranged in the form of a hierarchy (Figure 2-1) (Armitage *et al.*, 2013b). ‘Efficiency’ is generally a measure of pollutant removal capacity of a system, whilst ‘effectiveness’ refers to the degree to which the performance indicators are achieved. SuDS performance indicators cover a wide range of aspects.

In the CoCT, measures of performance of permeable paving systems are determined according to the goals set out by the CoCT Management of Urban Stormwater Impacts Policy (CoCT, 2009), such that the system:

- Improves the quality of stormwater runoff;
- Controls the quantity and rate of stormwater runoff; and
- Encourages natural groundwater recharge.

Thus, the assessment of permeable pavement performance with regard to this policy can be divided into hydrological and water quality performance. However, additional assessment factors must be considered for the PPS, for example its clogging potential.

Figure 2-11 illustrates the general parameters that need to be considered when undertaking monitoring of any stormwater processes as depicted by Barbosa *et al.*, (2012). Because stormwater quantity and quality are both important concepts in terms of understanding environmental impacts – and owing to the fact that both are highly variable between different

sites and between rainfall events – monitoring variability becomes crucial to a comprehensive understanding of the behaviour of the permeable pavement system.

2.5.4.1 Hydrological monitoring

Generally, hydrological monitoring requires the installation of a primary flow measurement device (such as a flow meter or flume) with a data logger at the outlet of the permeable paving system, along with the installation of an on-site rain gauge (Rushton, 2001; Abbot & Comino-Mateos, 2003; Ball & Rankin, 2010). For the latter, local weather station data is sometimes used. Furthermore, indirect methods of flow calculation using hydrological models can be acceptable if flow measuring is unfeasible due to budget or other constraints (Barbosa *et al.*, 2012).

Infiltration rates, which give an indication of the hydraulic capacity of the pavement and can be a good indicator of performance loss due to clogging, can be measured by using single-ring or double-ring infiltration meters (Borgwardt, 2006; González-Angullo *et al.*, 2008; Al-Rubaei *et al.*, 2015). Examples of the type of equipment used for these infiltration tests in the field are given in Figure 2-12.

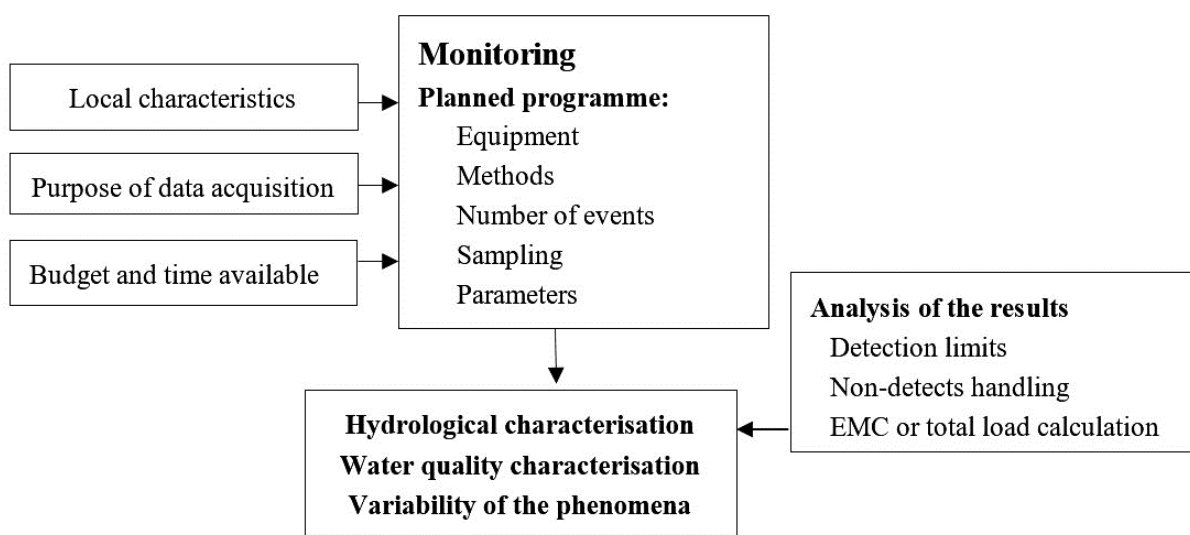


Figure 2-11: Monitoring stormwater processes
(Barbosa *et al.*, 2012)



Figure 2-12: Double-ring infiltrometer (left); Simple infiltration test (right)
(Bean *et al.*, 2004)

2.5.4.2 Water quality monitoring

Most methodologies in the literature make use of a combination of monitoring systems for permeable pavements. It is quite common to use automated, flow-actuated samplers for unsupervised sampling (Legret *et al.*, 1996; Rushton, 2001; Ball & Rankin, 2010; Page *et al.*, 2014; Smolek *et al.*, 2014). These samplers are flow-weighted, and collected samples are then subjected to standard water quality testing. As an alternative, multi-parameter probes may be used, which can record water quality parameters continuously (Alsubih *et al.*, 2014; Lariyah *et al.*, 2014). In order to make up for the limited number of parameters which probes can monitor, the use of these devices is usually supported by the collection of grab samples.

2.5.5 Hydraulic and hydrological features

2.5.5.1 Hydraulic and hydrological operations

Understanding the hydrological operations occurring within a pavement during storm events is important when evaluating the pavement's hydrological performance. Research into hydrological performance usually focus on measuring the rate and timing of flows as well as quantifying the water balance (Andersen *et al.*, 1999; Drake *et al.*, 2013). The various hydrological operations involved in PPS drainage are outlined in Figure 2-3. As discussed earlier the PPS structure can be divided into three parts; the porous wearing course (surface) layer, the base or reservoir layer and the in-situ subgrade material layer. A pavement's hydrological cycle begins with rainfall or storm flow making contact with the pavement surface, which can continue to run off the pavement and form overland flow, evaporate or infiltrate the surface. The amount

of surface runoff is primarily dependent on the infiltration capacity of the wearing course, the slope of the wearing course and the ratio of permeable area to total catchment area. A build-up of sediment and other solids deposited on the surface can prematurely cause clogging, reducing the infiltration capacity.

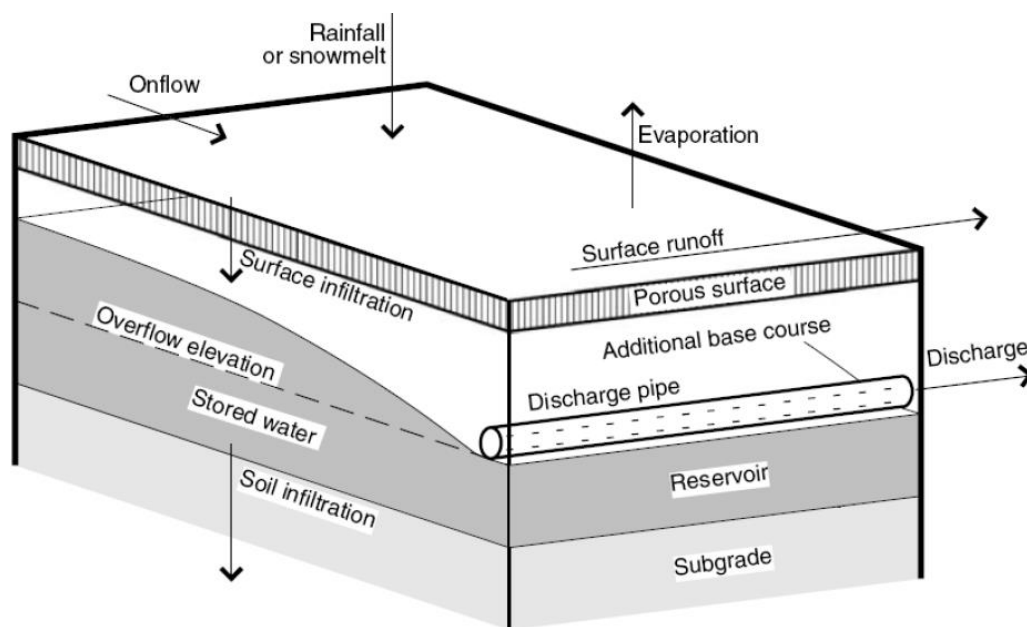


Figure 2-13: Hydrology and hydraulic features of permeable pavements
(adapted from Ferguson, 2006)

PPS are usually designed with a maximum slope of 5% (Lucke & Beecham, 2011). The most frequent concern for pavements with steep slopes is that storm flow or rainfall hitting the pavement is more likely to runoff due to the horizontal vector components of the flow, thus the runoff volume may exceed the infiltrated volume from the pavement (Haselbach *et al.*, 2006; Lucke & Beecham, 2011). Lucke & Beecham (2011) clearly identified a relationship between pavement slope and infiltration rate which suggested that the infiltration capacity at the surface of a PPS system will reduce as the slope of the system increases. However, there have been various studies which have shown pavements operating efficiently at slopes of 10% (Shackel *et al.*, 1995) and even 20% (Lucke & Beecham, 2011) suggesting a design slope guideline of 5% may be overly conservative. Additionally, the depression storage of the wearing course can affect the hydrology of the PPS considerably, particularly for small storm events or if the pavement is partially clogged. These small depressions need to be filled before runoff occurs. Depression storage, surface wetting and evaporation from the pavement necessitates a minimum amount of rainfall to make contact with the surface before it can infiltrate the base layers, let alone drain and reach the receiving waters.

The surface infiltration capacity of storm runoff or rainfall through the pavers into the base material depends on the PPS aggregate layer design, type of geotextile included (if any), the

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

saturation conditions of the paving and bedding layer and the boundary conditions of the base (storage) layer. The aggregate layer design needs to take into consideration the aggregate type, layer thickness and amount of compaction applied, all of which affect the permeability of the PPS. To maintain an acceptable infiltration rate through the PPS, it is critical that the permeability of the structure, defined as the ease with which a fluid (in this case stormwater) can move through pore spaces in the structure (Das & Sobhan, 2013) (i.e. pavers, geotextiles and base layers), is kept sufficiently high. Therefore, increasing the compaction, which decreases the aggregate layer thickness and reduces the average pore size of the aggregate material, which in turn reduces the permeability and infiltration rate of the base layers.

Furthermore, geotextiles can also inhibit the infiltration capacity of a PPS by requiring a minimum breakthrough head before they allow water to pass through their membrane. Inbetex® for example, has a 50mm breakthrough head with a through flow of 80ℓ/m²s. Additionally, saturated and unsaturated zones within the base layers also affect the infiltration rate as each zone has different hydraulic properties. The vertical flow of stormwater from an unsaturated zone to a saturated zone depends on the hydraulic conductivity, moisture content, aggregate water tension, the average depth of the upper zone and others. However, the hydraulic capacity of the aggregate layers usually far exceed that of the wearing course, geotextile, sub-grade or drain outlet and therefore are not generally considered to be a limiting factor in infiltration rate of stormwater through PPS (Pratt *et al.*, 2002a; James & Langsdorff, 2003).

Stormwater that has infiltrated the pavement surface and percolated through the unsaturated zone of the base layers can then drain laterally through a discharge pipe or continue to percolate through the sub-grade depending on the boundary conditions of the PPS. For very large storms, when a pavement is not clogged, these boundary conditions are generally the limiting conditions to the hydrological performance. If the PPS is constructed with an underdrain, particularly if the storage layer is confined by an impermeable layer, the correct sizing of the pipe is critical. The underdrain collects the treated water and supports the filtration media. Percolation to the sub-grade or out the underdrain can be reduced by an accumulation of sediment contained within the base layers (Haselbach *et al.*, 2006; Yong *et al.*, 2009).

2.5.6 Treatment and pollutant removal

Permeable pavements have the potential to have a high pollutant removal capacity relative to other SuDS technologies. Armitage *et al.*, (2013a) compiled a table containing the measured pollutant removal capacities of selected SuDS options and devices collected from the literature (Table 2-4) – unfortunately none was available from South African case studies. However, the removal efficiencies are dependent on a variety of factors including, inter alia, climate, pollution composition and concentration, technical design, and maintenance. As a result, the values should be considered as a guide only to the relative performance of selected SuDS options and technologies. None the less, Table 2-4 motivates for suitably designed and constructed PPS to be recognised as quality (as well as quantity) management devices.

Table 2-4: Measured pollutant removal capacities of selected local control SuDS options
(after Minton, 2002; Pratt *et al.*, 2002b; Debo & Reese, 2003; Woods-Ballard *et al.*, 2007)

Option / Technology	Pollutant Removal (%)					
	TSS	Hydrocarbons	TP	TN	Faecal Coli Forms	Heavy Metals
Bioretention areas	50-80	50-80	50-60	40-50	-	50-90
Filter strips	50-85	70-90	10-20	10-20	-	25-40
Infiltration trenches	70-80	-	60-80	25-60	60-90	60-90
Permeable pavements	60-95	70-90	50-80	65-80	-	60-95
Swales	60-90	70-90	25-80	30-90	-	40-90
Enhanced dry swales	70-90	70-90	30-80	50-90	-	80-90
Wet swales	60-80	70-90	25-35	30-40	-	40-70
Vegetated buffers *	50-85	70-90	10-20	10-20	-	25-40

TSS – Total Suspended Solids; TP – Total Phosphorus; TN – Total Nitrogen
* Estimated values based on similar SuDS options

Researchers continue to investigate devices and technologies that not only address the flow impacts of urbanization but the water quality impacts as well. Pollutants are primarily trapped within the PPS by mechanical and physico-chemical filtration, however biological processes such as biodegradation may also contribute to pollutant removal to some extent (Coupe, 2004; Smolek *et al.*, 2014; Hatt *et al.*, 2007; Scholz & Grabowiecki, 2007).

2.5.6.1 Assessing treatment performance

Treatment performance refers to the water quality improvement of storm runoff infiltrating the PPS which results from the retention of various pollutants within the internal structure. The majority of the treatment (and clogging) occurs within the top 150mm-200mm of the pavement (Balades *et al.*, 1995). The upper layers generally comprise small stone sizes (bedding gravel and pea gravel), while the lower stone layers serve more of a storage function. The storage layers are hypothesised to contribute very little to the overall treatment of the system.

Laboratory observations generally report higher pollutant removal efficiencies than field observations which indicate that the laboratory work may overestimate the treatment performance of the PPS. Water quality is inherently relative characterise due to its complex, highly variable nature – not only within storms, but among different storms at one site, as well as among sites. However, treatment performance should be evaluated from a ‘fit-for-purpose’ perspective, where ‘fit-for-purpose’ refers to matching water of a certain quality to a use appropriate for that quality. This will be discussed in further detail in section 3.2.5.

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

2.5.6.2 Pre-treatment

Pre-treatment is not common in the design of permeable pavements. Pre-treatment, however, may reduce the design life and performance of PPS since many problems with siltation and nutrient can emanate from the areas immediately surrounding the pavements. 'Pre-treatment' of stormwater could do a lot to improve the performance of the pavers – both from a quantity and quality point of view. However, typically PPS are expected to operate as a contained treatment device without the prior treatment assistance from other devices.

2.5.6.3 Treatment mechanisms

The principal mechanisms by which pollutants are removed and retained within a pavement structure are divided into three groups associated with the treatment process (summarised in Figure 2-14) as follows:

- Transport (linked to media characteristics and water chemistry principles);
- Removal / attachment (through filtration mechanisms within the PPS); and
- Degradation (of contaminants).

The first step in the removal is transport of the particles to immediate vicinity of the media. The storm runoff, containing the pollutants, is intercepted and stored within the PPS. Pervious pavements receive hydraulic and pollutant loadings that are intermittent and highly variable.

The next step involves the removal or attachment of pollutants in the storm runoff within the PPS structure. Various unit processes are possible. Filtration and sedimentation are the two primary removal mechanisms in permeable paving systems (Debo & Reese, 2003). There is a misconception that filters work primarily as strainers with solids lodging in the gaps between filter media. In reality, the more significant removal mechanism in PPS is sedimentation, primarily within the upper layers but also within the media, which occurs due to the laminar flow within the pavement and is especially effective at removing particulates (Minton, 2002). Filtration via particle adhesion can occur for small, dissolved particles when they come in contact with the filter media. The efficacy of sedimentation and filtration within the PPS is therefore related to the hydraulics of the pavement structure, in particular the velocity of flow through the pore spaces, as well as the size of particles in the water, water chemistry, and the type size and porosity of the media.

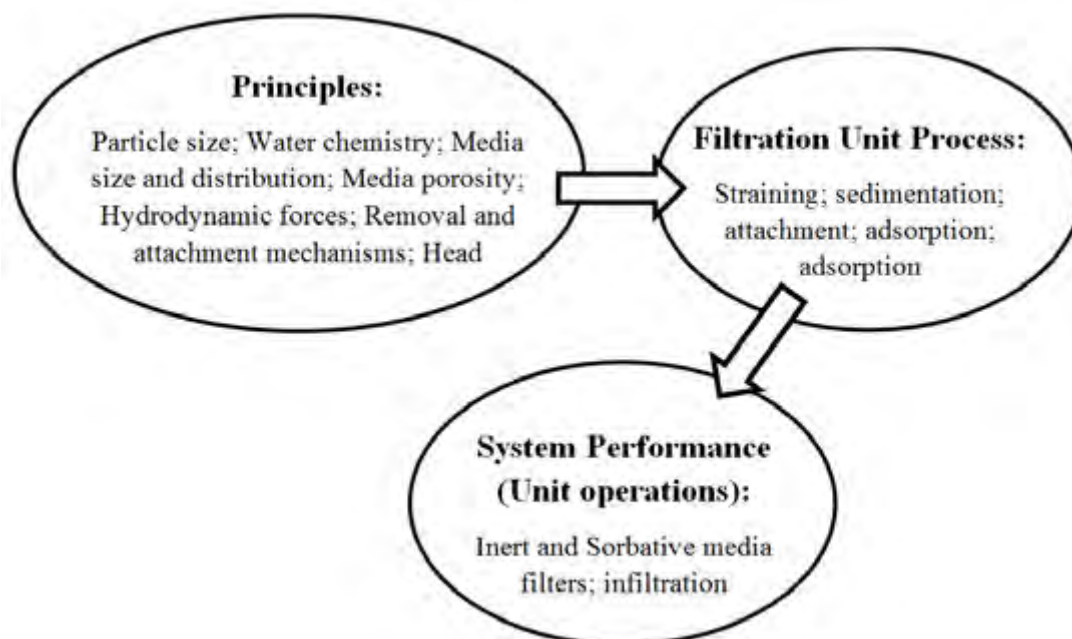


Figure 2-14: Treatment process involved with PPS

(Minton, 2002)

Precipitation and adsorption are two other unit processes that may occur within the PPS. These processes are of particular relevance to the removal of dissolved phosphorus and dissolved metals (Minton, 2002). Adsorption of dissolved pollutants also occurs when pollutants are trapped by the porous filter media (Tota-Maharaj, 2010). The capture of solid particles, which often have metal ions and other adsorbed pollutants to the sediment, in storm runoff occurs when small aggregate particles are either trapped on the pavement surface (Balades *et al.*, 1995; James & Gerrits, 2003) or settle within the PPS structure (Tota-Maharaj, 2010). Attachment, another unit process, is important in the removal of colloids and fine solids. For particles smaller than a few microns, attachment (electrochemical) is the dominant removal mechanism. For particles larger than 10 μm , efficiency increases with increasing size, with sedimentation and straining as the removal mechanisms.

Finally, after transport and removal of the pollutants has occurred on the surface or within the PPS, degradation of pollutants can occur. In some studies (Coupe, 2004; Wilson *et al.*, 2003; Nnadi, 2009; Newman & Pratt, 2002), biodegradation occurred within test pavements which facilitated the breakdown of, *inter alia*, hydrocarbons. This degradation occurred due to the growth of a biological slime layer, also called a *schmutzdecke* in sand filters, which developed within the structure. This layer develops when a layer of fine solids accumulates within slow-rate filters (such as PPS) and enhances the removal of sediments, bacteria, and viruses (Minton, 2002). Water treatment research on slow sand filtration has shown that immediately after the biological slime layer is removed, for example during maintenance procedures, the treatment efficiency of the system is decreased until the layer can reform (Minton, 2002, 166). It takes from

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

several hours to a few days of operation before the new layer is sufficiently thick to return performance to desirable levels. There has been a considerable amount of research on biofilms associated with geotextiles. Starting with Coupe's PhD thesis in 2004 (Coupe, 2004). If there is sufficient carbon in the incoming water to induce growth, the bacteria mass can significantly reduce the hydraulic conductivity of the media, increasing the risk of clogging and the subsequent failure of the PPS (Minton, 2002). However, the development of this layer enables microbes and biological organisms to breakdown nutrients and organic matter within the structure. Nitrifying bacteria are able to convert ammonia to nitrate, and denitrification of nitrate to nitrogen takes place if an anaerobic zone exists in the lower area of the bed. Organic compounds are consumed by bacteria as evidenced by the reduction of dissolved oxygen as water passes through the filter (Minton, 2002). It has been proposed that geotextiles encourage the development of this layer (Tota-Maharaj *et al.*, 2012; Nnadi *et al.*, 2014) and therefore the removal of nutrients and hydrocarbons from stormwater is improved.

Due to the fact that PPS not only remove particulate pollutants but have also shown the ability to remove dissolved pollutants (albeit with a far lower removal efficiency), these systems are classified as a combination of sorbative and inert media filters. The PPS physical properties of granular media, which are of particular importance in the treatment process, are size, size distribution, sphericity and porosity. The relative importance of each of the mechanisms described above and the factors that affect their respective roles are summarised in Table 2-5.

2.5.6.4 Performance

The use of PPS – particularly those including geotextiles – to remove certain pollutants from stormwater retained within the PPS structure could have far reaching impacts, significantly lowering levels of pollution reaching receiving waters and alleviating issues of pollution to underground aquifers. Whether the presence of geotextiles improve the treatment performance of PPS is a debated topic – covered in more detail in Section 2.5.9, however, in some cases when included they appeared to improve the removal of pollutants and biodegradation processes taking place within the PPS. The removal process, in which many studies reduced total nitrogen, BOD, total coliforms, and *E. coli* was aided by the presence of a geotextile as this layer improves the physical filtration – this is largely dependent on the pore size of the membrane, and may help facilitate the development of a slime layer (Yong & Deletic, 2008). Furthermore, the influence of pH and temperature on nutrient, sediment, and microbial pollutant removal was found to be insignificant (Yong *et al.*, 2008).

Table 2-5: Effect of media characteristics and water chemistry (Minton, 2002)

Factor	Treatment performance increases with
Effective size	Decreasing
Sphericity	Decreasing
Porosity	Increasing
Suspension stability	Decreasing, primarily on particles less than 5 µm
Ionic strength	Increasing, primarily on particles less than 5 µm
Calcium	Increasing, primarily on particles less than 5 µm
pH	Decreasing pH
Humic compounds	Decreasing, primarily on particles less than 5 µm
Temperature	Increasing
Media thickness	Increasing
Flow rate	Unaffected within the normal design range
Flow rate change	Unaffected if change is gradual

The removal of total suspended solids (TSS) varies. TSS removal rates have been observed at 50-64% (Legret *et al.*, 1996), 87% (Pagotto *et al.*, 2000) and 99% (Yong *et al.*, 2008) – the latter study maintained these high removal rates in all PPS, regardless of the presence of a geotextile, even after 17 years of simulated rainfall. Heavy metals removal is closely linked with solids removal as heavy metals are typically adsorbed to suspended solids. PPS, particularly those containing geotextiles, lowered Pb, Zn, Cu and Cd concentrations in the effluent by 79-84%, 72-73%, 52-70% and 67-77% respectively when compared to conventional stormwater systems (Legret *et al.*, 1996; Legret & Colandini, 1999). Legret *et al.* (1996) analysed material samples taken from a PPS and the soil directly underneath which showed that a number of heavy metals found in stormwater runoff (Cu, Cd, Pb and Zn) mostly accumulate within the wearing course (pervious asphalt, porous concrete or interlocking bricks) and at the level of the geotextile membrane. The soil under the structure appeared uncontaminated by heavy metals after 4 years of operation.

PPS have also shown the ability to infiltrate, retain and degrade hydrocarbons present in storm runoff. They provide a suitable environment for hydrocarbons to bio-degrade and the addition of microbial mixtures to improve removal rates is not necessary (Pratt *et al.*, 1999; Newman *et al.*, 2002). Various studies have indicated that hydrocarbon levels are below detection limits in the exfiltrate, suggesting that PPS can effectively remove hydrocarbons (Pratt, 1999; Rushton, 2001; Tota-Maharaj & Scholz, 2010; Drake *et al.*, 2013).

Tota-Maharaj & Scholz (2010) studied the nutrient removal capabilities of PPS systems. Removal efficiencies of ammonia-nitrogen (NH₃) and orthophosphate phosphorus in their laboratory test rig were found to be 96% and 98% respectively in the presence of a geotextile. Yong & Deletic (2008), when testing total phosphorus (TP) removal, observed that all three

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

pavements tested had a removal rate of around 80%, dropping to 60% after 17 years of simulated operation. Yong & Deletic (2008) further observed the initial total nitrogen (TN) removal to be 50% but after only 2 weeks, dropped down to 30% and stayed constant for the next 15 weeks of simulated operation. Total dissolved nitrogen (TDN) analyses of the inflow and outflow samples in Yong & Deletic (2008) showed 70% of the TN species in stormwater to be in the dissolved form. Almost no removal of TDN through the pavements was recorded. PPS are moderately efficient in removing particulate bound nitrogen but are not suited well for removing dissolved nitrogen. This is of particular important when considering PPS implementation in the CoCT, South Africa. The stormwater policy in the CoCT requires a 45% reduction of TP in post development runoff (CoCT, 2009). Therefore, if a high percentage of the TP contained in storm runoff is in the dissolved form the quality of effluent draining from a PPS, which intercepted this runoff, may not reach the CoCT TP removal target. Furthermore, Hatt *et al.* (2007), a study conducted on gravel filter media – a similar design to PPS, concluded that there was little or no leaching of particulate bound phosphorus but that outflow concentrations of phosphorus may increase with time, due to fine particles being slowly washed through the filter and/or desorption due to changing pH and oxygen levels as the filter clogs. However, it is expected that physical clogging will occur before pollutant breakthrough, and so sediment and heavy metal removal should remain high for the entire lifespan of the gravel filter.

2.5.7 Clogging

A major obstacle to the acceptance of PPS in South Africa is their potential for clogging. Research has shown that the top 100-150mm of the PPS are the most prone to clogging due to sediment build-up; it also tends to retain the majority of the pollutants – including particulate heavy metals which adhere to the fine-grained soil. Clogging is a process that occurs over time resulting from the accumulation and deposition of sediments from storm runoff (Bouwer, 2002). This process, illustrated diagrammatically in Figure 2-15, reduces the permeability and porosity, and therefore the infiltration rate of a system (Yong *et al.*, 2008). The primary factor that decreases the infiltration capacity of PPS, as with soil, is surface sealing – the development of a thin compressed layer on the surface (Schwab *et al.*, 1994). Surface sealing is largely driven by the breakdown of soil aggregates by rainfall energy which become dispersed and trapped within the upper layers of the pavement (Bosch & Onstad, 1988). This leads to clogging of the upper surface with larger sized particles (i.e. sand), where after fine particles become wedged within the bigger particles, preventing their migration in to the storage layers. Typically, the fine materials comprise silt, clay, or other material associated with tyre wear as well as the pavers themselves. The infiltration capacity will slowly decrease until a surface crust or impermeable layer forms (Balades *et al.*, 1995). The surface crust is generally less than 2mm thick (Balades *et al.*, 1995) and once it is formed, the infiltration capacity will not decrease any further (Ferguson, 1994). Surface sealing can be greatly reduced or eliminated when the soil surface nearby a PPS is protected, for example by vegetation (Schwab *et al.*, 1994). Surface clogging on pavement sections can be identified by ponding (see Figure 2-16).

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

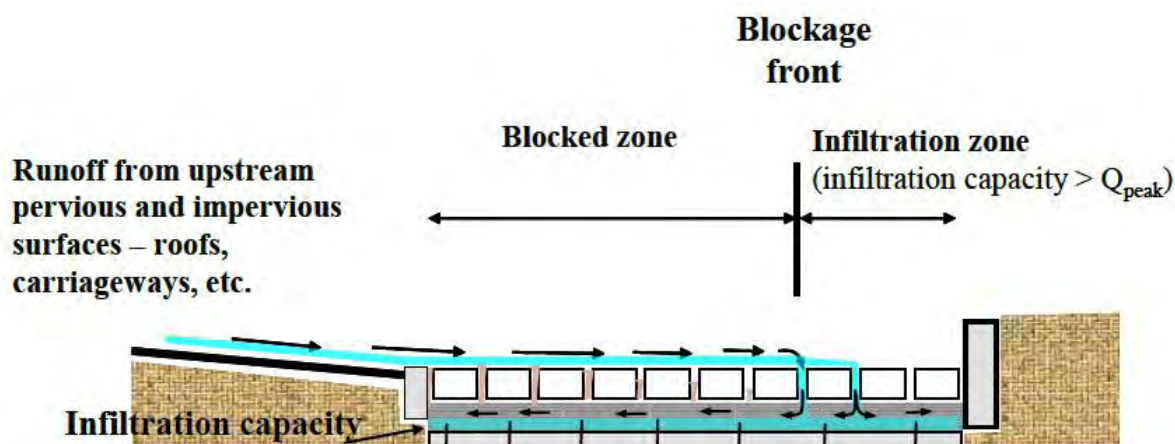


Figure 2-15: Concept of pavement clogging
(Beecham *et al.*, 2010)



Figure 2-16: Surface ponding on a section PPS indicating pavement failure
(Voogt, 2011)

Siriwardene *et al.* (2007) investigated clogging underneath PPSs and found that a clogging layer also often forms at the interface between the filter and underlying soil. The main driver in the development of this clogging layer is the migration of particles less than 6 microns in diameter through the pavement (Yong *et al.*, 2008).

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

2.5.8 Maintenance

Frequent inspection and maintenance are recommended for ensuring the long-term effectiveness of PPS (Kresin *et al.*, 1996; Legret *et al.*, 1996; Yong *et al.*, 2008). In many pavements, ‘pea gravel’ – 2-4mm quartzite/gritstone, is swept into the joints and slots between pavers to enable and maintain permeability of the structure. This ‘pea gravel’ should be removed and replaced periodically to prevent clogging (Formpave & Hanson, 2010). A number of studies (Balades *et al.*, 1995; Pratt *et al.*, 1995) have investigated possible methods of periodically removing the crust material from the pore space of permeable pavement installations. One possible method is washing with water at high pressure, using a man-operated portable, or vehicle-mounted pressure-washing unit. Power-washing would ideally be done in the direction of the nearest strip of grass. The material that has been washed from wearing course by the high pressure hose, perhaps rich in organic matter and pollutants, would then be washed into the grass where it can then be taken up, or left to naturally biodegrade. Nieswand *et al.* (1990) reported that buffer strips, or naturally-vegetated zones, could also be used for this purpose.

Other typical maintenance includes vacuum sweeping (see Figure 2-17) of the surface every three months (Woods-Ballard *et al.*, 2007; Armitage *et al.*, 2013b). However, Vaze & Chiew (2002) cautioned that street sweeping may have an adverse impact on pollutant wash off because the sweeping action releases the finer material without removing all of it, making the fine sediment readily available for wash off by the next storm. In many cases these forms of maintenance are anticipated to maintain pavement performance and extend pavement design life. However, Ferguson (2006) noted that in the event sedimentary clogging occurs, the essential step in most pavement restoration – particularly porous pavements, is vacuuming, because vacuuming pulls sedimentary particles back out of the pores. Low-pressure washing may help to mobilize sediment before it is removed by vacuuming. High-pressure washing only drives sediment deeper into the pores. Sweeping is worthwhile only when combined with immediate vacuuming.

In the event of pavement failure across a PPS, Woods-Ballard *et al.* (2007) suggest that the following procedures should be carried out for pavement rehabilitation:

- Remove the surface layering and laying courses;
- Remove the geotextile filtering layers;
- Inspect, remove, wash and replace sub-base if required;
- Renew or replace the geotextile layering; and
- Renew the laying course and/or the pavers.

In some permeable pavement installations that receive run-off from other sources and act as slow-sand filters, a pre-treatment device can be used to precede the filter with the aim of decreasing deposition of sediment within the filter, thereby decreasing the risk of clogging and improving the treatment performance of the system. Additionally, clogging in the PPS can be accelerated

by poor construction methods, particularly the deposition of dust and fines on the pavement – an example of this can be seen in Figure 2-18. It is important that contractors take precautions to not prematurely contribute to the clogging of the PPS, through *inter alia*, careful management of dust and sediment deposition during construction (Woods-Ballard *et al.*, 2007). To reduce the likelihood of a pavement clogging, careful consideration should be given location of the pavement. Locating permeable pavements away from large areas of open, unprotected (vegetated) soil or soil embankments is important if high surface infiltration rates of PICP are to be preserved (see Figure 2-18). Areas with exposed, sandy material can easily be wind-blown or carried by storm runoff onto a nearby pavement which could result in premature failure due to the build-up of sediment on the pavement surface (Drake *et al.*, 2013).



Figure 2-17: Various street sweeping techniques
(Voogt, 2011)

Having acknowledged the potential for clogging, there are many examples around the world of PPS that are still operating effectively after more than 15 or 20 years with minimal maintenance (Yong *et al.*, 2008; Aryal & Beecham, 2014). In many cases, the enormous infiltration capacity of the PPS – they are commonly designed for an infiltration capacity of over ten times greater than for the required design storm – allows considerable sediment and pollutant build-up in the PPS (i.e. up to 90% of the surface area clogged) before the system fails (Dhalla & Zimmer, 2010).

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements



Figure 2-18: Soil embankment located adjacent a PPS causing surface clogging
(Voogt, 2011)

2.5.9 Geotextiles

Geotextiles are often incorporated in PPS designs for their ability to separate sub-base layers preventing sand from migrating into the base or sub-base course (Scholz & Grabowiecki, 2007; Tota-Maharaj *et al.*, 2012), improve pollutant removal efficiencies, provide structural support, reducing rutting depth and maintaining a good level of serviceability within the pavement (Scholz & Grabowiecki, 2007; Drake *et al.*, 2013).

The inclusion of geotextiles has become a topic of debate within the design of PPS in recent years. There are two main schools of thought around the inclusion of geotextiles in PPS. One is that they are necessary for the effective capturing of stormwater pollutants, as they facilitate the development of a microbial slime layer (similar to a *schmutzdecke* in sand filters). This allows biological treatment to take place within the PPS which is important for nutrient removal (Tota-Maharaj & Scholz, 2010; Drake *et al.*, 2013). This microbial layer is also thought to enhance the removal of heavy metals and hydrocarbons (Pratt *et al.*, 1995, 1999; Newman *et al.*, 2002). The other school of thought is that geotextiles can easily block and will therefore cause accelerated failure of the PPS. Blocking is largely as a result of the settling of solids – resulting from laminar flow through the PPS, which are entrapped in the geotextile pores reducing the hydraulic performance (and potentially the treatment efficacy) of the system, which is a major obstacle hindering the widespread acceptance of PPS (Yong & Deletic, 2008; Drake *et al.*, 2013). Yong *et al.* (2007) observed pavement clogging that appeared to occur on the geotextile surface itself as well as the channels located at the ends of the pavers. The use of geotextile therefore, has its advantages and disadvantages. The decision to incorporate a geotextile layer in future installations should be based on a careful consideration of balancing the life expectancy and pollutant removal performance of the system, without compromising one or another (Yong *et al.*, 2009).

One of the most common modes of failure of subsurface drainage systems is clogging due to movement of fine soil from surrounding material into the drainage layer and material from the drainage layer into a collector pipe (CDoT, 2004). The movement of fines into the drainage layers can be initiated both by erosion from seepage flow and pumping action caused by the repetitive loading of traffic. As such, the selection of compatible filter – usually a geotextile material can be a critical aspect of subsurface drain design.

Geotextiles are also commonly wrapped around the underdrain pipe or used as the underdrain itself. Geotextiles underdrains provide two main functions in subsurface drains:

- Hold back erodible material from intruding the drainage layer and clogging the drain; and
- Allow free flow of water (the filter must be more permeable than the subgrade soil.).

In order to protect the drainage layer from intrusion of fines the geotextile must satisfy certain design criteria to prevent intrusion and clogging. Either granular material or geotextiles can be used as a filter. (CDoT, 2004)

2.5.10 Observations concerning PPS case studies in South Africa

PPS are relatively new to South Africa and little research has been on their treatment efficacy in South African conditions. However, Armitage *et al.*, (2013a) carried out some case studies on a number of PPSs in operation in South Africa and made the following comments concerning their operation and suitability:

- i) *‘Permeable paving systems can manage stormwater without the need to install catchpits and stormwater pipes. Even when provided with under-drains, permeable paving systems markedly reduce the peak discharge from the site in question. Urban litter cannot easily enter the stormwater drainage system as there are no catchpits.*
- ii) *Sand, silt and other fine material have a destructive effect on the drainage capacity and detention volume of a permeable paving system.*
- iii) *There is potential for the harvesting and reuse of stormwater that is temporarily stored in the sub-base layers of the permeable concrete block paving (PCBP) system.*
- iv) *PCBP systems are best constructed with small surface slopes – even flat. This ensures that stormwater does not run off, but sinks into the surface. On the other hand, the base of the excavation should be graded to assist the flow towards the outlet to ensure the pavement system empties during storm events.*
- v) *The performance of PCBP systems relies on adequate maintenance to reduce / remove clogging.*
- vi) *Permeable paving areas should be designed with particular consideration given to local landscaping to prevent fine material from embankments or planters washing onto the*

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

pavers and causing premature clogging. Ideally the paving should be higher than the abutting vegetated areas. Particular care needs to be taken during the establishment of the vegetation as this is when the risk is greatest.

- vii) *The many different colours and textures available in PCBP allow for more aesthetically pleasing environments.*
- viii) *PCBP is, under many urban conditions, more resistant to general wear from applied loads than most asphalt surfaces (Concrete Manufacturers Association, 2003). This typically increases the longevity of a paving system and lowers the maintenance costs.*
- ix) *Concrete grass block pavers are ineffective SuDS technologies in clayey soils. Furthermore, they tend to get very hot in warm climates which can inhibit the growth of the grass.*
- x) *It is currently difficult to source suitable material for filling the joints between permeable concrete blocks e.g. 1-3mm stone. This is likely to increase construction cost as a result of additional transportation expenses.'*

2.5.11 Advantages / benefits of PPS

The benefits associated with installing PPS are listed below (Armitage et al. 2013; Woods-Ballard et al. 2007)

- i) *'Permeable pavements reduce stormwater drainage rates and volumes from impervious areas;*
- ii) *Permeable pavements increase the 'usable' area on specified developments by utilising, inter alia, roadways, driveways and parking lots as stormwater drainage areas;*
- iii) *Stormwater runoff stored in permeable pavements can be used to recharge the groundwater table and for several domestic purposes;*
- iv) *Lined permeable pavement systems can be utilised where foundation or soil conditions limit infiltration processes; and*
- v) *If correctly designed, constructed and maintained, permeable pavements eliminate surface ponding and freeze-thawing in cold regions.'*

2.5.12 Disadvantages / costs of PPS

The disadvantages associated with installing PPS are listed below (Armitage et al., 2013b)

- i. *'The implementation of permeable pavements is generally limited to sites with slopes less than 5% (Melbourne Water Corporation, 1999);*
- ii. *Permeable pavements should not be constructed over fill materials as these soils could fail when saturated;*

Chapter 2 : Literature Review

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

- iii. *Permeable pavements are not normally suitable for high traffic volumes and speeds greater than about 50 km/hr, or for usage by heavy vehicles and/or high point loads (Woods-Ballard et al., 2007);*
- iv. *If managed incorrectly, there is great potential for clogging by fine sediment, which significantly reduces the effectiveness of the specified system; and*
- v. *The pollutant removal ability of permeable pavements is lower than most other SuDS options.'*

2.6 Summary and conclusions

Stormwater management in the urban areas of South Africa has and continues to predominantly focus on collecting runoff and channelling it to the nearest watercourse. This means that stormwater drainage presently prioritises quantity (flow) management with little emphasis on the preservation of the environment. The result has been a significant impact on the environment, particularly the receiving waters, through the resulting erosion, siltation and pollution. An alternative approach is to consider stormwater as part of the urban water cycle, a strategy which is being increasingly known as Water Sensitive Urban Design (WSUD) with the stormwater management component being known as Sustainable Drainage Systems (SuDS). SuDS attempts to manage surface water drainage systems holistically in line with the ideals of sustainable development. It aims to design for water quantity management, water quality treatment, enhanced amenity, and the maintenance of biodiversity. In so doing many of the negative environmental impacts of stormwater are mitigated and some benefits may in fact be realised (Armitage *et al.*, 2013b).

Permeable pavement systems (PPSs) – widely-adopted SuDS technologies in South Africa, are devices that reduce stormwater runoff and/or pollution of stormwater at or near the source by infiltrating stormwater into their porous sub-structures. Consequently, PPS reduce drainage volumes, attenuate peak stormwater flows and potentially trap pollutants. Additional benefits include the capture of stormwater for reuse – potentially alleviating the demand on the water supply system, and/or increased groundwater recharge. Furthermore, they are easily constructed and do not normally take up any additional plan area. As a result, PPSs are now widely considered sustainable substitutes for conventional impervious surfaces. While there have been a number of international studies investigating the pollutant through put of permeable pavements, few or no studies have been conducted in a South African context. This study, therefore, intended to address the literature ‘gap.’ The following chapter provides a description of the research method carried out to address the research aims by, *inter alia*, providing locally-relevant data on the impact of unwashed aggregate on water quality emanating from PPS for possible re-use in fit-for-purpose applications.

3. Research method

3.1 Introduction

This chapter details the laboratory PPS experimental method conducted for this dissertation. A controlled laboratory simulation experiment was designed to test the impact of unwashed aggregate on the water quality improvement capabilities of PPS for pollutants such as ammonia nitrogen (NH_3), orthophosphate (PO_4^{3-}), nitrate (NO_3^-) and TSS. The research method was divided into three primary phases namely: flushing the laboratory system with clean tap water and monitoring the water quality emanating from each; testing the pollutant removal capacity of the system; and lastly stripping and examining the pavements for the presence of sediment.

This section describes the experimental apparatus, material selection, ‘design’ stormwater, assessment of stormwater quality, system flushing, pollutant retention capacity, experimental sampling, and the laboratory pavement disassembly.

3.2 Laboratory experimental design and methodology

The laboratory experiment aimed to develop a robust methodology that can be used in the future to assess whether appropriately designed PPS can improve the quality of stormwater drainage for stormwater harvesting, by retaining and even treating stormwater pollutants within the pavement structure. If designed and constructed appropriately, PPS have the potential to retain pollutants within the pavement structure and thereby reduce pollutant loading on receiving waters (Scholz & Grabowiecki, 2007). The laboratory pavement designs and construction methods were informed by the design and construction of the NEB parking area which took place adjacent the laboratory building during the early phases of the dissertation – a description of the NEB design and construction procedure can be found in Appendix D: New Engineering Building parking area. The effectiveness of PPS in the laboratory was considered by evaluating the water quality performance of PPS against varying standards, and comparing PPS performance to that of traditional, impervious surfaces.

The primary objectives of the study were designed to provide substantial evidence in the lab to understand pollutant throughput and potential for harvesting water. The NEB permeable pavement design – design drawings can be seen in Appendix B – adopted a typical Hanson / Formpave ‘Aquaflo’ pavement design (depicted in Figure 3-1) with some adaptations – such as a thicker reservoir aggregate layer to increase storage capacity of the system. The ‘Aquaflo’ design is a commonly used pavement design in the greater CoCT region. Some of the pavement materials used in the construction of the laboratory experiment were taken directly from the NEB pavement site stockpiles – most important to note was the use of unwashed aggregate, to produce as far as possible laboratory conditions representative of existing pavements in the CoCT. It is important to note that the type of aggregate/crushed stone taken from the NEB site that was transported from a nearby Lafarge quarry was mined from natural Hornfel deposits, locally

termed ‘Hornfel Malmesbury Shale’. The objectives were investigated by way of the following activities, in three different stages:

- i) Flushing the laboratory system with clean tap water to establish ‘base-line’ pollutant values prior to the addition of typical stormwater pollutants and to assess whether the construction materials themselves contribute to effluent pollutant loads.
- ii) Testing the treatment efficacy of the system by adding pollutants to each pavement surface and simulating rainfall events to determine whether stormwater can be harvested from PPS for ‘fit for purpose’ use. Hydraulic monitoring was carried out manually using measuring cylinders and a stopwatch, recording total drainage volumes at specific times to indicate flows.
- iii) Lastly, the pavements were stripped and examined for the presence of sediment.

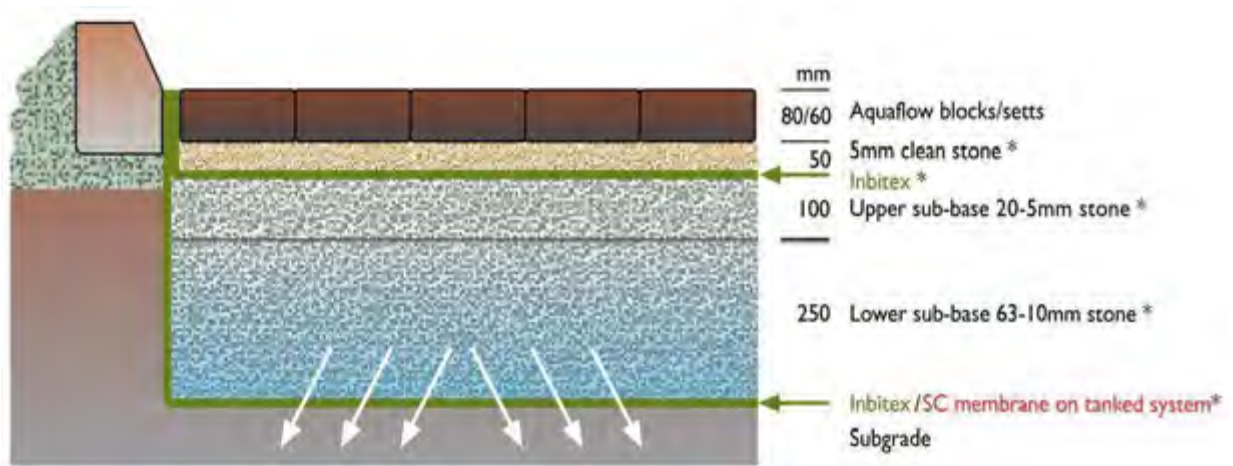


Figure 3-1: Typical Aquaflo infiltration system subject to light vehicle activity
(Formpave & Hanson, 2010)

3.2.1 Experimental apparatus

The PPS laboratory apparatus comprised four separate units, each unit comprising a container housing a different permeable pavement layer configuration. The containers were high density polyethylene (HDPE) plastic MPact® ‘Jumbo Bins’ (Figure 3-2) that were selected as they are robust, relatively low-cost and easy to work with. The plan area of each Jumbo Bin is approximately 1.2m x 1.1m with an inside depth of 0.6m. They were each fitted with a perforated under-drain that was deliberately not wrapped with a geotextile – although it is common practice to wrap the underdrain with a geotextile in PPS construction – so as to ensure that the test results reflected the impact of the PPS unaffected by the under-drain design as shown in Figure 3-3. The outflow from the PPS could be controlled via the installation of a valve on the outlet. The pavement materials were placed inside each cell according to the selected design (Figure 3-4).

To avoid excess ponding on the bottom of the bins, the raised sections of the outlet fittings were ground down to reduce the height of the outlet above the base surface. The outlets were then connected with a T-piece and drained to a drainage bin through a shut-off valve.

Each Jumbo bin was positioned on a concrete footing to accommodate a drainage bin below the outlet, and given a base slope of approximately 2.5% ensuring that water passing through the PPS drained out of two 25mm outlets positioned near the edges of each bin (Figure 3-2). Most permeable pavement design guidelines recommend a maximum base slope of 5% for the installation of these systems (Lucke & Beecham, 2011). A base slope of 2.5% was selected as it minimised the storage effect of the raised outlets. Due to the shape of the Jumbo Bin base and position of the outlets, a greater (or lesser) slope would have increased the storage volume of the system.



Figure 3-2: Bins positioned on concrete blocks to accommodate drainage tray

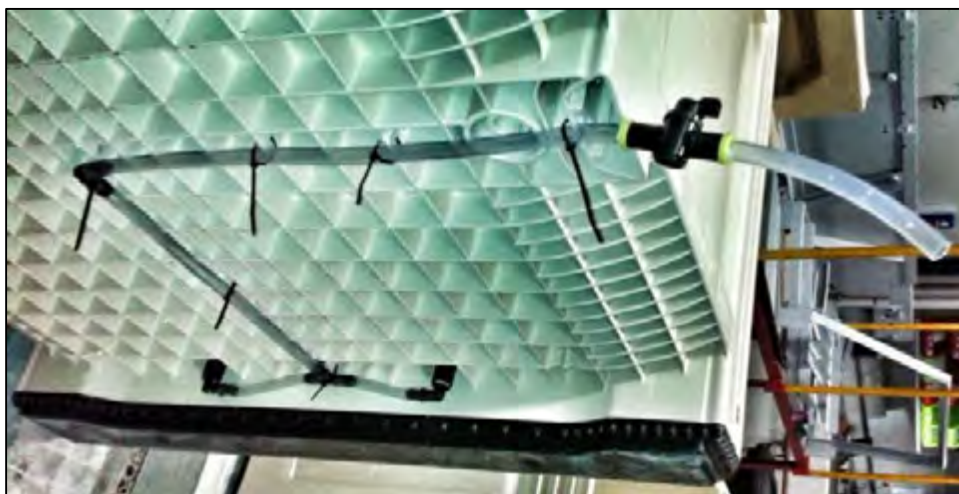


Figure 3-3: The underdrain system for the PPS model

Chapter 3 : Research method

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

The paving surface was kept horizontal to ensure that the applied water infiltrated through the entire paving surface and not along the box edge. Subgrade drainage from each cell was collected in a drainage tray situated below the drainage valve as illustrated in Figure 3-3.

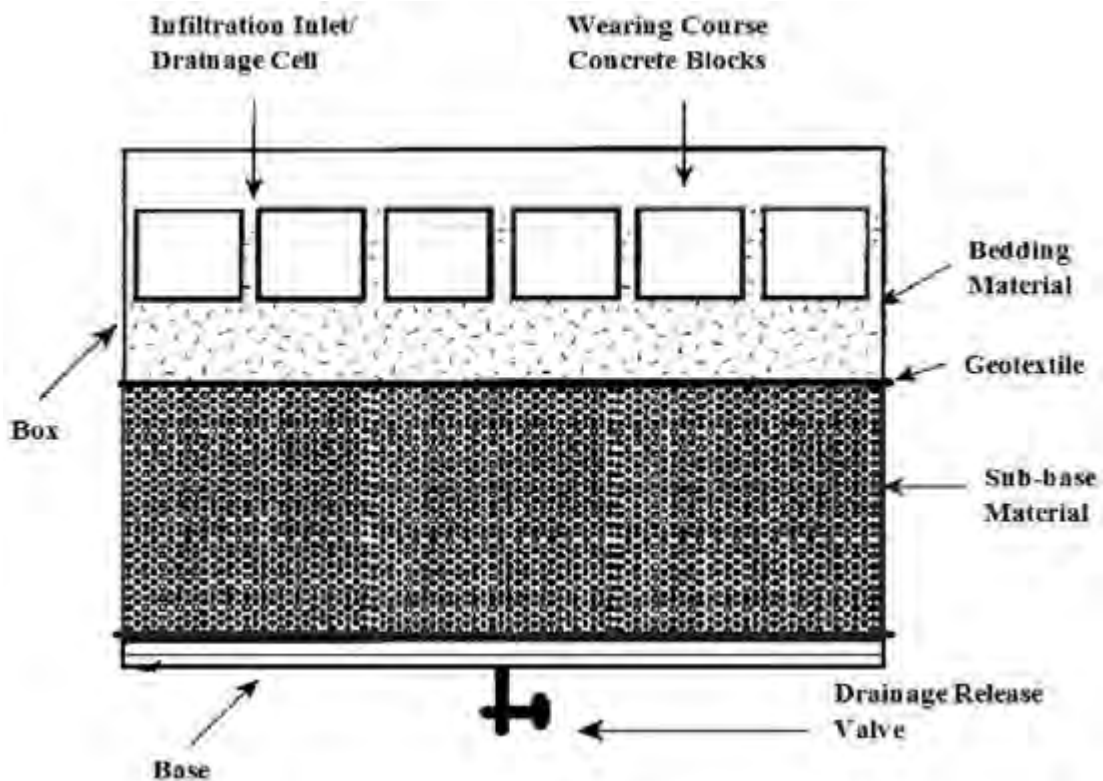


Figure 3-4: Cross section through a typical permeable pavement testing structure

3.2.2 Selection of surface wearing course and pavement materials

Aquaflow blocks®, pavers widely used in the Western Cape as shown in Figure 3-5, comprising slotted permeable paving blocks manufactured by INCA Concrete Products, were selected as the representative surface wearing course in each design. These blocks were used in the laboratory to replicate the NEB paving design under controlled conditions to observe how the system performed under accelerated testing. The primary function of the wearing course is to facilitate a load bearing surface while allowing stormwater to infiltrate to the base layers below. The paver dimensions are 100 x 200 x 80 mm and are designed for use in car parks, drives and moderately trafficked areas.

The pavers were placed on 2-6mm bedding gravel with additional ‘pea- sized’ gravel – 2-4mm quartzite/gritstone - grit (‘pea-sized’) placed between the blocks that lock them together whilst allowing a high infiltration rate. The construction method used in the laboratory

Chapter 3 : Research method

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

experiment mimicked the NEB parking area construction method in an attempt to replicate the conditions found in local construction practices. Unwashed crushed stone – ‘Hornfel Malmesbury Shale’ – taken directly from the NEB parking area construction site stockpiles was utilised both for the bedding gravel as well as the various layers of 19 and 50-60mm aggregates.

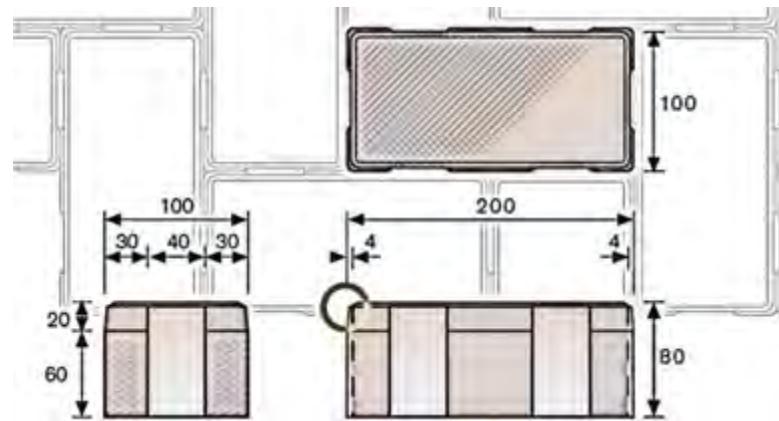


Figure 3-5: Aquaflow block® dimensions
(Hanson-Formpave , 2010)

Four different pavement designs (pavements A, B, C and D) were selected for the laboratory simulation – the materials and layerworks selected are shown in

Figure 3-6. Various studies (Pratt *et al.*, 1989, 1995, 2002a; Pratt, 1999; Myers *et al.*, 2011) have shown that the design and condition of the pavement materials impact on the quality of water being stored or passing through the structure; e.g. conductivity, alkalinity and pH of stored stormwater. In particular, the total suspended solids (TSS) exiting the structure can show considerable variability deriving from the condition of the internal construction materials themselves (Pratt *et al.*, 1995). Furthermore, Myers *et al.*, (2011) noted initially significant increases in the levels of TSS and turbidity when water came in contact with the reservoir base course aggregate. Consequently, the material selection and associated condition in PPS design should be considered carefully according to the design objectives.

Design objectives can include: infiltration into the sub-soils, temporary attenuation before release into the receiving waters and/or storage within the structure for reuse. The selected designs thus attempted to be indicative of the range of designs commonly used in practice. Two of the pavements (A – ‘no geotextile’, and B – standard Aquaflow design) were also designed to ‘mirror’ the two bays being monitored as part of the NEB parking area field testing (see Appendix B). Pavement C – ‘no small stone,’ was constructed to assess the impact of excluding the upper unwashed aggregate reservoir layer (19-25mm stone) on the water quality emanating from the pavement. This layer has more surface area than the ‘Big stone’ – 50-63mm stone – which could allow proportionally more sediment to adhere to the aggregate surface. Pavement D – ‘Sand,’ incorporated bedding rather than bedding gravel. Sand is a common, cost effective material and

Chapter 3 : Research method

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

has been used extensively in slow rate filters. It is a useful alternative to bedding gravel due to its treatment capabilities however, its use additional poses clogging risks in conjunction with PPS. To further understand the influence geotextiles have on the treatment efficacy of PPS, Inbitex[®] geotextile was included in the design for Pavements B, C and D, while Pavement A acted as the control without geotextile.

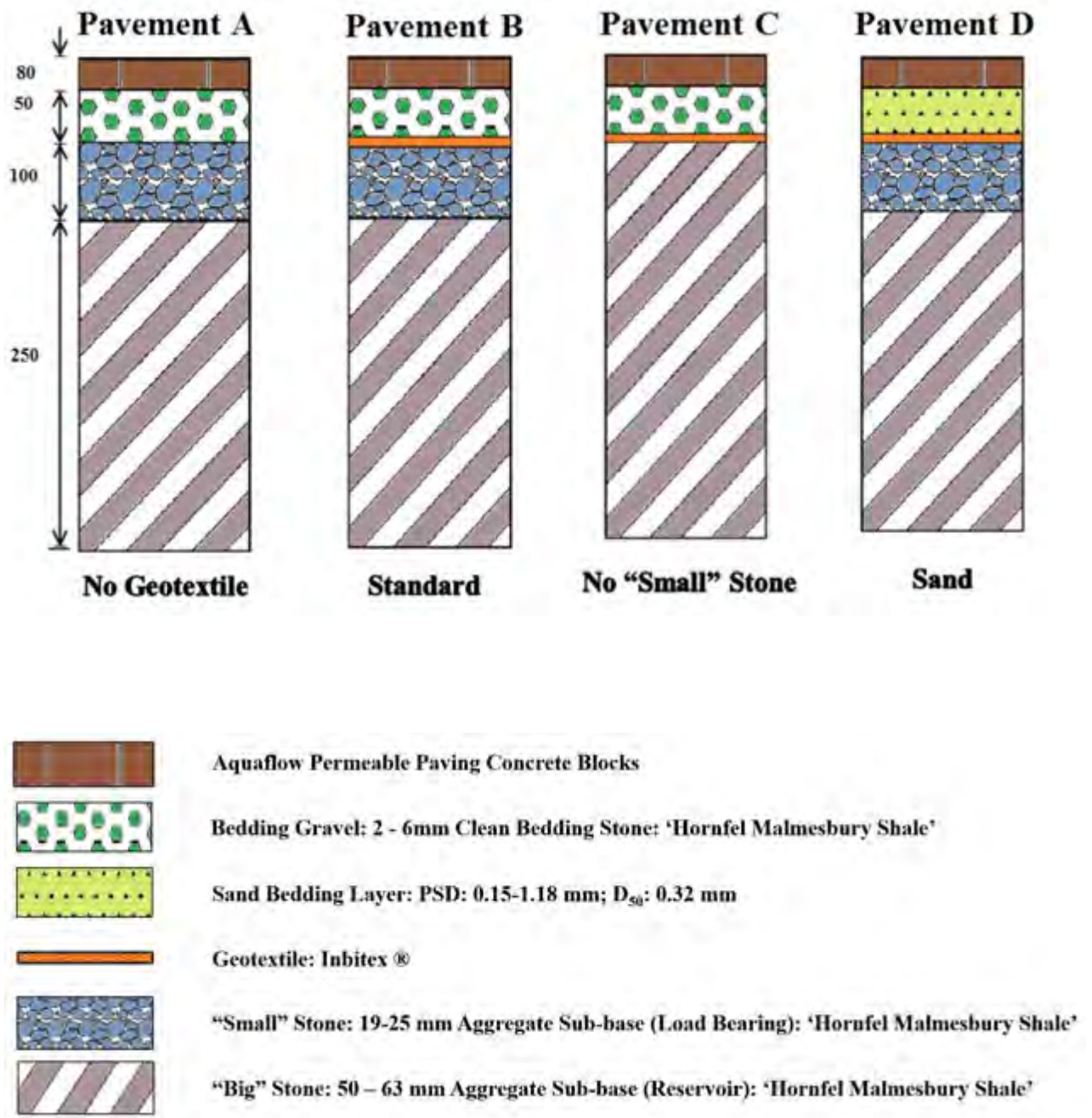


Figure 3-6: Four pavement designs with varying base layers

Chapter 3 : Research method

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

3.2.3 Laboratory testing - construction considerations

The construction process itself highlighted several important construction considerations that needed to be addressed which included the following:

- i) **Inconsistent drainage times and volumes** – The experimental set-up was initially provided with the same base slope of 2.5% for each bin to facilitate similar drainage characteristics at each outlet. This slope was selected to allow similar drainage times and volumes at each outlet and to minimize the residual storage effect due to the raised outlets. Before the pavement materials were added, the drainage characteristics for each bin was tested by adding equal volumes of water to the empty bins and measuring the drainage volumes and associated drainage times. Although the outlets were all sanded down to the same height in each bin and the base slopes were the same, differing drainage times and volumes for each bin were initially recorded. If left unchanged, this would have facilitated inconsistent drainage conditions for each bin. Therefore, the slope of each bin was adjusted accordingly and the test repeated until the drainage times and volumes converged to a reasonably similar value (Table 3-1 shows two of the iterations). The differences in drainage characteristics were mostly likely caused by variations in the bin base shapes and the bin underdrain system. As can be seen in Table 3-1, a residual volume of roughly 2.5ℓ remained in the empty bins however, some of this water ponding on the base was displaced by the stone.
- ii) **Water storage and dilution ratio** – a depression storage of between 2 and 3 litres occurred in the base of the bins due to the configuration of the pipes below the bins, as well as the slightly raised outlets. The raised outlets were filed down as much as possible (roughly 1mm from the bottom of the bin) and the length of the piping was also minimised to reduce the storage effect. It is acknowledged that the residual volume present at the bottom of the bins could potentially alter the effluent quality results. However, similar occurrences are likely in existing PPS, which usually contain underdrains, sometimes an impermeable underlay, and a slightly raised outlet, i.e. at the position of the underdrain pipe.

Raised supports for the bins – choosing suitable supports was an important safety factor, as the self-weight of the PPS model containing the layerworks was in excess of 1 tonne. The bins were raised off the ground with reinforced concrete slabs in order to provide the drained water exiting the outlets with an adequate head to enable flow collection.

Table 3-1: Two iterations measuring the drainage times and volumes for each bin

Bin	Final slope	Volume added (ℓ)	Drainage volume (ℓ)		Drainage time (s)	
			Reading 1	Reading 2	Reading 1	Reading 2
A	2,7%	4	780	1160	2150	1780
B	2,4%	4	1750	1590	1505	1505
C	2,2%	4	1950	1690	1520	1520
D	2,6%	4	950	1640	375	975

Chapter 3 : Research method

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

3.2.4 Design stormwater

A number of international studies (US EPA, 1983; Marsalek et al., 1993; Duncan, 1999; Marsalek, 2000; Debo & Reese, 2003) that quantified ‘typical’ or ‘average’ stormwater pollutant concentrations for different land uses were grouped together as shown in Table 3-2. Due to the lack of locally available stormwater quality data it was decided to derive ‘typical’ or ‘design’ pollutant concentrations from these studies to be used in this study. The complex, variable nature of stormwater makes it inherently difficult to quantify, and for this reason Debo & Reese (2003) suggests using the event mean concentration (EMC) as a stormwater quality baseline. Where possible, the upper bound values were selected from three of the four studies: Debo & Rees (2002), Duncan (1999) and U.S. EPA (1983) – these studies were separate sewer systems, to derive a ‘typical’ stormwater quality. As a reference, some studies also compare with typical combined sewer overflow (CSO) values. However, South Africa generally uses separate sewers and therefore the use of CSO values was unsuitable to derive representative pollutant values.

3.2.5 Assessment of stormwater quality for ‘fit for purpose’ use

Water quality is inherently relative; however, treatment performance should be evaluated from a ‘fit-for-purpose’ perspective. Fit-for-purpose use refers to matching water of a certain quality to a use appropriate for that quality. Fitness for purpose of the drainage can be assessed by way of the South African Water Quality Guidelines, with the following four broad categories of water use having most relevance:

- i) domestic purposes (DWAF, 1996c);
- ii) industrial purposes (DWAF, 1996d);
- iii) agricultural purposes (DWAF, 1996a); and
- iv) recreational purposes (DWAF, 1996b).

Table 3-2: Design stormwater quality

Contaminant	Units	Pollutant concentrations for different land uses (3s.f.)				Design stormwater quality (3s.f.)
		Residential	Commercial / Industrial	Urban stormwater		
Source		Debo & Rees (2002)		Duncan (1999)	U.S. EPA (1983)	
BOD	mg/l	10.0	9.30	14.0	9.00	14.0
COD	mg/l	73.0	57.0	80.0	65.0	80.0
TSS	mg/l	101	69.0	150	100	150
Total Lead (Pb)	µg/l	144	104	140	144	144
Total Copper (Cu)	µg/l	33.0	29.0	50.0	34.0	50.0
Total Zinc (Zn)	µg/l	135	226	240	160	240
Total Nitrogen	mg/l	-	-	2.60	-	2.64
TKN	mg/l	1.90	1.18	-	-	1.90
NO ₂ + NO ₃	mg/l	0.736	0.572	-	-	0.736
Total Phosphorus	mg/l	0.383	0.201	0.350	0.330	0.383
Soluble Phosphorus	mg/l	0.143	0.0800	-	-	0.143
Oil and Grease	mg/l	-	-	8.70	-	8.70
Faecal Coliforms	FCU/100m l	-	-	8000	-	8000

Chapter 3 : Research method

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

The South African Water Quality guidelines provide a comprehensive set of target ranges for a wide selection of chemical components that may be present in the water. These guidelines were intended to provide the information to make judgements on the fitness of water to be used in one (or more) of the various categories.

Of these categories one of the most pertinent to this study was thought to be uses related to agricultural purposes (which includes use for domestic garden watering in this context), in which case the South African Water Quality Guidelines: Volume 4 Agricultural Use – Irrigation would apply. However, other likely uses for stored water from PPS include flushing toilets, car washing etc. – but none of the South African Water Quality Guidelines specifically deal with these quality requirements. Suitable applications were therefore to be identified according to the quality of effluent exiting the PPS, which depended on the treatment efficacy of the system. If there are numerous suitable ‘fit-for-purpose’ applications, then practical and economic viability of PPS harvesting increases

3.2.6 System flushing

Clean tap water was applied to each unit in quantities roughly representative of a typical rainy season in the CoCT but at an accelerated rate. The discharge was collected and analysed with a view to establishing ‘base-line’ pollutant values prior to the addition of typical stormwater pollutants. This section details the simulated ‘flushing’ process for each PPS laboratory design, which includes the selection of a suitable rainfall regime typical of the greater CoCT region (hereafter referred to as the CoCT), the application process and the effluent sampling.

3.2.6.1 The need for flushing

In South Africa, it is common practice for the base layers of PPS to be constructed with unwashed crushed stone (Wium, 2015). The use of unwashed stone can severely pollute pavement effluent particularly with small particulate solids that adhere to the surface of the stone (German & Svensson, 2002; Ellis, 1977). In order to mimic local construction practices exemplified by those employed in the NEB parking area, unwashed crushed stone (50-60mm and 19mm stone, and 2-6mm bedding / pea gravel) collected from the NEB parking area was utilised in the construction of the laboratory structure.

Local PPS construction typically makes reference to SABS 1200M as the standard specification. It refers to the use of ‘clean’ stone but this is more to do with the detritus and contamination rather than ‘washing’ the stone. Generally the stone used in CoCT PPS construction is received from the quarry and placed immediately in the layer. A big problem lies in ensuring the loader at the quarry does not load the underlying soil, or even the lowest layer of stone, where all the fines accumulate (Wium, 2015).

Dust or small particulates coating the stone in PPS can be flushed or washed from the system during storm events. It was expected that an initially high concentration of sediment

Chapter 3 : Research method

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

would be washed from the lab structures' base layers during simulated storm events, but that concentrations would diminish and stabilise after a period of time. This was supported by a small scale demonstration project which was carried out to illustrate the importance of washing / cleaning the aggregate stone before placement in the PPS base layers. Two miniature pavements – one permeable and one impermeable – were constructed to illustrate how effectively the PPS could infiltrate stormwater (Figure 3-7 and Figure 3-8).



Figure 3-7: Permeable demonstration pavement illustrated in plan and elevation

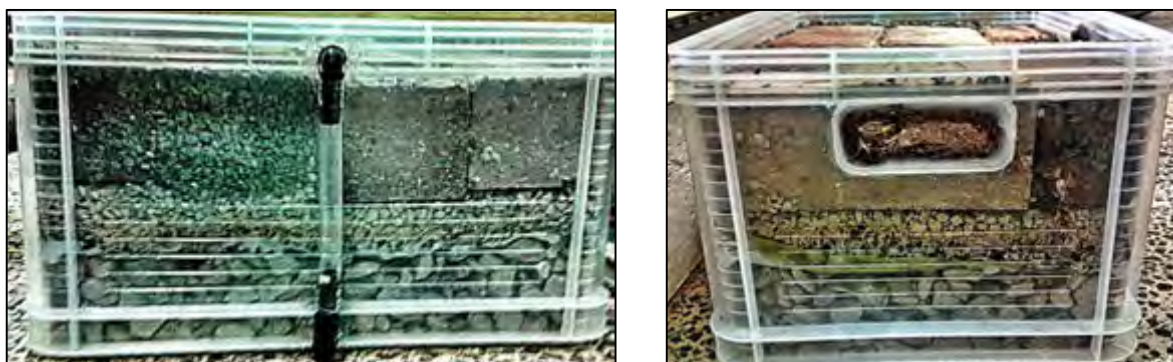


Figure 3-8: Impermeable demonstration pavement illustrated in plan and elevation

When clean tap water was applied to the surface of the permeable demonstration structure (which made use of the same materials as the lab project and the NEB Parking area), a significant amount of sediment was flushed from the system. In fact, for this small demonstration PPS (plan area 400mm x 200mm), roughly 70ℓ of water was required to flush the pavement so that the effluent quality was no longer visibly discoloured by sediment. However, the application intensity was considerably higher than what can be expected in existing sites. Nevertheless, this volume equates to about 875mm of rainfall – more than 1.5 times the CoCT annual average – meaning

Chapter 3 : Research method

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

that this pavement required roughly a year and half of effective rainfall (under CoCT conditions) to flush out the base layers before it visually stabilised and was no longer leaching considerable amounts of sediment from the unwashed stone. It should be noted that the high application intensity could have accelerated the flushing process. It was decided that the larger scale laboratory pavements, constructed with the same stone and method as the demonstration pavements, would also need to be flushed.

3.2.6.2 Flushing regime

In order to determine the amount of rainfall needed to ‘wash’ the base layers and stabilise each system, a rainfall regime needed to be applied to each pavement. Selecting a suitable rainfall regime was necessary to simulate, as far as possible, ‘typical’ CoCT rainfall conditions in the laboratory. However, representing ‘typical’ rainfall conditions in a controlled environment was challenging due to the inherent variability of rainfall. Factors such as rainfall depth, rainfall intensity and rainfall application all affect the characteristics of each rainfall simulation. Rainfall data from the Cape Town International Airport was selected because it is central to the greater CoCT region and provided easily accessible daily rainfall data for over 40 years. The annual mean rainfall from the Cape Town International Airport rain gauge was 531.4mm between the years 1960 and 2002 (1stWeather.com, 2002). In 2002, 522.5mm fell which equates to 98% of the annual mean rainfall. Due to the similar mean, 2002 was selected as a representative rainfall year for the laboratory rainfall regime (Table 3–2). Although rainfall intensity plays an important role in the mobilising pollutants, for practical reasons it was decided that the rainfall intensity would be kept reasonably constant for each application. Therefore, the rainfall depths of each event varied to mimic rainfall depths of an actual rainfall season but the intensity was kept constant.

Potable ‘tap’ water was applied to the surface of the PPS via a 10ℓ garden watering can to simulate the rainfall. Any pollutants in the effluent could then be directly linked to the leaching from the pavement base layers. To simplify the rainfall simulation process – and in appreciation of the essential random nature of rainfall – the water was simply sprinkled over the surface in units of 5ℓ (or parts thereof) with an interval of around 9 minutes between applications at more-or-less the same rate regardless of the rainfall depth being applied. In general, the effective storm intensity was in the order of that typical of a 10 year recurrence interval storm for the CoCT (31mm/hr), a reasonably high intensity.

In the CoCT, the majority of the rainfall (62% in the case of this station) and most of the heavier showers likely to impact the PPS (nominally greater than 5mm) occur in the months of May, June, July and August according to rainfall data collected from the South African Weather Service (1stWeather.com, 2002). These months were thus chosen to be representative of the rainy season in CoCT. Non-rain days, defined as days with less than 0.1mm of rainfall (Chowdhury & Beecham, 2013), were removed from the 2002 daily rainfall data to produce a rainfall schedule as shown in Table 3-4.

Chapter 3 : Research method

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

Table 3-3: Monthly rainfall (in mm) data (2002) and average monthly rainfall from 1960-2002 (1stWeather.com, 2002)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2002	60.9	14.9	9.3	28.0	71.9	76.4	98.2	65.7	26.1	32.5	23.6	15.0
Average (mm)	12.6	14.9	9.3	43.8	68.5	100.8	82.2	71.9	42.0	32.8	17.0	17.3
Percentage of average	483	100	100	64	105	76	119	91	62	99	139	87

3.2.6.3 Rainfall application for the flushing phase

The 52 rainy days are indicated by month in Table 3-4, which also shows that there were never more than 14 rainy days in any given month. To speed up the test procedure, the rainfall events were simulated in quick succession in this first, base-line, phase as the main aim here was to determine the impact – if any – of the pavement layers prior to the addition of ‘polluted’ stormwater in the second phase. Essentially, as soon as the pavement was completely drained, the next ‘rainfall event’ was applied to the surface. A simulated rainfall event was thus produced roughly each hour.

Table 3-4: Proposed laboratory rainfall schedule for ‘flushing’ the system

Month	Rainfall schedule (mm)														Total
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
May	1.6	4.4	11.8	1.6	0.2	1.4	17.4	1.4	2.8	7.6	7.6	2.4	11.7	-	71.9
Jun	10.8	14.3	0.2	1.0	4.9	0.2	2.0	3.0	1.0	0.4	11.0	8.8	7.9	4.9	76.4
Jul	2.0	13.8	0.2	12.6	7.5	0.5	0.2	26	2.0	8.6	1.8	18.4	3.6	1	98.2
Aug	4.2	3.6	0.2	0.2	7.5	5.6	2.0	4.5	1.0	34.0	2.9	-	-	-	65.7
															312.2

The most suitable choice of source of water (i.e. tap water, rainwater or distilled water) for the laboratory based experiments was an issue requiring consideration. The experimental methodology needed to sufficiently replicate field conditions without introducing significant bias to the results of the investigation. Distilled water would have been ideal for this study, but was considered impracticable as large quantity of water was required. Tap water was readily available but there was need to ensure this source of water would not significantly introduce bias to the outcome of this study. This tap water tested for the presence of nitrates, ammonia, EC, turbidity, TSS and pH and found to be within the limits prescribed by the South African Water Quality Guidelines: Volume 1 - Domestic Use, which prescribe water primarily for human consumption. It was therefore considered ‘clean’.

Chapter 3 : Research method

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

Rainwater use was also a possibility but it is inherently variable and needed to be captured from roof runoff. Rainwater use was not selected for practical and economic reasons. Some preliminary experiments were conducted on the flushing of pollutants (TSS, Nitrates (NO_3^-), Ammonia (NH_3) etc.) using de-ionized water and tap water. The results showed that there was no significant difference between the flushing of selected pollutants using either de-ionized water or tap water. These results were reinforced by the findings highlighted in Nnadi (2009). Consequently, tap water was used in the laboratory investigation. A concern was that chlorinated tap water had the potential to inhibit the formation of any *schmutzdecke* / slime layer (Nnadi, 2009), essential for biodegradation. However, it was assumed that the effects from the use of tap water would not be significant compared to the impacts that could arise from using other sources of water (i.e. rainwater, which could introduce variable levels of nutrients and dust to the system).

3.2.6.4 Sampling and monitoring of pavement flushing

Manual grab samples were taken at regular intervals and analysed to determine the concentration of selected pollutants being flushed from the system throughout the simulated 'rainy season'. These pollutants included: PO_4^{3-} , NH_3 , NO_3^- , TSS, turbidity and EC. These samples were analysed individually to determine the concentrations of the mentioned indicator 'pollutants', the changes in pollutant concentration over time and to identify peak concentrations of pollutants. Samples were initially taken at 5ℓ (3.8mm of rainfall) intervals of drained effluent. Thereafter, the drainage volume interval between samples was increased to 10ℓ; then increased to every 20ℓ as changes in sample turbidity became less observable. The sampling schedule for the sampling of TSS is illustrated in Figure 3-9.

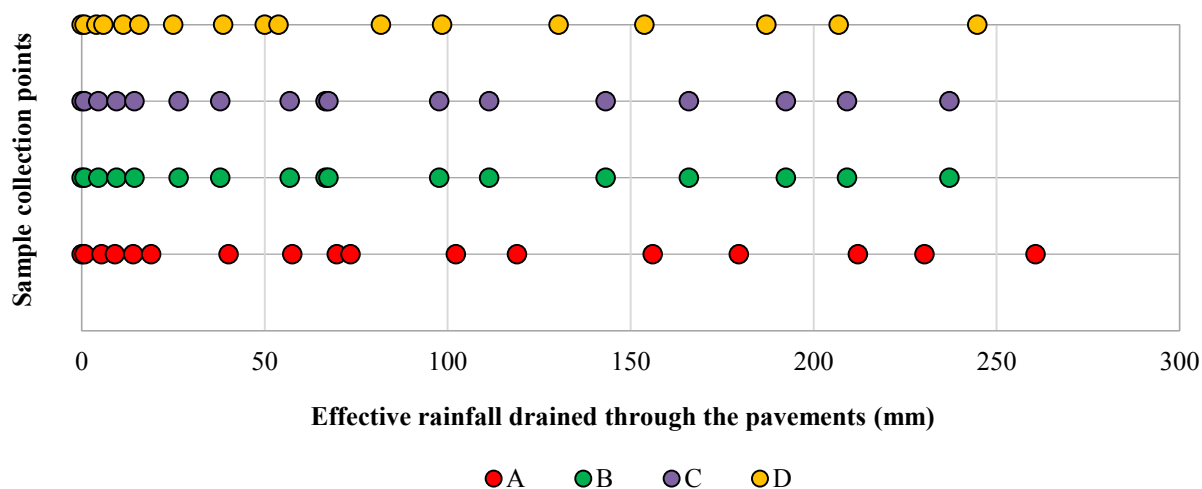


Figure 3-9: Sample collection intervals throughout the flushing process

Hydrological (flow) monitoring was carried out manually with the use of measuring cylinders and a stopwatch. Flows were estimated by timing how long the drainage flow took to fill a specified volume. ‘Effective rainfall drained through the pavements’ was used to represent the progression of the flushing process rather than total volumes drained through each pavement. Effective rainfall depth is a more relatable function than volume drained as it allowed the flushing volumes to be measured in terms of the number of ‘rainy seasons’ passing through each pavement.

3.2.6.5 Final flushing

After one ‘rainy’ season of simulated rainfall, the pavements had not yet been fully flushed. Turbidity levels in the effluent of each pavement were considerably higher than that of tap water, suggesting that the pavement materials were still leaching sediment and possibly other pollutants. The flushing process was then accelerated by running clean tap water via a hose pipe directly onto each pavement at a rate that equalled the drainage rate. Each pavement was filled to the surface of the pavers and then flushed at a constant flow rate (the same as the drainage flow rate) for a number of hours. More than 1900mm of effective rainfall was applied to each unit equating to more than 3.6 years of annual average rainfall for the CoCT.

A target turbidity range of 1-3 NTU was selected for the flushing process as this range falls within the second target water quality range (1-5 NTU) for domestic use (DWAF, 1996c) – above the requirements for non-potable use – and in the first target water quality range for industrial use (DWAF, 1996d). The initially high turbidity levels exiting each pavement, which are presented in Section 4.1.4, were reduced substantially by the end of the final flushing process. In Pavement B for example, turbidity levels were reduced by 3 orders of magnitude after 1970mm of effective rainfall passed through the system. Effluent turbidity levels exiting the pavement followed a logarithmic trend, tending towards the turbidity of clean tap water. The clean tap water values, measured from numerous samples, varied between 0.51 and 0.99 NTU with a mean of 0.83 NTU. Once a turbidity range of between 3-5 NTU was reached, the rate of decrease became less apparent and large volumes of water were required to reduce turbidity levels below 3 NTU. Once effluent turbidity levels dropped below 3 NTU the flushing process was stopped.

3.2.7 Testing the treatment efficacy of the PPS

Whilst it is accepted that small-scale laboratory experiments are an approximation of the functioning of the systems under study, simulations using model rigs are frequently used to study specific aspects of their performance (e.g. Fach & Geiger, 2005; Yong *et al.*, 2009; Charlesworth *et al.*, 2012). Testing the treatment efficacy of the PPS involved monitoring the retention capabilities of the various pavement models when exposed to high levels of contamination by various pollutants after the flushing exercise described in the previous sections. Polluted synthetic stormwater – the selected pollutant concentrations are discussed in detail in sections

3.2.7.1 and 3.2.7.2, was applied to each pavement and the water quality of the effluent draining from the system was monitored. The pollutant retention capacity of the system was assessed by comparing influent and effluent concentrations of selected pollutants. The methodology for this study largely followed common methodologies found in supporting literature (Newman *et al.*, 1996; Andersen *et al.*, 1999; Pratt *et al.*, 1999; Fach & Geiger, 2005; Yong *et al.*, 2008; Nnadi, 2009; Mullaney *et al.*, 2011), but elements such as the rainfall regime were adapted to the South African case, and especially to specific local CoCT conditions. It was imperative that the sampling methodology captured the wide degree of variability inherent in stormwater flows and pollutant concentrations. Previous laboratory studies have assessed treatment performance of PPS designs by comparing concentrations of various pollutants in the influent (usually comprising synthetic polluted stormwater) and effluent and then determining the pollutant retention capacity of the system (Drake *et al.*, 2013). This is easier to achieve in the laboratory under controlled conditions than at existing permeable paving sites, where issues such as monitoring equipment safety and access to the drainage outlets arise.

Selecting suitable pollutants for the treatment efficacy testing of the PPS laboratory investigation was critical to the relevance of the study for South African conditions. A number of factors informed the selection of pollutants in the study: the CoCT stormwater policy (CoCT, 2009) supports WSD principles and SuDS objectives through targeting, *inter alia*, stormwater quality improvement. In this policy, the criteria for achieving the SuDS objectives in various development scenarios focuses on suspended solids (SS) and total phosphorus (TP) removal to the undeveloped catchment levels; or targets an 80% SS reduction and 45% TP reduction, whichever requires a higher level of treatment. Furthermore, Scholz & Grabowiecki (2007) noted that the most important target pollutants relating to water quality from PPS are hydrocarbons, heavy metals and nutrients (nitrogen and phosphorus). TSS was added to this list of parameters as it is an important parameter in the context of harvesting stormwater from pavements for re-use for several reasons. Firstly, heavy metals tend to be transported in the stormwater system by adhering to suspended solids, therefore removing TSS aids metals removal. Secondly, high TSS levels could potentially cause blockages in irrigation systems, and lastly, ultraviolet (UV) disinfection is typically used to render water fit for use, and this is impeded by high levels of TSS in the water. Therefore, the pollutants selected for addition to each system can be classified as soluble pollutants: nitrogen and phosphorus (and other nutrients) in the form of a soluble fertilizer; and insoluble pollutants: comprising collected sediment from a filter drain and clean engine oil. However, due to technical issues in the laboratory, results for hydrocarbons and heavy metals were not obtained.

3.2.7.1 Addition of soluble pollutants

Soluble pollutants used in this study comprise nutrients, *inter alia*, nitrogen (anhydrous ammonia, ammonium nitrate and urea) and phosphorus (orthophosphate comprising PO_4^{3-} anions), which were obtained in the form of liquid fertilizer called ‘Growing Orchids’ produced

by Starke Ayres (Pty) Ltd. The nutrient ratios for this soluble fertilizer, shown in Table 3-5, closely compare with the design stormwater quality ratios shown in Table 3-6.

Table 3-5: Soluble fertilizer nutrient ratios

Nutrient	g/kg	Ratio
Soluble Nitrogen	310	6.3
Soluble Phosphorus	49	1
Potassium	91	1.9

Two mixing rates were applied to the pavement to assess how the pavement responded to a range of soluble nutrient concentrations. The first 5 storms incorporated a synthetic stormwater mixture of roughly 65g/100ℓ of soluble fertilizer. The amount of soluble fertilizer was then reduced to between 6-10g per 100ℓ for the remaining 4 storms. Influent and effluent concentrations were recorded for each event. The fertilizer was mixed into a 150ℓ tank, stirred well until dissolved and directly sprinkled on the pavement surface with a watering can. Soluble pollutants were easier to work with because they could be dissolved in tap water to form the synthetic stormwater applied to the pavements.

Table 3-6: Design stormwater quality ratios as characterised in Section 3.2.4

Nutrient	Concentration (mg/l)	ratio
Total Nitrogen	2.64	6.9
Total Phosphorus	0.383	1
Total Potassium	-	-

Other laboratory investigations have also included variable pollutant addition rates; Fach & Geiger (2005) for example used five different concentrations addition rates of heavy metals in the laboratory study for the determination of the pollutant retention capability of PPS. Additionally, Mullaney *et al.*, (2011) applied three different categories of pollutants to each pavement; metals, oils and street dust. Each pollutant was added at three different loading concentrations. Contaminants representing a total of ten years were applied to the test rigs in batches of 1, 2 and 7 years. Testing used an accelerated timescale in which the estimate load of pollutants for each of the periods (1, 2 and 7 years) was applied with one year of rainfall (1200mm) over a period of approximately 100 minutes. In the case of street dust a total of 20 years was applied in batches of 660g, 880g and 1110g, representing 3, 4 and 5 year additions respectively. Moreover, Newman *et al.*, (1996) applied oil (simulating crank-case leakage) to each laboratory pavement (except the controls, one per structure type) by means of previously calibrated oil drippers. The amount of oil added per event was increased in a stepwise manner

Chapter 3 : Research method

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

(starting at 0.8ml per oil application and increasing to 20ml) over the experiment in an attempt to try to reach saturation potential of the PPS in a reasonable period.

3.2.7.2 Addition of Oil

Oil was ‘dumped’ directly onto the pavement surface in known quantities, followed by a simulated rainfall of synthetic stormwater, by the author. The synthetic stormwater applied to the pavement to ‘wash’ off the oil also contained soluble nutrients, mixed in the concentrations described in the previous section. Therefore, the soluble and insoluble pollutants were added concurrently to each pavement. Previous studies (Milandri *et al.*, 2012) have highlighted difficulties applying insoluble pollutants using a rainfall simulator when kept in suspension in the stormwater mix..

Various studies carried out at Coventry University on oil retention and degradation in PPS (Pratt *et al.*, 2002; Newman *et al.*, 1996; Newman & Pratt, 2002 etc.) were used to inform this method. Outdoor tests conducted in a car park at Coventry University, UK by Coupe (2004), reported that a Formpave car park retained 50 ml/m² but when oil loading reached 100ml/m², detectable levels of oil were found in the stormwater exiting the pavement. Bond (1999) proposed 0.2ml/m² as a typical daily input of oil to a car parking area. The application method used in Pratt *et al.* (1999) dripped oil onto the pavement surface over a period of approximately 10 hours, simulating a dripping crank case. However, the method used in Nnadi (2009) was deemed to be most suitable. In Nnadi (2009) clean engine oil was applied once every 4 weeks to each unit via a series of does at a rate of 25ml/m² with a calibrated syringe. During this oil addition, Nnadi (2009) applied the 25ml/m² of oil in 10 x 2.5ml aliquots at randomly spaced intervals across the marked surface of the test rig.

Therefore, in this UCT laboratory investigation, 25ml/m² (33ml application per unit) of clean Engen Premium 40 mineral engine oil, a commonly used mineral oil for petrol automobile engines in South Africa, was applied directly to the surface of each pavement with a calibrated syringe (see Figure 3-10). Oil was applied to the surface in 3 x 1ml aliquots at randomly spaced intervals near the centre of the pavement. 14 storms were applied to each pavement after the oil application (see section 3.2.7.4). To ensure that oil application was conducted over a reasonable portion of the pavement surface so as not to concentrate all applications at one point, each oil addition was positioned a minimum of 10mm apart, beginning in the centre of the pavement surface. The nozzle of the syringe was held approximately 10mm from the surface of the pavements and injected via a syringe to mimic oil drippings from vehicles parked in a PPS parking area. The same syringe was used for all the models at each oil application event. It is hypothesised that if this process is repeated numerous times it will lead to a slow accumulative addition of oil to the system until oil begins to leach out of the pavement.



Figure 3-10: Oil application to laboratory pavement surfaces

3.2.7.3 Addition of sediment

Selecting sediment from a suitable source and applying it in a suitable manner at a suitable rate was an important factor in the pollutant addition process. Wilson *et al.* (2003) and Nnadi (2009) both used a sediment application method of ‘dumping’ sediment directly onto the pavement surface. The application rate in both studies was 21g/m^2 .

In this UCT laboratory investigation, a similar application method to the afore mention studies was used by the author but a higher application rate of 150g/l was applied to stress the treatment process beyond what was expected of ‘typical’ TSS stormwater levels (defined in in Section 3.2.4). A 35g (26.5g/m^2) application every 7 storm events was used to simulate stormwater sediment (TSS) loading. This averaged 250mg/l over seven storms – 100mg/l more than the ‘design’ storm TSS concentration of 150mg/l .

Selecting suitable source material was also critical. Sediment could be obtained from a number of sources including, *inter alia*, street sweepings, collection from an existing drainage system or creating synthetic sediment. For this study, sediment was collected from a filter drain inlet adjacent to the MyCiti bus depot in CoCT. The depot comprises a large permeable pavement area and is designed such that any excess water onsite flows directly into the filter drain. Due to the site design and location, it was hypothesised that the sediment collected from this filter drain was, as far as possible, reasonably representative of the conditions expected at other existing PPS sites in and around CoCT. It was also assumed that the sediment would have a reasonably representative concentration of metals attached. The sediment was dried and sieved through a large 2.0mm mesh to remove litter and other large particulates from the collected matter, as indicated by other laboratory studies (e.g. Charlesworth *et al.*, 2003; Siriwardene *et al.*, 2007; Milandri *et al.*, 2012).

Chapter 3 : Research method

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

3.2.7.4 Rainfall regime

Identifying and simulating rainfall and runoff conditions that can be expected in the field was critical to the success and relevance of the laboratory PPS experiment. Testing the pollutant removal and treatment ability of the PPS required relatively low volume rainfall events – so as to prevent excessive dilution of the pollutants and allow for adequate adhesion of the pollutants to the base layer materials. Thus, a ‘reasonable storm’ was applied to the PPS to assess how the system handles water quality treatment for the day-to-day average events where water quality treatment is mostly likely to occur. When storms of 5mm (6.6ℓ) or less were applied to the laboratory test rigs no drainage was collected from the underdrain, indicating that the depression storage of the system was roughly 5mm.

When storms of between 5-10mm (6.6-13.2ℓ) were applied to each pavement, it took a relatively long time (roughly an hour) to drain small (1-3ℓ), trickling amounts of effluent. This made sampling drainage volumes and recording drainage characteristics difficult. Therefore, it was reasoned that events greater than 10mm (13.2ℓ), termed the ‘design rainfall’ events, would be applied to each pavement when testing the treatment efficacy of each system. Furthermore, in the CoCT during an ‘average’ ‘rainy season’ – as defined in Section 3.2.6.2, more than ten ‘10mm’ (or greater) storms occur. However, selecting a reasonable design rainfall event became a somewhat philosophical issue, asking the question: ‘what is representative rainfall?’. Rainfall is inherently stochastic in nature and therefore difficult to replicate in the laboratory. However, most laboratory PPS studies (Yong *et al.*, 2008, 2009; Nnadi, 2009; Nnadi *et al.*, 2012) apply a fixed rainfall intensity. Using rainfall data provided by Smithers & Schulze (2004) and Kjeldsen *et al.* (2002) to inform the selection of a reasonable design rainfall event, it was decided that each ‘design rainfall event’ for the treatment efficacy testing would comprise 15mm (20ℓ) of synthetic stormwater applied at an intensity of 31mm/hr, as highlighted in Table 3-7.

Table 3-7: Conditions of artificial rainfall
(Smithers & Schulze, 2004)

Performance testing	Representative area	Return period (yr)	Rainfall depth (mm)	Intensity (mm/hr)	Duration (min)	Surface area (m ²)	Volume (ℓ)
Treatment	CoCT	0.25	15	31	45	1.32	20

The selection of the most suitable rainfall event frequency for treatment performance was also given careful consideration. It is preferable to mimic the actual number of rain days and associated antecedent dry days per month for a specific area (for example, the number of rain days the CoCT experiences on average during the month of July) to obtain representative pollutant removal data. This also simulates a relatively realistic environment for the development of a slime layer (*schmutzdecke*) within the PPS which is important for nutrient removal (Newman & Pratt, 2002; Newman *et al.*, 2002; Charlesworth *et al.*, 2012). However, this requires having consecutive non-testing days to mimic the antecedent low rainfall days over a period of time,

Chapter 3 : Research method

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

which would considerably limit the number of tests that could be done. Therefore, whilst it would be desirable to mimic natural conditions more exactly – particularly given the potential significance of the development of slime layers – it is not reasonable.

The second consideration is that a larger data set can be secured by simulating a rainfall event every day, allowing more tests to be completed. However, this creates an environment which may not be completely representative of the site conditions. Daily wetting of the model may encourage the slime to develop slightly faster than expected and skew the pollutant removal results. Due to the uncertainty of the rate of development of the slime layer and the benefit of running as many tests as possible, it was decided that the design rainfall event would be applied daily to each PPS model. Expected volume reductions in drainage were calculated by comparing the influent and effluent volumes and flow rates, plotted over time to determine peak flow attenuation characteristics. Storage volumes are influenced by the volumes evaporated from the structure. However, evaporation volumes were assumed to be negligible due to the relatively fast application rate of 1-3 storms per day (see section 3.2.7.5) and the fact that daily evaporation rates for PPS according to Andersen *et al.*, (1999) – although dependent on environmental conditions, typically amount to less than 0.5mm/day. Therefore, water stored within the structure was calculated using the simple mass balance equation illustrated in Equation 3-1.

$$V_S = V_I - V_{Eff} - V_{Evap} \quad (3-1)$$

Where V_S is the total storage volume within the sub-base reservoir at any time, V_I is the influent volume applied to the surface up until this point in time, V_{Eff} is the effluent volume drained from the structure at this time and V_{Evap} is the volume evaporated from the structure after the influent is applied.

3.2.7.5 Rainfall application

The main factors that affect the selection of rainfall simulation components are: spatial variability; drop size distribution; terminal velocities; and application control. For the purposes of this experiment, the most significant factor identified was flow rate control. Drop size distribution was not considered very important as much of the polluted water entering the pavement is runoff and not rain. It was thus decided that a simple 10ℓ plastic watering was suitable to simulate each rainfall event, based on the fact that the application volumes will be very small – between 16 and 28 litres. For such small events it was deemed unpractical and uneconomical to use a sophisticated rainfall simulator with pressure and flow controls. Additionally, the considerable storage capacity in a rainfall simulator makes it difficult to dispense the correct amount of water. When done by hand, the volumes can be accurately measured out before application, carefully added to a watering can and applied to the surface as required.

To mimic the duration of the event, fractions of the total volume were added to the surface of the pavement at regular intervals, with ‘dry spells’ in between. This may raise the question as to whether this method is representative of a real storm, as there will be ‘dry’ periods during the

design storm. However, according to literature (Legret *et al.*, 1996; Kjeldsen *et al.*, 2002; Nnadi *et al.*, 2012), rainfall intensities change during storm events and there is not one consistent rainfall intensity that is truly representative. Furthermore, there is a significant lag time between application and drainage through PPS; therefore a non-uniform application rate was deemed acceptable. In order to measure the lag time between the start of rainfall and the start of drainage, data was recorded at regular time intervals during the experiment. A handheld watering can and a measuring cylinder were used to simulate the rainfall events and measure the surface water application accurately respectively.

3.2.7.6 Sampling and analysis after pollutant addition

Manual grab samples (375ml glass screw cap bottles) were collected from the effluent exiting each pavement structure at regular intervals and analysed individually to determine the concentration of selected pollutants in the effluent. These pollutants included: PO_4^{3-} , NH_3 , NO_3^- , TSS, turbidity and EC. Three samples were taken from each synthetic stormwater application process; the first being the synthetic influent before surface application, the second immediately after the effluent started to flow (indicative of a ‘first flush’ measurement), and the third from an EMC measurement as indicated in Table 3-8. Figure 3-11 and Figure 3-12 shows the sample collection points throughout the pollutant addition process. After collection, each sample was analysed at the Environmental and Geographical Science (EGS) laboratory and the Chemistry Laboratory at UCT.

Table 3-8: Sampling regime for each event during the treatment efficacy process

Pavement structure	Sample Bottle	Sample volume (ml)	Sample
A	A1	375	Influent
	A2	375	First flush
	A3	375	EMC
B	B1	375	Influent
	B2	375	First flush
	B3	375	EMC
C	C1	375	Influent
	C2	375	First flush
	C3	375	EMC
D	D1	375	Influent
	D2	375	First flush
	D3	375	EMC

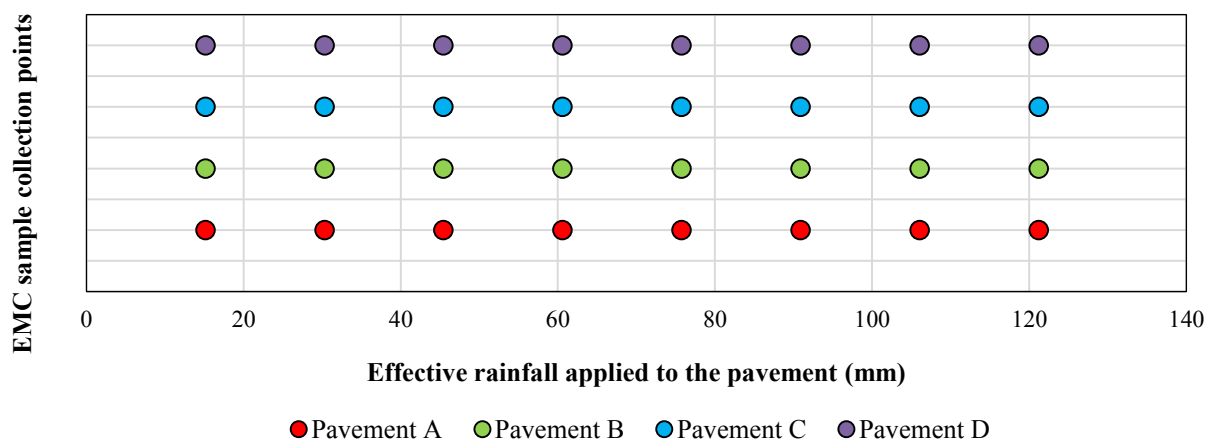


Figure 3-11: EMC Sample collection points throughout the pollutant addition process

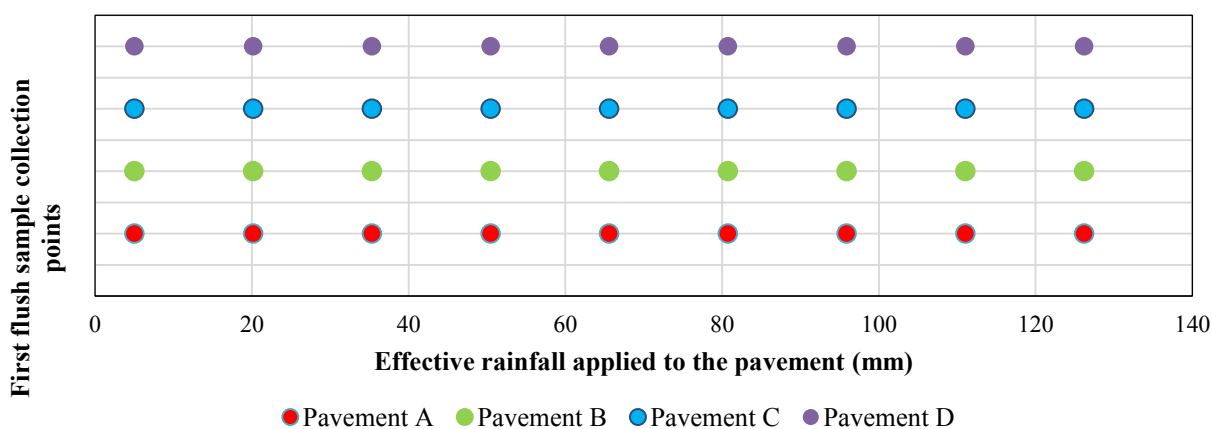


Figure 3-12: First flush sample collection points throughout the pollutant addition process

3.2.8 Experimental sampling

Both the pavement flushing and treatment efficacy testing relied on manual grab samples – individual samples collected from the drainage outlet by hand-held equipment – for water quality monitoring. Two samples were collected during storm simulation: an initial drainage sample was used to characterise pollutants associated with the first flush and a second EMC sample was also collected from the drainage bin containing the entire captured drainage volume that was used to characterise the mean effluent pollutant readings. Each sample was tested for the presence of various selected pollutants, as described in the following sections.

3.2.8.1 Probe measurement

Electronic probes were inserted into the drainage samples collected from the model structure and used to measure parameters such as DO, EC, pH and temperature for each grab sample taken throughout the course of the experiment. These readings were recorded manually.

3.2.8.2 Ammonia nitrogen

Hach Company Ammonia Nitrogen Method, Method 8155 (Salicylate Method), was used to detect levels of ammonia nitrogen (hereafter referred to as ammonia) in the samples (Hach Company, 2014). Tests were carried out in the EGS laboratory. Preserved samples were kept at or below room temperature (there was no available refrigeration spaced) for a maximum of 14 days before testing.

3.2.8.3 Reactive Orthophosphate

Hach Company Reactive Orthophosphate Phosphorus Method, Method 8048 (Ascorbic Acid), was used to detect levels of reactive orthophosphate phosphorus (hereafter referred to as Ortho-P) in the samples. Tests were carried out in the EGS laboratory. Preserved samples were kept at or below room temperature (there was no available refrigeration space) for a maximum of 14 days before testing.

3.2.8.4 Nitrates

Hach Company Nitrate Method, Method 8039 (Cadmium Reduction Method), were used to detect levels of nitrates in the samples. The tests were carried out in the EGS laboratory. Preserved samples were kept at or below room temperature (there was no available refrigeration spaced) for a maximum of 14 days before testing.

3.2.8.5 Nitrites

Hach Company Nitrite Method, Method 8507 (USEPA Diazotization Method), were used to detect levels of nitrites in the samples. The tests were carried out in the EGS laboratory. Preserved samples were kept at or below room temperature (there was no available refrigeration spaced) for a maximum of 14 days before testing.

3.2.8.6 Turbidity

Hach Company Turbidity Method was used to detect turbidity levels in the samples. Tests were carried out in the EGS laboratory.

Chapter 3 : Research method

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

3.2.8.7 Total suspended solids (TSS)

USEPA Method 160.2: Total Suspended Solids (TSS) (Gravimetric, dried at 103-105 °C) (US EPA, 1999) was chosen to measure the amount of TSS leaching from the structure. This method utilised vacuum filtration of the sample using a Buchner funnel. Fibre-glass filter paper was placed on the plate, and moistened to prevent initial leakage. The sample was drawn through the perforated glass disc and filter paper by vacuum suction, which speeds up the filtration process. The filter paper was then dried in an oven and weighed. These analyses were carried out in the Chemistry Department Laboratory at UCT. TSS is calculated as follows:

$$\text{TSS} = (A-B) \times 1000/C \quad (3-2)$$

Where TSS (mg/l); A is the weight of filter and dish plus the residue (mg), B is the weight of filter and dish (mg), and C is the volume of sample filtered (ml).

The particle size distribution and leaching from the test rig was measured using the hydrometer method. The fines were graded using the Hydrometer Method (TMH1 A6), which utilises a hydrometer to determine the distribution of the grain sizes in the material. A relatively large sample of between 75-100g was required for both sieve analysis and the hydrometer testing. Therefore, particle size analysis was only able to be done after a number of successive storm events had washed out sufficient amounts of TSS.

3.2.8.8 Hydrocarbon (oil) and metal sample and analysis

Samples were sent for testing for the presence of hydrocarbons and heavy metals – namely, zinc, copper and lead. However, due to technical and administrative problems, the laboratory was not able to test for the presence of oil or heavy metals. Therefore, no hydrocarbon or heavy results were obtained.

3.2.9 Assessment tools

Nel *et al.* (2013) defined what is meant by ‘acceptable water quality’ in order to verify practical and achievable objectives and therefore concentration ranges for a number of stormwater pollutants posing a risk to the CoCT riverine system. In this investigation, these values were used to ‘benchmark’ the concentrations for the various pollutants exiting each pavement structure as it is assumed that high values will likely cause ecological degradation. To assess the severity of the leaching concentrations of pollutants exiting each pavement, effluent concentrations were compared with ‘acceptable’ stormwater quality values as defined by Nel *et al.* (2013), and shown in Table 3-9 and Table 3-10.

Stormwater quality is difficult to characterise due to its complex, highly variable nature – not only within storms, but among different storms at one site, as well as among sites. In order

to categorise the quality of flushed effluent exiting the laboratory pavements, various pollutant EMC values were compared with ‘typical’ or ‘design’ stormwater quality values derived from literature (section 3.2.4) as well as tap water concentrations.

Table 3-9: SASS5 categories for the river health programme
(Nel *et al.*, 2013)

Category	Description
Natural	No or negligible modification (relatively little human impact)
Good	Biodiversity and integrity largely intact (some human-related disturbance but ecosystem essentially in good state)
Fair	Sensitive species may be lost, with tolerant or opportunistic species dominating (multiple disturbances associated with socio-economic development)
Poor	Mostly only tolerant species present; alien species invasion; disrupted population dynamics; species are often diseased (high human densities of extensive resource exploitation)
Unacceptable	River has undergone critical modification; almost complete loss of natural habitat and indigenous species with severe alien invasion

Table 3-10: Ecosystem health criteria: categories
(Nel *et al.*, 2013)

Variable	Units	Natural	Good	Fair	Poor	Unacceptable	Comments
Temperature*#	°C	Depends on background (Upper boundary = 90th percentile; Lower boundary = 10th percentile); Good ±2°C; Fair ±4°C; Poor ±>4°C					Need to determine typical background water quality – not essential for prioritisation exercise
Total suspended solids*#	mg/l	Depends on background (Not more than 10% higher than background)					Need to determine typical background water quality – not essential for prioritisation exercise
Conductivity (EC)*#	mS/m	Depends on background (not more than 15% different from normal cycles)					Need to determine typical background water quality – not essential for prioritisation exercise
pH*	units	8–6.5	9–8 or 6.5–5.75	10–9 or 5.75–5	>10; <5		Need to determine typical background water quality – not essential for prioritisation exercise
Dissolved oxygen*	mg/l	>8	8–6	6–4	4–2	<2	Also dependent on background DO levels to some extent. No unacceptable range given but if one selects equal bands then 2 mg/l is the next logical band and is applicable to assessing the actual data
Soluble reactive phosphorus*	mg/l	<0.005	0.005 – 0.025	0.025 – 0.125	0.125–0.250	>0.250	Ranges as recommended in the latest water quality benchmarks for the ecological reserve (DWAF 2005)
Total inorganic nitrogen*	mg/l	<0.25	0.25–1	1–4	4–10	>10	
Ammonia (NH ₃ -N)*	mg/l	<0.015	0.015–0.058	0.058–0.1	0.1–0.2	>0.2	No unacceptable range given but if one selects equal bands then 0.2 mg/l is the next logical band and is applicable to assessing the actual data
Blue-green algae toxins (microcystins)@	µg/l	<10		10–50	>50		Ranges as recommended in the World Health Organisation (WHO) guidelines
Algae (Chl-a)*	µg/l	<10	10–20	20–30	30–40	>40	No unacceptable range given but if one selects equal bands then 40 µg/l is the next logical band and is applicable to assessing the actual data

South African Water Quality Guidelines (DWAF 1996b)
* Ecological reserve water quality benchmarks (Jooste & Rossouw 2002)
@ World Health Organisation Recreational Guidelines (2003)

Chapter 3 : Research method

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

3.3 Laboratory pavement disassembly

To assess the internal condition of the pavements and to understand the migration of sediment through the structure, the laboratory pavements were carefully excavated / disassembled and inspected. Some photographs were taken during this process and discussed in Section 4.3. Each pavement had been exposed to two experimental phases, namely the pavement flushing process and the pollutant addition process, respectively. Care was taken to disrupt the aggregate as little possible while excavating.

3.4 Summary

In summary the most urgent aspects to note with regard to the above method are:

- The laboratory pavement designs and construction methods were informed by the design and construction of the NEB parking area which took place adjacent the laboratory building during the early phases of the dissertation – a description of the NEB design and construction procedure can be found in Appendix D: New Engineering Building parking area
- Some of the pavement materials used in the construction of the laboratory experiment were taken directly from the NEB pavement site stockpiles – most important to note was the use of unwashed ‘Hornfel Malmesbury Shale’ aggregate, to produce as far as possible laboratory conditions representative of existing pavements in the CoCT.
- The impact of the unwashed aggregate and pollutant removal capacity of the laboratory PPS was considered by evaluating the water quality performance of PPS against varying standards, and comparing PPS performance to that of traditional, impervious surfaces. These were investigated by way of the following activities, in three different stages:
 - i) Flushing the laboratory system with clean tap water to establish ‘base-line’ pollutant values to assess the impact of unwashed aggregate on water quality emanating from PPS. This was done prior to the addition of typical stormwater pollutants to investigate whether the construction materials themselves contribute to effluent pollutant loads.
 - ii) Testing the pollutant removal capacity of the system by adding pollutants to each pavement surface, simulating rainfall events and monitoring the effluent water quality. This was done to determine whether stormwater can be harvested from PPS for ‘fit for purpose’ use.
 - iii) Lastly, the pavements were stripped and examined for the presence of sediment.

4. Results and analysis

This chapter details the laboratory PPS experimental results and analysis obtained after carrying out the Research Method (detailed in Section 3) that set out to address the Research Aims (outlined in Section 1.3) for this dissertation. The findings report the three phases of the laboratory investigation, namely the water quality results from the pavement flushing process, the water quality results from the pollutant addition process and the disassembly and inspection of the sediment for the presence of sediment.

4.1 Laboratory experiment – pavement flushing process

This section reports the water quality results from the pavement flushing process. Pollutant concentrations exiting each test unit have been recorded, analysed and discussed. Of primary concern to the health of river systems are the leachate concentrations and the effective leaching period (time) of the selected pollutants. The primary factors affecting these two elements were the pavement design and the flushing rainfall depths applied.

Hydrological (flow) monitoring was carried out manually with the use of measuring cylinders and a stopwatch. Flows were estimated by timing how long the drainage flow took to fill a specified volume. ‘Effective rainfall drained through the pavements’ was used to represent the progression of the flushing process rather than total volumes drained through each pavement. Effective rainfall depth is a more relatable function than volume drained as it allowed the flushing volumes to be measured in terms of the number of ‘rainy seasons’ passing through each pavement.

Guidelines were added to the graphs, where possible, to compare experimental values against pollutant values provided in other studies so that concentrations are given a context. Firstly, context was provided by comparing experimental pollutant values to a ‘design value’ or ‘typical value’ that was determined from a number of international studies (US EPA, 1983; Marsalek *et al.*, 1993; Duncan, 1999; Marsalek, 2000; Debo & Reese, 2003). This ‘design value’ quantified ‘typical’ or ‘average’ stormwater pollutant concentrations for different land uses were grouped together as shown in Table 3-2. Secondly, to assess the severity or hazard of the leaching concentrations of pollutants exiting each pavement, effluent concentrations were compared with ‘acceptable’ stormwater quality values as defined by Nel *et al.* (2013), and shown in Table 3-9 and Table 3-10. Nel *et al.* (2013) defined what is meant by ‘acceptable water quality’ by categorising pollutant values into 4 categories: Good, Fair, Poor and Unacceptable. This categorization was done in order to verify practical and achievable objectives and therefore suitable concentration ranges for a number of stormwater pollutants posing a risk to the CoCT riverine system.

Therefore, in this investigation, pollutant values were ‘benchmarked’ against ‘average’ or ‘design values’ and categorised according to the ecological hazard posed by the pollutant range

in the effluent. Due to the categorisation values provided by Nel *et al.* (2013), only Ammonia and Ortho-phosphate could be categorised into one of the four divisions. The other pollutants could only be compared to the 'Design Value' determined in Table 3-2.

4.1.1 Orthophosphate

The orthophosphate (hereafter referred to as PO_4^{3-}) flushing results (Figure 4-1) indicate an initially low concentration being flushed from Pavements A and B after construction. However, after two or three storm events, the PO_4^{3-} drainage concentrations in these two pavements increased substantially surpassing 'typical' or 'design' storm runoff values and resulting in the drainage quality as 'poor' for much of the flushing process. PO_4^{3-} concentrations in Pavements C and D remained relatively constant in the 'Fair' category throughout the flushing process.

The results suggest that PPS incorporating similar designs to Pavements A or B have a high PO_4^{3-} pollution potential for some time after construction with unwashed stone. After an entire typical rainy season, the PO_4^{3-} drainage concentrations in the discharges from Pavements A and B had only dropped slightly below design storm runoff values. It is most probable that this PO_4^{3-} is coming from the dirt associated with the unwashed stone. The reduced PO_4^{3-} levels in pavements C and D relative to pavements A and B are likely due to the absence of the 19-25 mm aggregate in the storage layer.

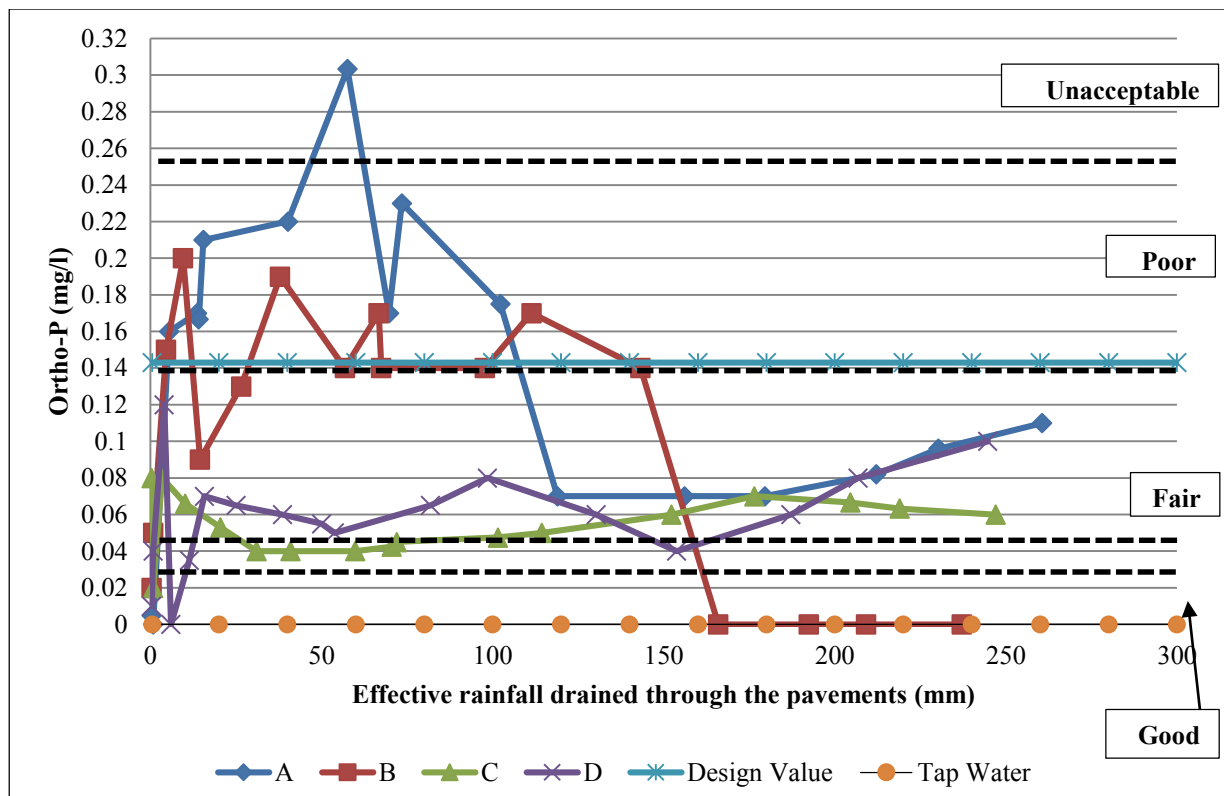


Figure 4-1: Orthophosphate concentrations in drainage from pavements compared with potable tap water and design storm runoff concentrations

Chapter 4 : Results and analysis

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

4.1.2 Ammonia nitrogen

The ammonia nitrogen (hereafter referred to as NH_3) concentration results from the flushing experiment (Figure 4-2) were initially high but, with time, decreased to very low levels. Pavements A and B consistently discharged water with higher NH_3 concentrations than Pavements C and D.

The NH_3 concentrations in the drainage from Pavements A, B and D were at ‘unacceptable’ levels as categorised by Nel *et al.* (2013) for approximately half the simulated ‘rainy season’ or 150-200mm of rainfall after construction. Furthermore, Pavement A exhibited a flushing ‘spike’ – perhaps due to the lack of a geotextile within its structure as discussed previously. This ‘spike’ (sample A4) was collected after the application of a relatively large simulated rainfall event of 17.4mm (23ℓ) applied in 5 intervals every 9min (5ℓ, 5ℓ, 5ℓ, 5ℓ and 3ℓ). The large comparative volume of this rainfall event in the regime was the most likely cause of the exaggerated flushing of pollutants from the PPS. Apart from the spike in NH_3 levels in sample A4, all four designs exhibited similar NH_3 discharge characteristics throughout the flushing process. After the application of one simulated rainy season, the NH_3 concentrations dropped to low values that appeared to be reasonably stable. Therefore, it appears that PPS constructed with unwashed aggregate has the potential to release large amounts of NH_3 from the pavement into the receiving environment.

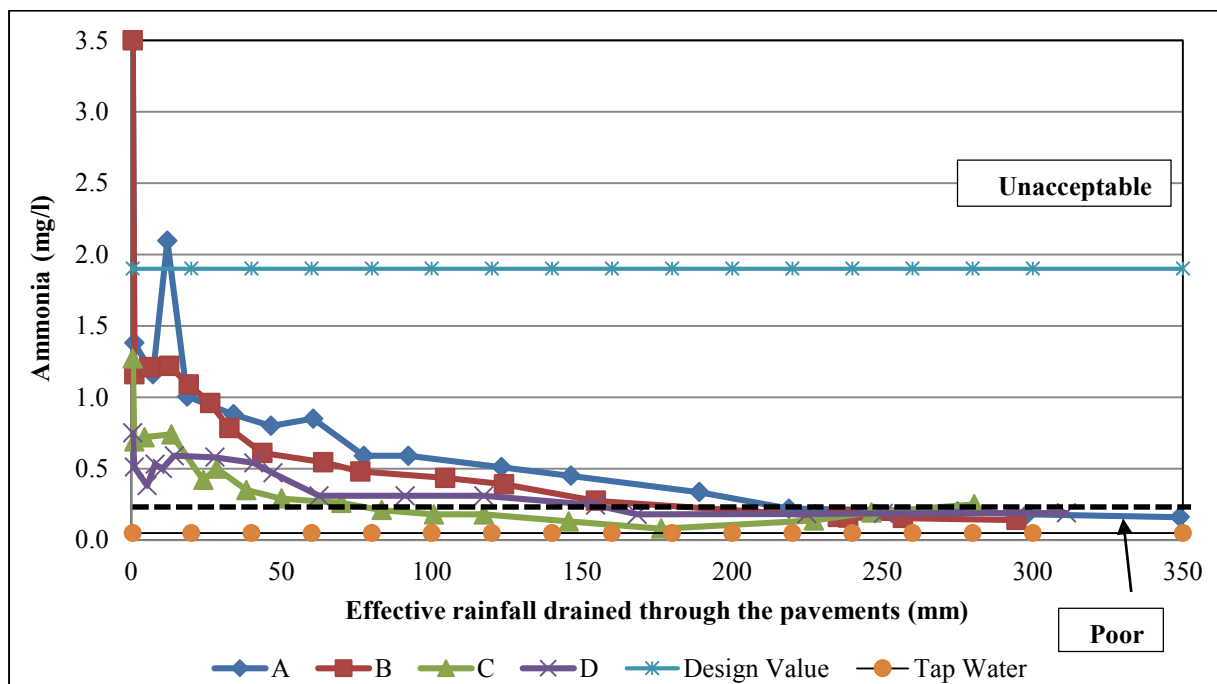


Figure 4-2: Drained ammonia nitrogen concentrations compared with potable tap water and design storm runoff concentrations

4.1.3 Nitrate

The flushed nitrate (hereafter referred to as NO_3^-) results shown in Figure 4-3 reflect low NO_3^- effluent concentrations in structures B, C and D. Spikes in NO_3^- concentration were observed for Pavement A after rainfall events A2 and A12 that far exceeded the other measured sample concentrations, with the most pronounced ‘spike’ – a NO_3^- reading of 134 mg/l – recorded in A12. The rainfall events associated with each spike were not very large, namely 11.8 mm (15.6 l) and 7.9 mm (10.4 l) respectively. The most likely cause of exaggerated NO_3^- effluent concentrations in Pavement A is the use of unwashed stone during construction and the absence of a geotextile. These results suggest the possibility of erratic, high concentrations of NO_3^- being leached from designs similar to pavement A. After the application of one simulated rainy season, the NO_3^- effluent concentration appeared both low and stable.

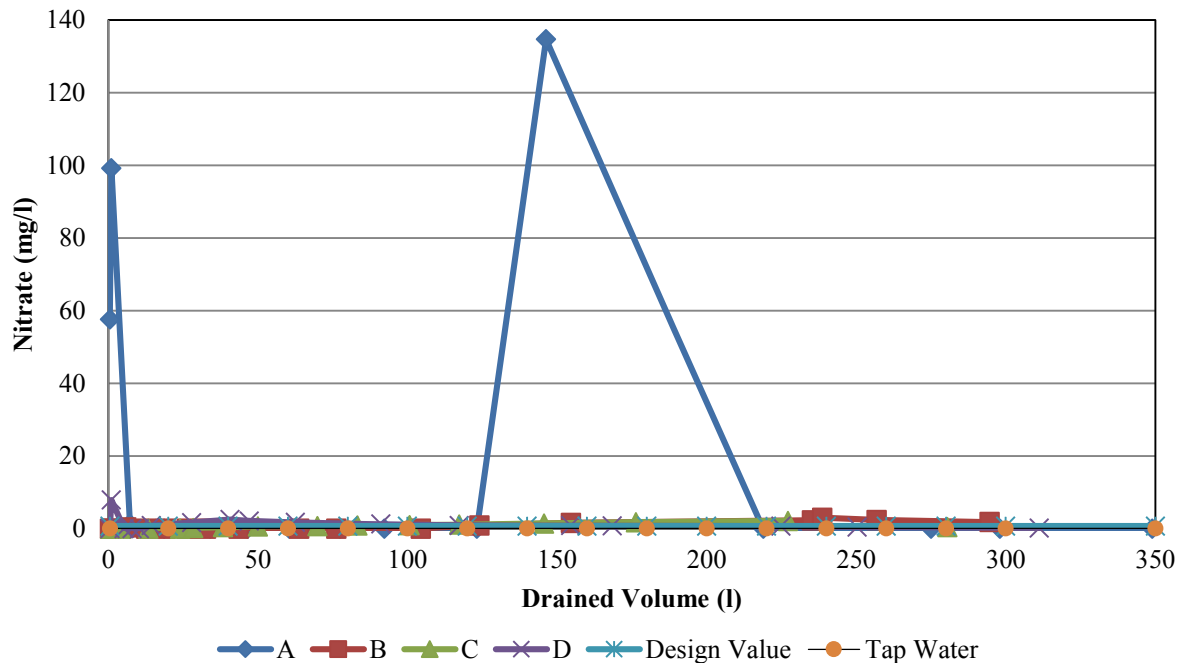


Figure 4-3: Drained nitrate concentrations compared with potable tap water and design storm runoff concentrations

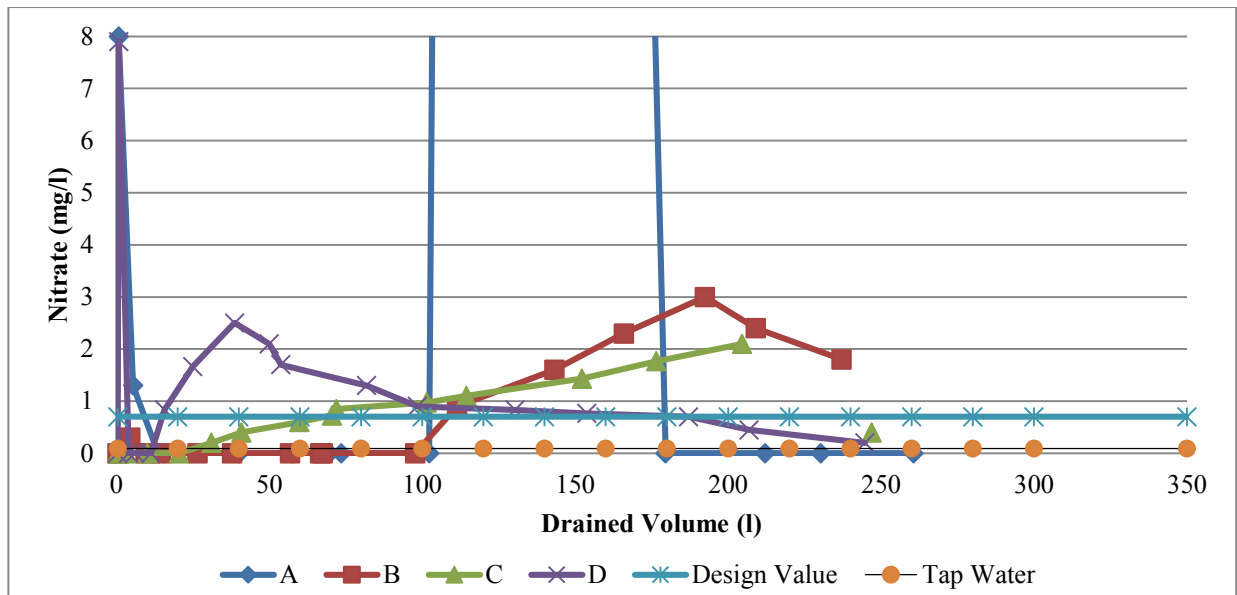


Figure 4-4: Drained nitrate concentrations (without Rig A spikes) compared with potable tap water and design storm runoff concentrations

4.1.4 TSS and turbidity

Harmful stormwater pollutants such as heavy metals and hydrocarbons adhere to sediment attached to unwashed aggregate stone within PPS. The flushing of sediment from PPS base layers therefore has the potential to carry adhered pollutants, such as heavy metals to receiving waters thereby threatening the health of the related ecosystems. Total suspended solids (TSS) and turbidity measurements taken during the flushing process (Figure 4-5 and Figure 4-6), indicate very high values that were moreover highly variable – presumably depending on the mobilisation of fines trapped within the pavement matrices. There did however appear to be a general decrease in the TSS and turbidity concentrations as the flushing progressed.

Pavements A and D initially discharged relatively high TSS that greatly exceeded the ‘typical’ storm values; however the TSS rapidly decreased after the first two samples to similar levels recorded in the other pavements. The TSS values from Pavements A, C and D only dropped below the ‘typical’ stormwater threshold some way into the flushing process. Furthermore, the TSS values from Pavements A and D were consistently higher than those of Pavements B and C throughout the experiment. Pavement A (without a geotextile) appeared to be the most susceptible to TSS peak discharges with very high readings in the first two samples – and then again some time later at sample A12.

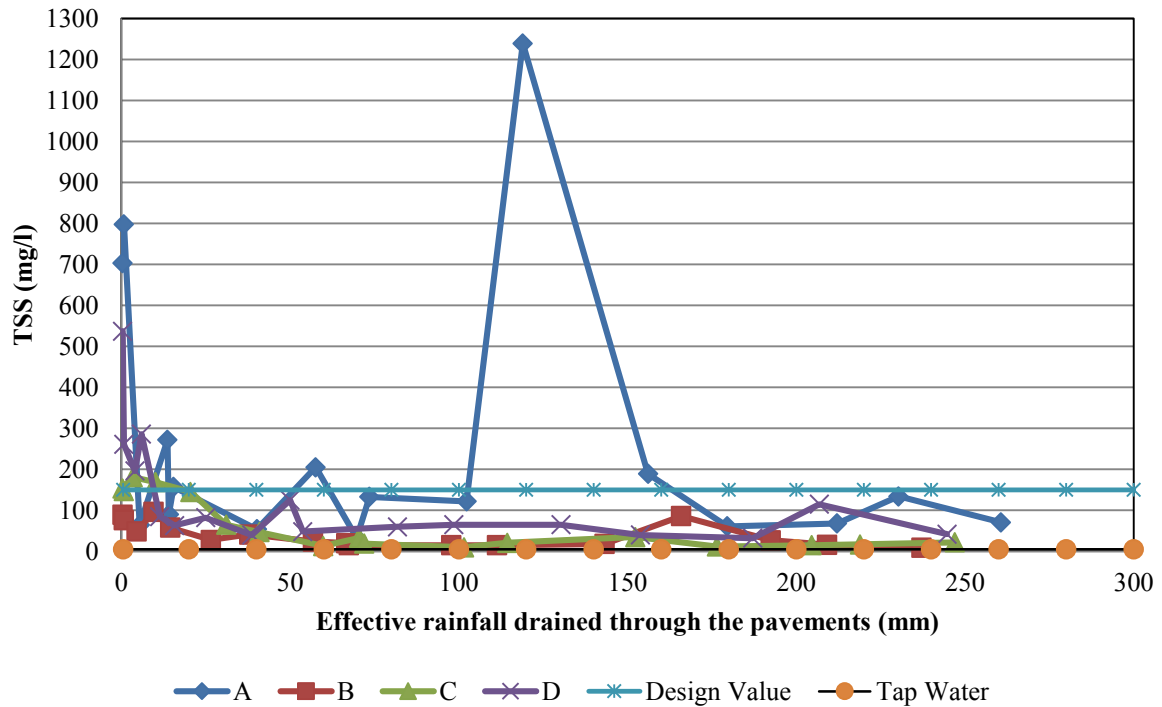


Figure 4-5: Drained TSS concentrations compared with potable tap water and design storm runoff concentrations

Rainfall variation may partly explain the TSS ‘spikes’. Before the collection of sample A12, three rainfall events were applied in relatively quick succession resulting in the application of 27.7mm (36.6ℓ) of rainfall in less than 2 hours. This was the highest applied rainfall depth preceding a grab sample in the entire experimental sequence.

The varying TSS released in each pavement could also relate to the material selection of each design. Pavement D used sand as a bedding layer whilst Pavement A – a very similar design to Pavement B – does not include the Inbitex® geotextile layer. The fact that the Inbitex® geotextile requires a 50mm ‘breakthrough’ head before it allows water to pass through it also results in intermittent ‘surges’.

The results indicate that unwashed stone used in the construction process of PPS, particularly where geotextiles are not included, has the potential to release considerable amounts of TSS into receiving waters.

Chapter 4 : Results and analysis

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

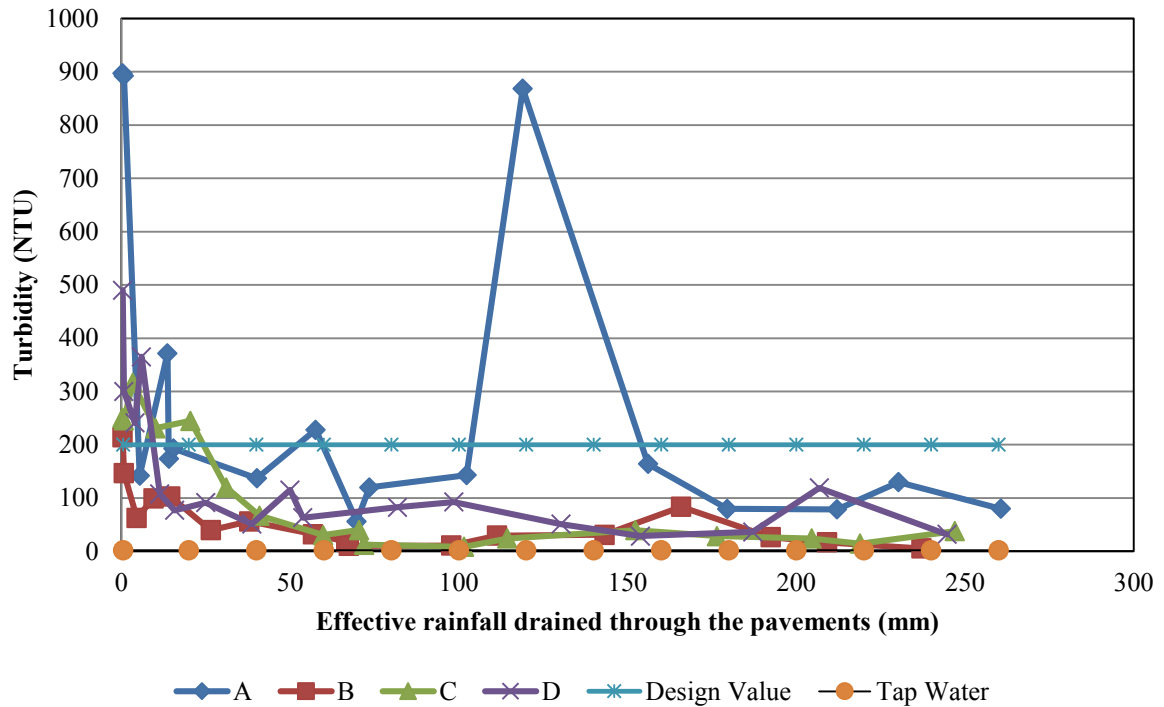


Figure 4-6: Drained turbidity concentrations compared with potable tap water and design storm runoff concentrations

4.1.5 EC

Electrical conductivity (EC) is a measure of the ability of a solution to conduct an electrical current, and is used as an indicator of the amount of dissolved material (specifically salts) in the sample. It is thus directly related to the concentration of dissolved ionised solids and can be measured using a conductivity meter or TDS meter. EC usually provides an approximate value for TDS.

The EC values for the drainage throughout the flushing process are provided in Figure 4-7. EC values in structures A, B and C exceed ‘typical’ storm runoff values for much of the ‘rainy’ season, decreasing gradually from the outset until the end of the flushing process. An electrical conductivity ‘spike’ in A4, the same sample which reported increased levels of NH_3 , is most likely due to the same factors causing the high NH_3 levels. These include a high volume rainfall event of 17.4mm (23ℓ) when compared with other rainfall events in the regime (applied in 5 intervals every 9min – 5ℓ, 5ℓ, 5ℓ, 5ℓ and 3ℓ); and the lack of an Inbitex® geotextile layer.

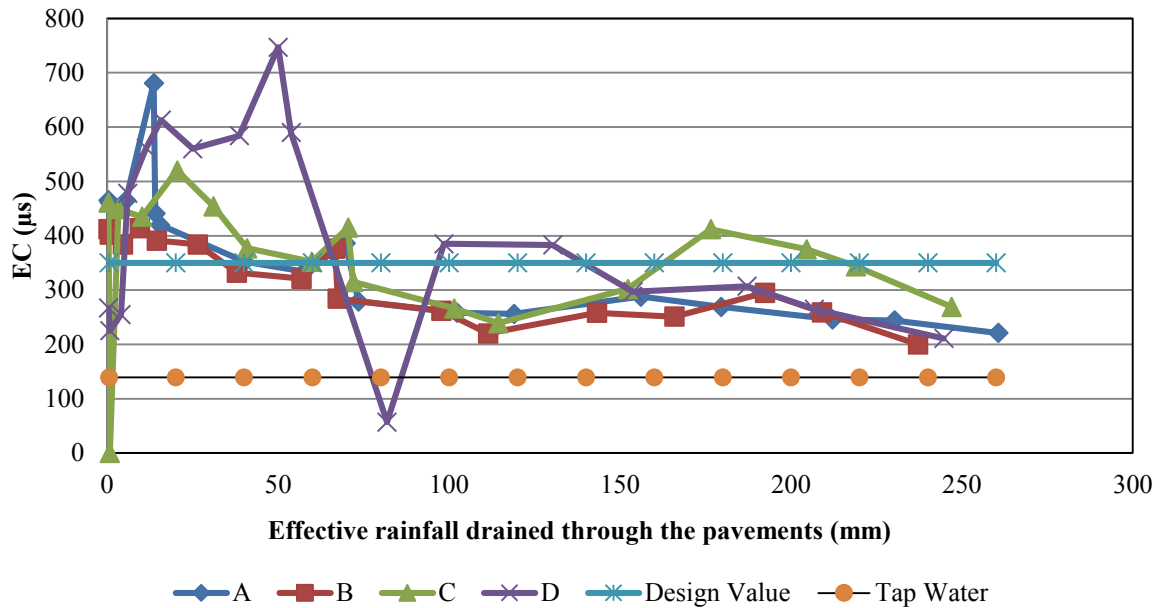


Figure 4-7: Drained conductivity levels compared with potable tap water and design storm runoff concentrations

The conductivity of samples draining from structure D fluctuated considerably. At the outset, effluent conductivity was low but then increased to over 700 μs and then decreased again to similar levels found in the effluent from the other structures. After the application of one rainy season, the EC concentrations did not appear completely stable.

Structure D is the only pavement that included sand as a bedding layer instead of gravel. These results suggest that the sand used in the pavement structure may have been responsible for the increase in conductivity of the effluent relative to those pavements constructed with gravel bedding layers.

4.1.6 Leaching period

After application of the equivalent of one rainy season (312mm) worth of tap water, the pollutant concentrations in the drainage had still not yet reduced to zero. Rather than continue with the application of more tap water, curves were fitted to the TSS (Figure 4–7) and NH_3 (Figure 4–8) data and extrapolated in an attempt to indicate how long it would take to reach reasonably low values (Table 4-1). These were selected rather than the PO_4^{3-} data as the latter showed considerable scatter.

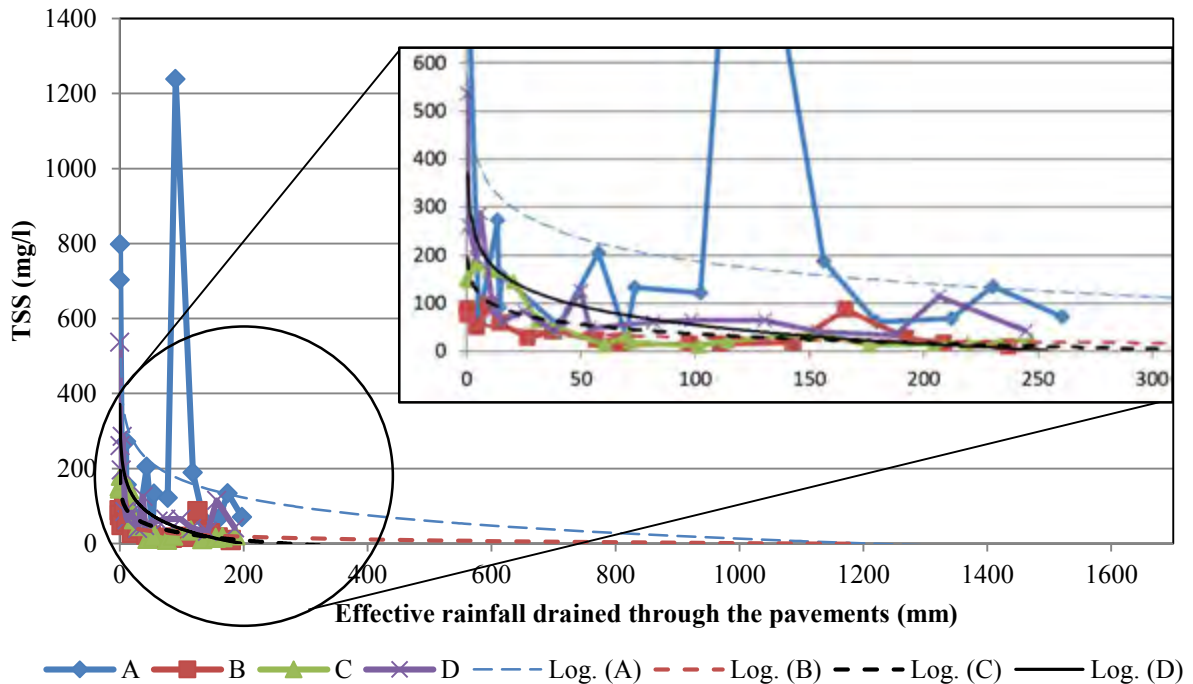


Figure 4-8: Extrapolated trend lines for TSS concentrations drained from pavement

In all the pavements except Pavement C, the structures constructed with unwashed aggregate stone required more than one rainy season of flushing before showing signs of stabilisation. Pavement A, constructed without a geotextile, required the longest stabilisation period according to the TSS (1520mm) and NH_3 (4150mm) extrapolation curves, which roughly equate to 6 and 16 rainy seasons respectively. In Pavement B – identical to Pavement A except for the addition of an Inbitex® geotextile layer – the TSS and NH_3 flushing requirements were reduced to 980mm (4.5 rainy seasons) and 230mm (one rainy season) respectively. Pavement C, which was similar to Pavement B except for the substitution of 50-63mm aggregate for the 19-25mm aggregate, displayed the shortest stabilisation period of roughly one rainy season for both TSS and NH_3 . The TSS flushing requirements of Pavement C (250mm) was considerably less than that of Pavement B (980mm) with the only difference in design was that B included a 19-25mm aggregate layer. For Pavement D – that had sand as the bedding layer, the TSS dropped quickly, however 2350mm (10 rainy seasons) was required for NH_3 stabilisation.

Chapter 4 : Results and analysis

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

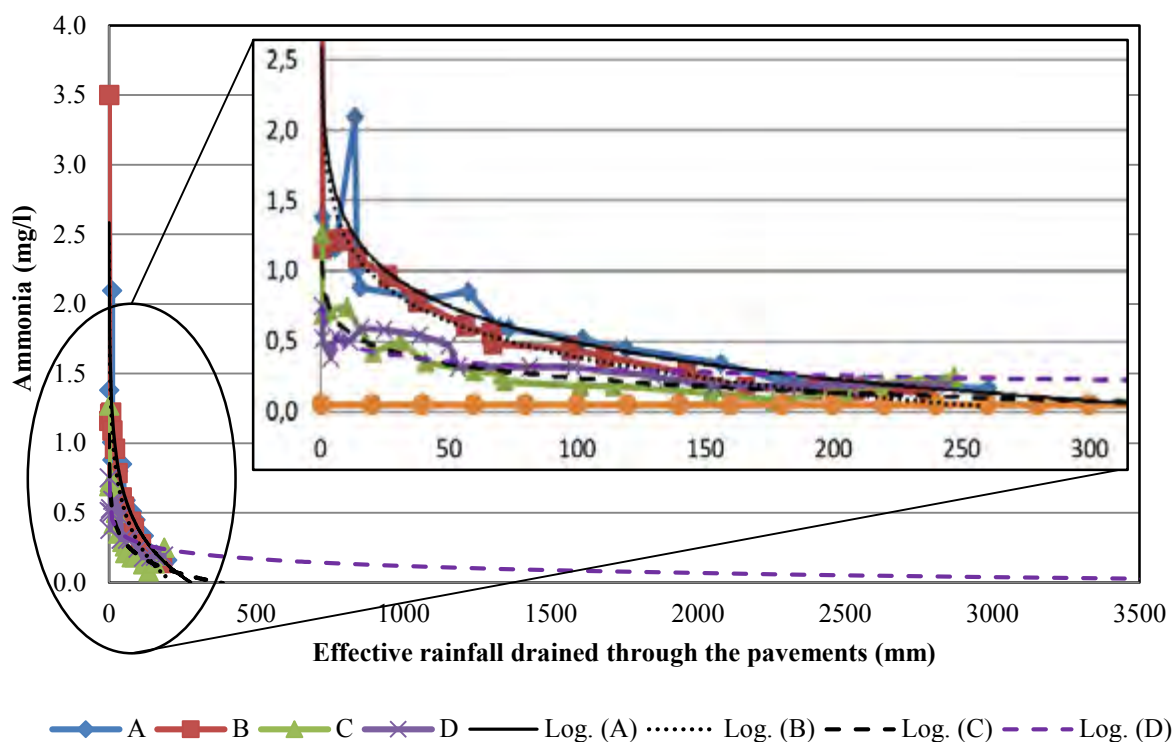


Figure 4-9: Extrapolated trend lines for Ammonia concentrations drained from each pavement

Table 4-1: Predicted rainfall depths (derived from drainage volumes) required by the lab PPS for TSS and ammonia leaching stabilisation

Pavement	Effective rainfall drained through the pavements (mm)	Predicted rainfall required for stabilisation (mm)	
		TSS	Ammonia
A	266	1520	4150
B	225	980	230
C	215	250	260
D	237	270	2350

4.2 Laboratory experiment – pollutant addition process

This section reports the sample water quality results from the PPS treatment efficacy experiment. Treatment efficacy of each PPS was assessed by comparing the concentrations of various pollutants before treatment (from the influent) and after treatment (from the effluent), thereby determining the pollutant retention capacity of the internal pavement structure. Influent, first

flush and EMC samples were taken during the application of each of the 9 simulated storm events according to the sampling regime as was shown in Figure 3-11 and 3-12.

4.2.1 Orthophosphate

Orthophosphate (hereafter referred to as PO_4^{3-}) sample concentrations from the pollutant addition phase can be seen in Figure 4-10 (first flush) and Figure 4-11 (EMC). Influent levels ranged from 5.42 to 6.17 mg/ℓ .

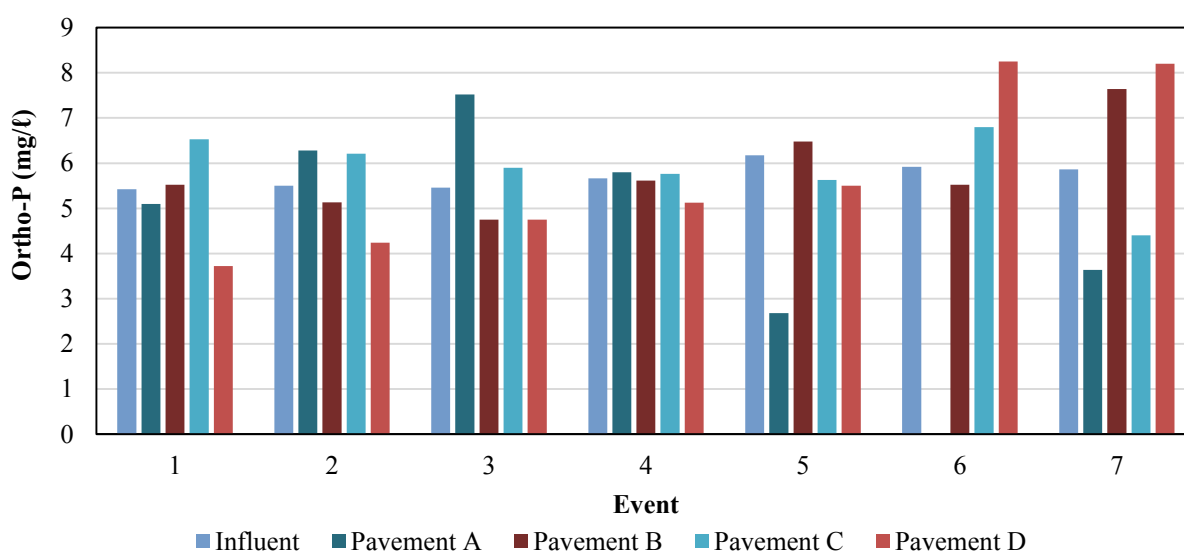


Figure 4-10: Orthophosphate first flush and influent concentrations for each PPS design

First flush PO_4^{3-} concentrations (Figure 4-9) in Pavement A were the most variable, ranging from zero to 7.52 mg/ℓ but reflected the best average treatment efficacy of 22.9%. First flush PO_4^{3-} concentrations in Pavement D increased throughout the pollutant addition phase; initially, in events 1 to 4, the first flush PO_4^{3-} removal efficacy of pavement D was the best of all the designs. However, in the last two events this trend was reversed and the first flush PO_4^{3-} levels began exceeding influent levels, presenting the worst removal efficacy of all the designs. Pavement B and C posted the most stable first flush characteristics, oscillating around the influent concentration level. Pavement A at first flush is the most susceptible to pollutant spikes due to the lack of a geotextile layer. Pavements B, C and D reflected increasingly climbing PO_4^{3-} EMC trends throughout the pollutant application phase, surpassing influent concentrations, and therefore polluting the stormwater as it infiltrates the system. This suggests that the internal structure of the system was not sufficiently flushed at the outset of the experiment.

Pavement A reflected the best average treatment efficacy (in terms of PO_4^{3-} EMC) of 9.2% for the seven events although the mean concentrations fluctuated considerably across the

experiment. Influent concentrations were commonly exceeded by effluent EMCs in each pavement design indicating insufficient system flushing. Again, EMCs in Pavement A are the most susceptible to pollutant spikes; this can be explained through the lack of a geotextile layer. Furthermore, the reduced maximum infiltration rates as a consequence of the breakthrough head of 50mm associated with the geotextile layer creates an additional physical filtration. These factors in turn reduce the likelihood of sediment and their adhered pollutants such as NO_3^- being released during high volume storms. As a result of insufficient flushing, the first flush and EMC PO_4^{3-} removal results of each of the PPSs were inconclusive. Therefore, more research needs to be conducted before suitable fit-for-purpose applications for the treated effluent can be suggested.

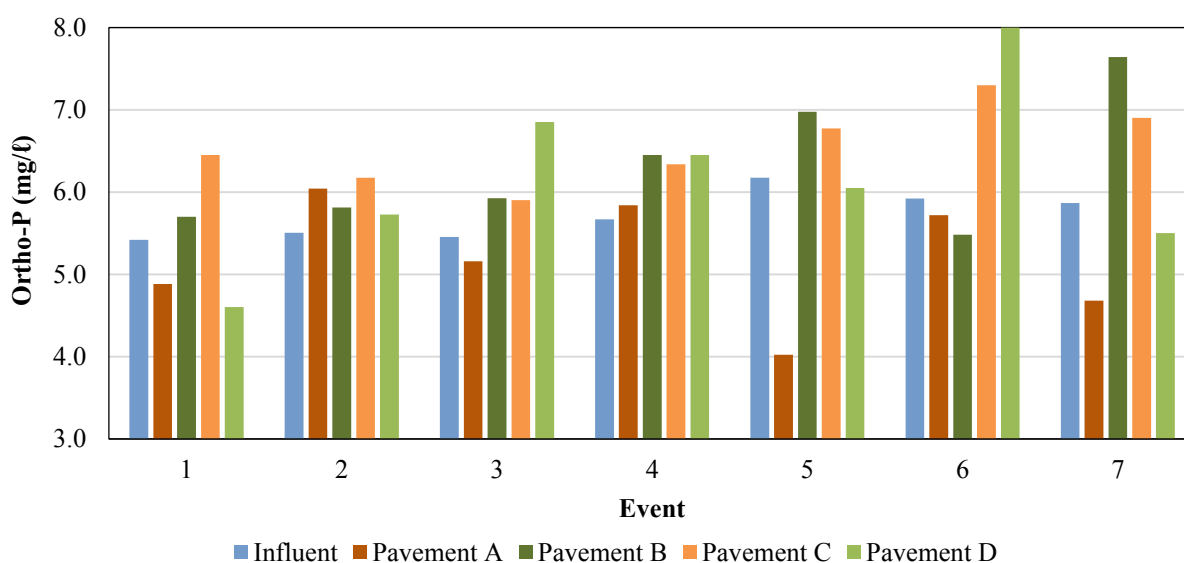


Figure 4-11: Orthophosphate EMCs and influent concentrations for each PPS design

4.2.2 Ammonia nitrogen

Ammonia nitrogen (hereafter referred to as NH_3) first flush concentrations and EMCs from the pollutant addition phase are shown in Figure 4-12 and Figure 4-13 respectively. Influent concentrations remained relatively constant for each pavement, ranging between 5.62 and 7.64 mg/l. Pavement C reflected the only consistent decline in concentrations of NH_3 in the first flush from the first to the fifth event, with average removal rates of 15.4%. However, at events 6 and 7, concentrations increased to a similar level to the other pavements. Pavement D reflected the highest first flush NH_3 concentrations for each event of the experiment, with effluent concentrations consistently exceeding influent concentrations. This suggests that Pavement D was not sufficiently flushed with clean water at the outset. However, the first flush trend in Pavement D decreased from 9.28 to 7.52 mg/l between the first and last event.

NH₃ EMCs in Pavements B and D were similar, with influent concentration trends oscillating closely to one another. Pavement C retained the most NH₃ in the substructure of all the pavements, emulating the first flush trend, and reflected the highest average treatment efficacy of 26.5% throughout the events. However, after Sample 5, effluent NH₃ concentrations in Pavement C reverted to levels similar to the other designs. The design difference between Pavement C and the others relates to the 53mm stone present in the storage layer which is unlikely to improve the treatment efficacy of Pavement C, so this result could relate back once again to insufficient flushing at the outset. The NH₃ treatment results were inconclusive and therefore, fit-for-purpose use cannot be specified from the findings.

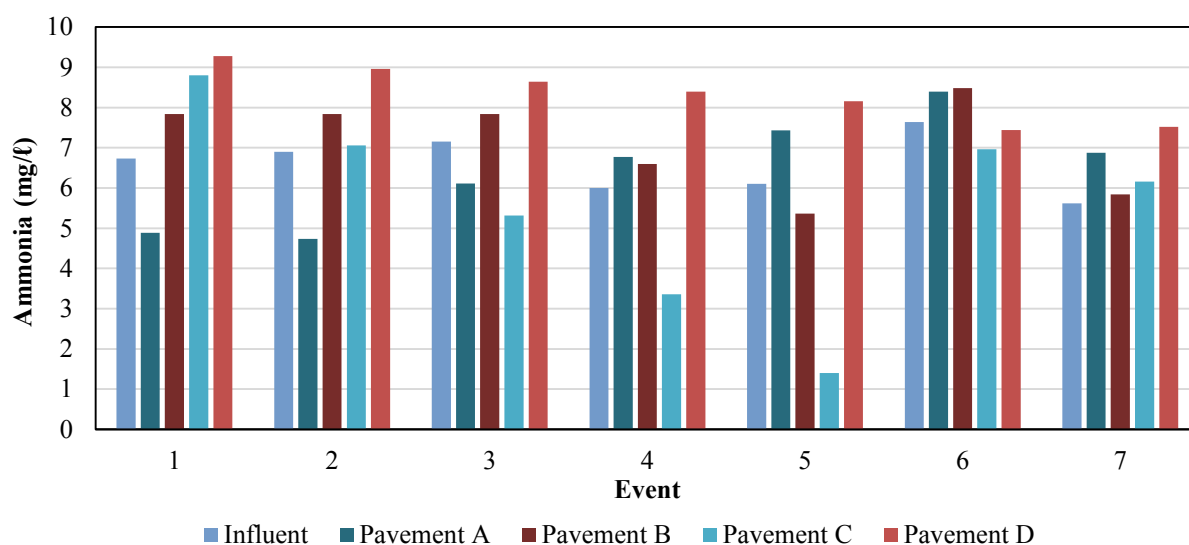


Figure 4-12: Ammonia first flush and influent concentrations for each PPS design

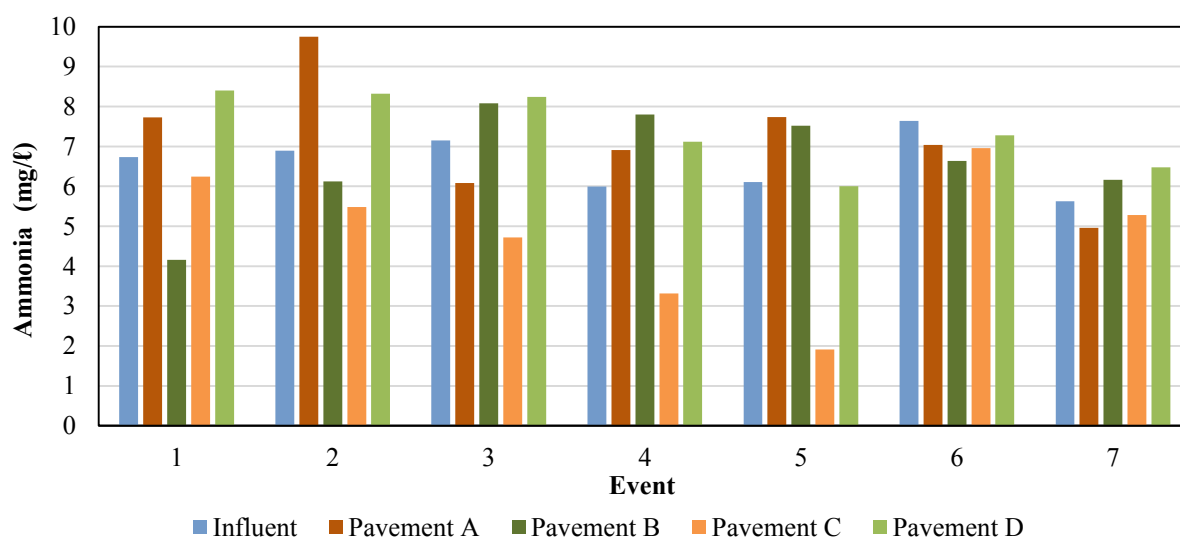


Figure 4-13: Ammonia EMCs and influent concentrations for each PPS design

Chapter 4 : Results and analysis

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

4.2.3 Nitrate

Pavements B, C and D had similar average first flush nitrate (hereafter referred to as NO_3^-) removal efficacies of 23.1%, 18.3% and 19.7% respectively (Figure 4-14). The best removal rates for these pavements were obtained in Event 1 (68%, 57% and 56%), after which the NO_3^- levels increased to levels similar to influent concentrations across the experiment. In other words, after Event 1 there was no NO_3^- quality improvement in Pavements B, C and D. Average first flush concentrations in Pavement A were 44.5% higher than average influent concentrations, as well as posting considerable spikes in events 2 (34.4mg/l), 3 (60.7mg/l) and 4 (32.1mg/l). The behaviour in Pavement A can be explained through the lack of a geotextile layer which requires a breakthrough head of 50mm, thereby reducing the maximum infiltration rates through the system. This in turn reduces the likelihood of sediment and their adhered pollutants such as NO_3^- s being released during high volume storms.

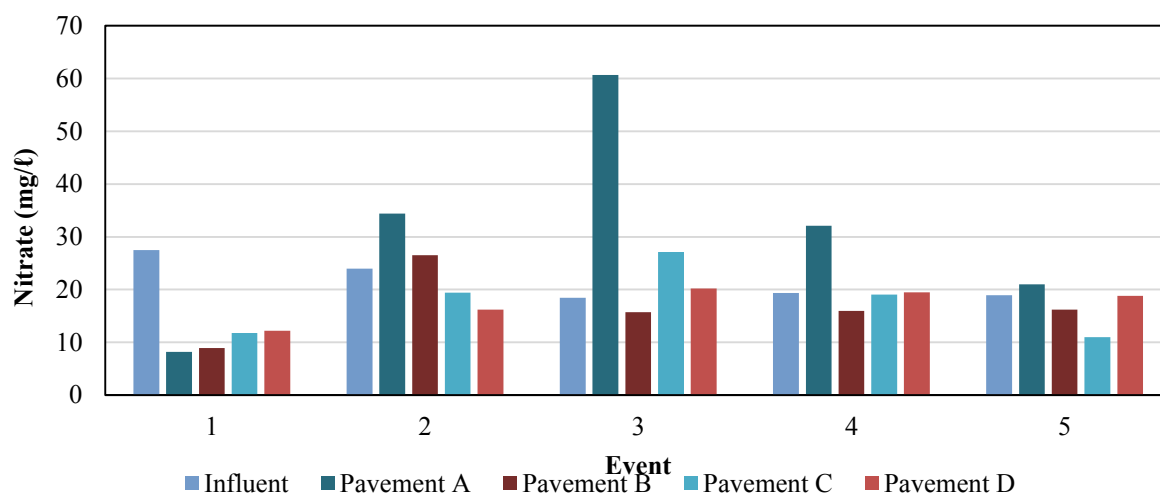


Figure 4-14: Nitrate first flush and influent concentrations for each PPS design

Pavements B, C and D on average reduced NO_3^- EMCs throughout the experimental process to levels slightly below influent levels. Pavement A increased the NO_3^- EMCs on average compared with influent EMCs, once again indicating insufficient system flushing.

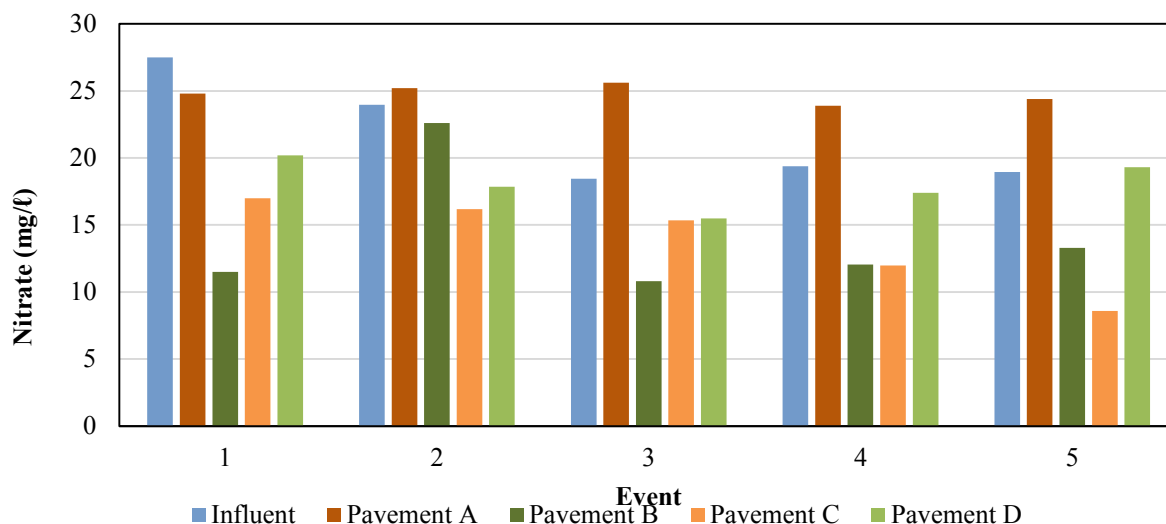


Figure 4-15: Nitrate EMCs and influent concentrations for each PPS design

4.2.4 TSS and turbidity

TSS test results are shown in Figure 4-16 and Figure 4-17. Pavement A reflected extremely high concentrations of sediment in both the first flush and EMC effluent samples when compared with the other pavements. Pavement A's lack of ability to retain sediment within a structure was due to the absence of a geotextile layer. As with previous examples, the geotextile layer improves treatment efficacy for certain pollutants, due to the addition of a physical filtration layer and reduction in infiltration rate. As a result of the effluent readings in Pavement A exceeding influent readings, this system appeared to not have been adequately flushed. Pavements B, C and D all showed similar TSS removal tendencies, oscillating around the influent level. These pavements are less susceptible to TSS effluent spikes as a result of the presence of a geotextile layer. However, effluent concentrations commonly exceeded influent levels in each pavement suggesting that the system had not been adequately flushed at the outset to eliminate the leaching of pollutants from the internal pavement structure. Further research needs to be conducted to obtain more conclusive TSS treatment efficacy results and in so doing allow fit-for-purpose use recommendations to be made.

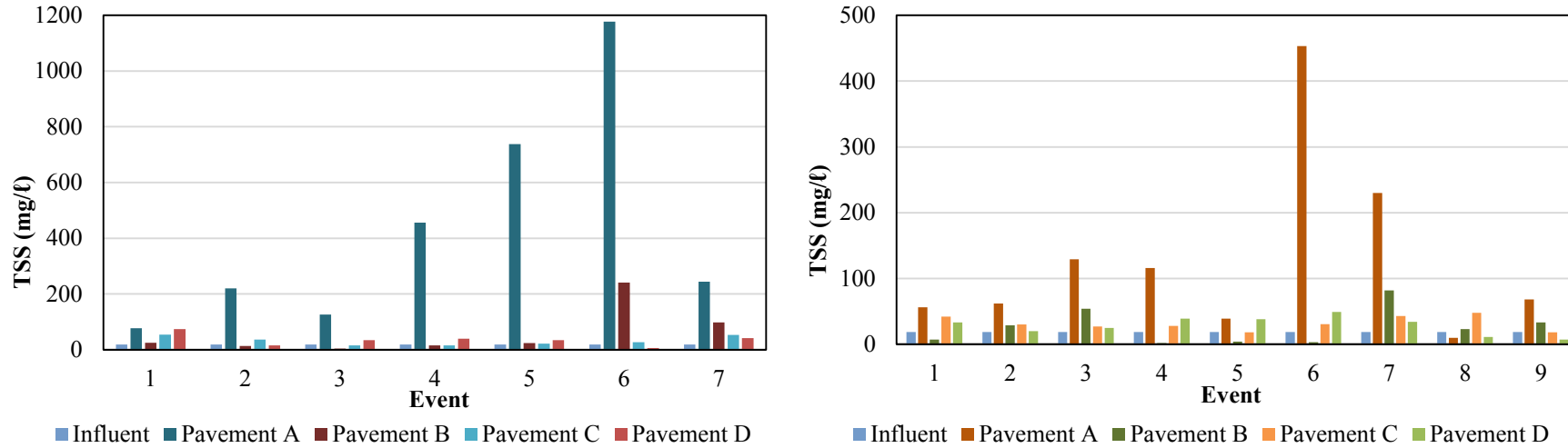


Figure 4-16: TSS influent, first flush (left) and EMC (right) concentrations for each PPS design

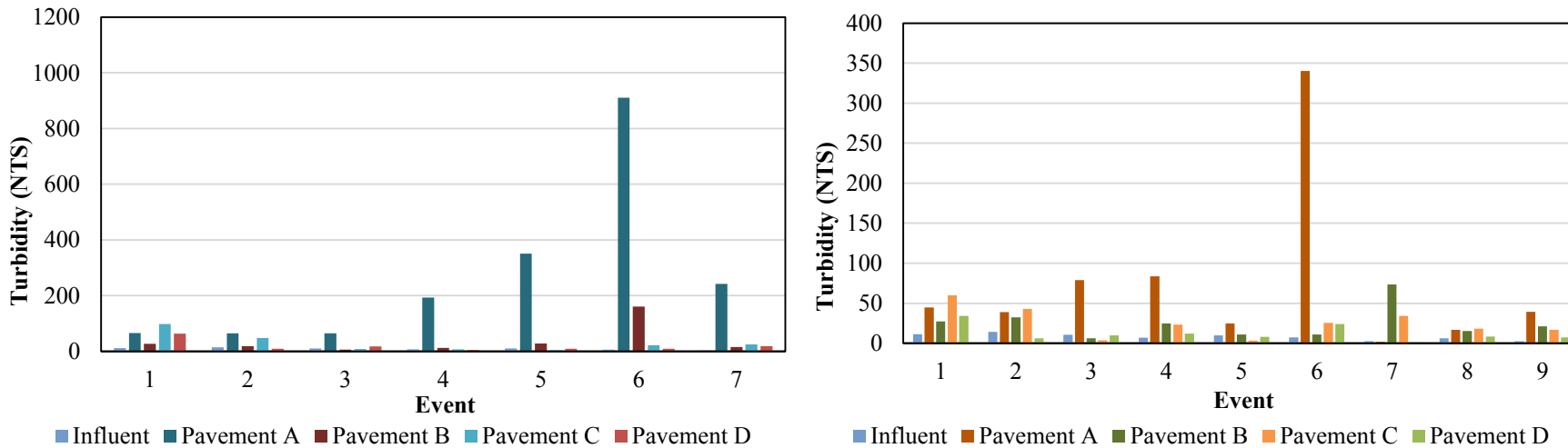


Figure 4-17: Turbidity influent, first flush (left) and EMC (right) concentrations for each PPS design

Chapter 4 : Results and analysis

The impact of unwashed aggregate on water quality emanating from permeable pavements

4.3 Laboratory pavement disassembly

The ‘Results and Analysis’ chapter indicated that the pavements had not been adequately flushed at the outset as the leaching of pollutants from the internal pavement structure was not eliminated – i.e. effluent concentrations commonly exceeded influent levels in each pavement for various pollutants. For this reason, the laboratory pavements were carefully excavated / disassembled and inspected. Some photographs taken during this process are shown in Figure 4-18. Note that these pavements had been exposed to two experimental phases, namely the pavement flushing process and the pollutant addition process, respectively. This section will describe the post-investigation condition of each pavement as observed during the excavation process first, by describing observations common to all four designs, and then by describing observations specific to each design.



Figure 4-18: Pavement excavation documenting the internal condition of each structure

4.3.1 Observations common to each pavement during excavation

In each design, oil staining was observed on the material directly below the point of application on the pavers, as shown by the dark patches in Figure 4-19, indicating that the oil was transported around the pavers by water infiltrating the surface. However, the oil that reached the bedding layer was confined to this layer and did not creep down to the layers below. This supports the literature promoting PPS as effective oil retaining structures.



Figure 4-19: Oil stain on the bedding layer directly below the pavers

Another common trait observed during the disassembly process was that each pavement retained moisture very effectively below the paving surface. In fact, after some 4 months of sitting in the laboratory with no water being applied to the surface, the bedding layer in each of the pavements remained damp and only began drying out once the pavers were removed during excavation. The evaporation protection provided by the PPS design is favourable for stormwater storage and subsequent harvesting directly from the pavement as water losses will be minimised.

Lastly, each of the pavements retained a residual volume of water on the pavement base, a consideration that was noted during the construction in section 3.2.3, outlining ‘construction considerations’. This residual volume present at the bottom of the bins could potentially alter the effluent quality. However, similar occurrences are likely in existing ‘tanked’ PPS (systems containing an impermeable underlays) with underdrains that have a slightly raised outlet.

4.3.2 Pavement A – ‘no geotextile’

The excavation of Pavement A – the only design without the Inbitex ® geotextile, revealed a number of interesting insights. Firstly, of all, the pavement design Pavement A had the largest amount of ‘dust’ adhered to the bedding gravel (the layer positioned directly below the pavers), which can be seen by the dust marks on the hand in Figure 4-20. After the entire flushing process and the addition of the storms during the pollutant addition process, the dust on the bedding gravel was still not removed. This indicates how difficult it is to ‘clean’ unwashed aggregate once it is placed within the pavement structure.

Chapter 4 : Results and analysis

The impact of unwashed aggregate on the quality of water emanating from permeable pavements



Figure 4-20: Early stages of the excavation of Pavement A where large amounts of ‘dust’ were found adhering to the bedding gravel

Sediment continued to be found throughout the pavement profile but became more noticeable towards the lower third of the layerworks, as shown in Figure 4-21, indicating that sediment freed from unwashed aggregate tends to migrate downwards through the layers. The movement of sediment downwards was most likely caused by the flushing action of the water as it percolated through Pavement A, which unlike the other designs did not contain Inbitex[®] geotextile. Of particular interest is that the occurrence of considerable amounts of sediment throughout the profile of Pavement A indicates that the flushing regime applied was not sufficient to ‘clean’ the *in-situ* stone.

4.3.3 Pavement B – ‘standard’, and Pavement C – ‘no small’ stone

During the excavation of Pavement B – the ‘standard’ Aquaflow Permeable Paving design – and Pavement C – ‘no small’ 19-25mm stone – it was observed that a considerable amount of sediment was retained on the Inbitex[®] geotextile. This sediment would have largely originated from the bedding gravel layer situated directly above it (see Figure 4-22). Although no drainage problems were encountered by the completion of testing, with time and continued sediment release onto the geotextile, the geotextile in Pavement B and Pavement C may have become clogged, reducing drainage flows considerably.

Additionally, Pavement B appeared to have the least sediment distributed within the aggregate layers of all the designs (see Figure 4-20). This finding would have been expected in Pavement C, which was the most favourable design with regard to minimising system flushing – statistically this pavement only required an additional 250mm to be stabilised. However, Pavement C displayed more sediment in the aggregate profile when excavated than Pavement B.

Chapter 4 : Results and analysis

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

Therefore, the excavation observations somewhat disagreed with the TSS leaching period estimations for Pavement B outlined in Section 4.1.6. Pavement B – identical to Pavement A except for the addition of an Inbitex® geotextile layer – was estimated to require an additional 980mm (4.5 rainy seasons) of rainfall before the TSS levels in the effluent were to stabilise. However, the excavation observations did support the ‘TSS and Turbidity’ pavement flushing results in Section 4.1.4 that reported TSS effluent values of Pavements B (and C) being consistently lower than those of Pavements A and D throughout the experiment.

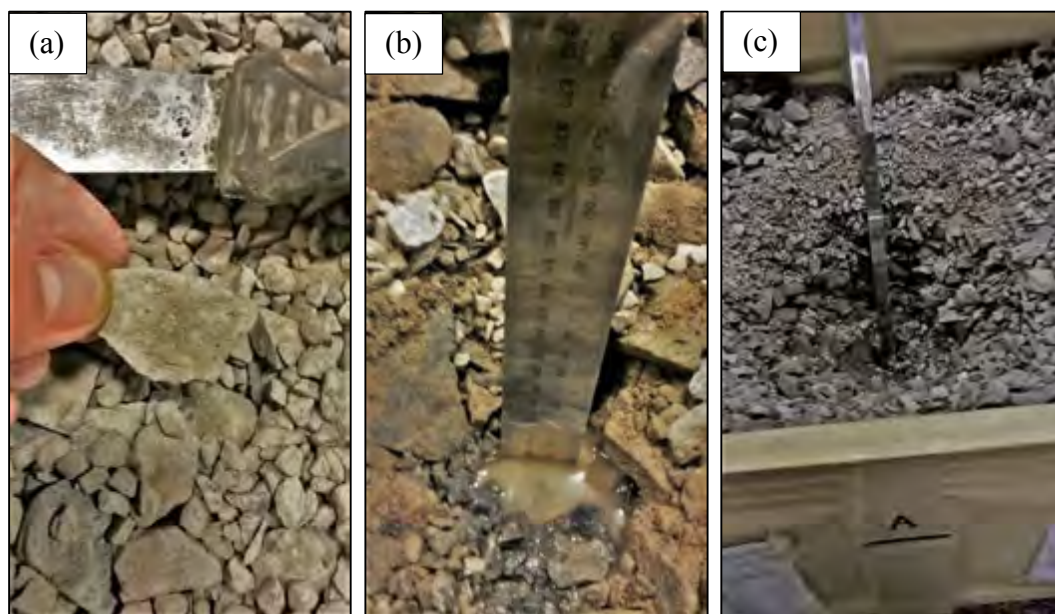


Figure 4-21: Sediment observed at different depths within Pavement A: (a) ‘upper’ base 19-25mm aggregate layer; (b) bottom of the ‘lower’ base 50-63mm aggregate layer; (c) profile of the excavation

These observations serve to show how difficult it is to predict what is happening inside the pavement structure. Without additional knowledge or tests, the conclusions drawn from this PPS flushing process are difficult to verify.

Additionally, it should be re-stated that the considerable flushing applied to each pavement was not adequate to prepare the aggregate stone for the pollution addition phase. It is very difficult to ‘clean’ aggregate once *in-situ*.

Chapter 4 : Results and analysis

The impact of unwashed aggregate on the quality of water emanating from permeable pavements



Figure 4-22: Excavation of Pavement B revealing the condition of the Inbitex® geotextile

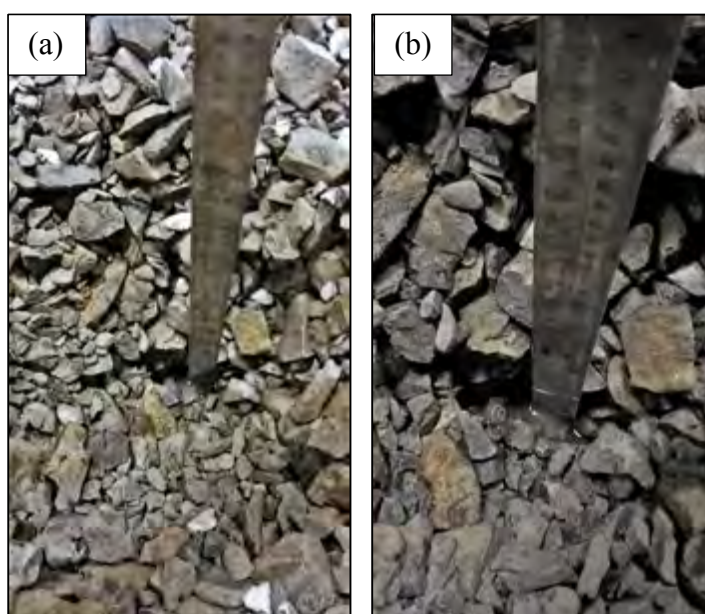


Figure 4-23: Sediment observed at different depths within Pavement B: (a) profile of the excavation; (b) bottom of the 'lower' base 50-63mm aggregate layer

4.3.4 Pavement D – 'sand'

The excavation in Pavement D, in contrast to the Inbitex® geotextile in Pavements B and C, revealed a virtually untouched Inbitex® geotextile that looked 'brand new' apart from some minor punctures from the underlying 19-25mm aggregate (see Figure 4-25). There were no signs of clogging whatsoever. This suggests that the bedding sand layer not only protected the geotextile from clogging but itself leached very little sediment, lowering the leaching risk. For future studies on quality performance of PPS, substituting a sand bedding layer for the usual 2-

6mm bedding gravel may have some interesting prospects. However, if sand was to be used as a bedding layer then other practical considerations particularly that of clogging, need to be investigated further.



Figure 4-24: Sediment observed at different depths within Pavement C: (a) bottom of the 'lower' base 50-63mm aggregate layer

Interestingly, of all the pavements, Pavement D contained the most sediment within the aggregate layers below the geotextile, i.e. in the 19-25mm and 50-62mm stone, as shown in Figure 4-26. Instead of the usual 'sandy' sediment found in Pavement's A, B and C, the sediment in Pavement D was rather 'clayish' making the aggregate 'muddy' to touch (see Figure 4-26). This was an unexpected finding that was not indicated by the 'TSS and Turbidity' results in Section 4.1.4 or by the 'Leaching period' results in Section 4.1.6. Based on the high TSS concentrations in the effluent during the flushing process and pollutant addition process, one would expect rapid cleaning of the aggregate in Pavement A and consequently a relatively small amount of sediment would be expected internally. Furthermore, when inspecting the predicted rainfall required for stabilisation, Pavement A required 1520mm of rainfall (as opposed to 270mm for Pavement D), again indicating that the sediment in Pavement A was more prevalent in the effluent than in Pavement D. A possible reason for the internal structure of Pavement D being the least 'flushed' of all the pavement post-testing could be due to the inclusion of a sand bedding layer and an Inbitex ® geotextile layer, both of which reduce the infiltration rate through the pavement. This reduction in infiltration rate would reduce the flushing potential of water passing through the pavement layers and therefore, reduce the 'cleaning' action of the water passing through the aggregate layers.

Chapter 4 : Results and analysis

The impact of unwashed aggregate on the quality of water emanating from permeable pavements



Figure 4-25: Excavation of the Inbitex® geotextile below the bedding sand

These observations noted during the excavation process serve to show how difficult it is to predict what is happening inside the pavement structure. Judgements from test results were in some cases brought into question once the pavement was excavated and inspected. The uncertainties from this study motivate for additional studies to investigate the dynamics of the internal structure of a PPS. It would be very helpful in terms of understanding the dynamics of a PPS to construct future laboratory models such that the researcher is able to observe what happens inside the pavement while testing – for example, installing a ‘window’ of clear Perspex or other suitable material or an inspection chamber.

Chapter 4 : Results and analysis

The impact of unwashed aggregate on the quality of water emanating from permeable pavements



Figure 4-26: Sediment observed at different depths within Pavement D

4.4 Summary

In summary the most urgent aspects to note with regard to the above findings are:

- i) The use of unwashed stone may seriously pollute stormwater infiltrating the pavement for a significant amount of time. The pollutants of particular concern are TSS, PO_4^{3-} and NH_3 .
- ii) Once in-situ, it is very difficult to ‘clean’ the unwashed aggregate by running water through the system. Alternative, suitable flushing methods aggregate need to be determined for PPS constructed with unwashed aggregate. However, a better proposal than washing the aggregate in-situ is simply to use washed stone during pavement construction.
- iii) Due to the unforeseen delayed release of the pollutants from the ‘Hornfel Malmesbury Shale’ aggregate, the attempted flushing of the in-situ stone proved inadequate. The pollutants continued leaching into the effluent showing an excess of the flushing volumes

Chapter 4 : Results and analysis

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

applied and thus the treatment efficacy results after the accelerated flushing were contaminated.

- iv) The Inbitex ® geotextile appeared to reduce pollutant ‘spikes’ during the flushing process and was particularly effective in reducing excessive TSS effluent concentrations.
- v) Pavement C – constructed with no ‘small’ stone, appeared to stabilize the fastest when considering the effluent pollutant concentration results. However, when the pavement was disassembled, Pavement B appeared to have the least sediment within the sub-base profile, while pavement D had the most. Observations made during excavation illustrated how difficult it is to predict what is happening inside the pavement structure. Although judgements were made from the investigation phases – pavement flushing and pollutant addition, these assumptions need to be investigated further to understand the dynamics of the internal structure of a PPS before they can be verified.

5. Conclusions and recommendations

5.1 Conclusions

The following sections outline the main findings from the various aspects of this study. The conclusions for each phases of the research are presented separately at first and are then combined in a final section to address the main questions relating to this study; i.e. *‘Is there scope to use PPS as stormwater harvesting systems? Can they aid in treating stormwater, and if so, to what extent?’* Some of the methodological and operational challenges associated with the management and implementation of permeable pavement systems are also discussed, as well as the limitations of this project – both in terms of time and scope – so that recommendations can be made.

5.1.1 Observations from laboratory experiment pavement flushing

- The use of unwashed stone in the construction of PPS appears to contribute to the amount of pollution exiting the pavement system. In PPS construction practice it is commonly assumed that negligible quantities of pollutants are flushed from the unwashed pavement materials; however, the concentrations of TSS, PO_4^{3-} and NH_3 in this study were found to be unexpectedly high in many samples. Furthermore, the concentrations of pollutants leaching from each pavement remained high for a considerable flushing duration.
- The most favourable design with regard to minimising the flushing requirements was Pavement C. The inclusion of a geotextile below the bedding layer appears to limit the number of rainfall events that are required in order to flush the system for TSS and NH_3 . Additionally, it appears that replacement of the 19-25mm ‘Hornfel Malmesbury Shale’ aggregate with 50-63mm ‘Hornfel Malmesbury Shale’ aggregate in the storage layer may decrease the flushing rainfall volumes required to stabilise the system. This reduction in required flushing volumes could be due to the reduction in aggregate surface area and therefore less sediment attachment is possible. Lastly, it should be noted that the inclusion of sand as a bedding layer as opposed to gravel may result in the increased leaching of NH_3 into receiving waters. The presence of the pollutants in the leachate is likely due to the amount of ‘dust’ in the system prior to stabilisation.
- The presence of pollutants leaching from the base materials was exacerbated by an increase in rainfall depth applied to the system (not rainfall intensity as the application intensity was kept constant for each pavement). However, the inclusion of the Inbitex® geotextile seemed to reduce the severity of the pollutant ‘spikes’ – most likely due to the reduced infiltration rate through the pavement and the additional physical filtration layer.
- Overall, it can be concluded that the use of unwashed stone in the construction of PPS should be avoided as this is likely to result in considerably polluted leachate for some time after construction.

5.1.2 Observations from laboratory experiment pollutant addition process

- Selected pollutant effluent concentrations in all pavement designs commonly exceeded influent concentrations indicating insufficient system flushing. As a result of insufficient flushing, the first flush and EMC pollutant removal results from each of the pavement designs were inconclusive. Therefore, more research is required before fit for purpose use can be recommended.
- Pavement A was the most susceptible to pollutant spikes due to the lack of an Inbitex® geotextile layer. The inclusion of the Inbitex® geotextile seemed to reduce the severity of the pollutant ‘spikes’ – most likely due to the reduced infiltration rate through the pavement and the additional physical filtration layer. These factors in turn reduce the likelihood of sediment and their adhered pollutants such as NO_3^- being released during high volume storms.

5.1.3 Overall findings

One of the most important findings from this research relates to the use and impact of unwashed stone ‘Hornfel Malmesbury Shale’ aggregate in the base layers of PPS. Whilst local standard specifications typically refer to the use of ‘clean’ stone in PPS construction, this is more to do with detritus and other contamination rather than ‘washing’ the stone; and generally the stone used is received directly from the quarry and placed immediately in the base layer. This leads to the dust or small particulates that are coating the stone being flushed from the system during rainfall events. The extent and characterisation of this pollution, and the length of time it takes to ‘adequately’ flush out a PPS after construction, therefore became a major focus of this research. This was particularly the case for the laboratory experiment, the methodology for which was thus limited in terms of highlighting the treatment efficacy of different pavement designs. The laboratory experiment was able to show that the inclusion of Inbitex® geotextile in the PPS design seems to reduce the severity of pollutant ‘spikes’ – most likely due to the reduced infiltration rate through the pavement and the additional physical filtration layer. The laboratory findings relating to increased levels of TSS in the effluent from newly-constructed pavements (with unwashed stone aggregate) were confirmed in the field tests at the NEB PPS (as reported in Appendix D: New Engineering Building parking area).

5.2 Recommendations

5.2.1 Recommendations for implementation and management of PPS

- A set of construction guidelines should be drawn up for the implementation of PPS. The current state of the NEB PPS and its significant TSS discharge could have been avoided by improved construction practice. While this does not necessary suggest that the UCT PPS is polluting downstream environments (this is difficult to discern without taking the

Chapter 5 : Conclusions and recommendations

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

effect of flow attenuation on loading into account), it does decrease the overall effluent quality and also compromises any significant conclusions about water quality performance. The effect is likely to be temporary, but any monitoring done thus far is likely to have been biased by the impact of the unwashed stone.

- Guidelines for PPS maintenance should also be investigated. It appears that owners may either be unaware of the maintenance requirements of PPS, or unwilling to bear the costs. In areas where PPS and other SuDS are implemented, clear obligations regarding maintenance should be drawn up. Methods of maintenance, their costs and benefits, and the stakeholders responsible for the costs and benefits should be thoroughly investigated and carefully regulated.
- It is suggested that a simple infiltration test, such as the one developed by NC State University (see Figure 2 12) could provide a feasible alternative to more complex infiltration tests, and should form part of the maintenance regime for permeable pavements.
- The use of washed aggregate stone during the construction of PPS in South Africa should be investigated further.

5.2.2 Recommendations for future research

- Conduct laboratory experimental testing using washed stone in the pavement sub-structure to assess treatment efficacy of design variations. Thereafter, suitable fit-for-purpose applications for the treated effluent can be suggested.
- Consider various alternative PPS designs, including the use of different types of aggregate stone, i.e. alternatives to ‘Hornfel Malmesbury Shale’.
- Further research is needed to determine more suitable methods of system flushing when unwashed stone is incorporated in the PPS sub-structure.
- Test for heavy metals, hydrocarbons, and microbial activity in PPS should be investigated further.
- Methodological issues should be revised and incorporated into future PPS studies in a South African context.
- Geotextile clogging is a serious concern in PPS. The performance of geotextiles (of different types) in PPS should be investigated further.
- Consider the different nutrient / other pollutant leaching capabilities of different aggregate types.
- Develop a set of standard procedures for the washing of aggregate, as well as tests for aggregate materials prior to delivery from the quarry. This would include consideration of the costs involved.

Chapter 5 : Conclusions and recommendations

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

- This study did not include effluent flow data for PPS. Given the inherent difficulties of using percentage reduction as a performance metric, a better way of assessing PPS performance would be to calculate the total load that the pavement contributes to downstream ecosystems. To do this, flow data for each sample would be required. This would also enable the calculation of a flow-weighted average for PPS effluent rather than the unweighted average used in this study.
- These observations noted during the excavation process serve to show how difficult it is to predict what is happening inside the pavement structure. Judgements from test results were in some cases brought into question once the pavement was excavated and inspected. The uncertainties from this study motivate for additional studies to investigate the dynamics of the internal structure of a PPS. It would be very helpful in terms of understanding the dynamics of a PPS to construct future laboratory models such that the researcher is able to observe what happens inside the pavement while testing – for example, installing a ‘window’ of clear Perspex or other suitable material or an inspection chamber etc.

Chapter 5 : Conclusions and recommendations

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

References

- 1stWeather.com. (2002). Rainfall data: Cape Town International Airport. South African Weather Service. Cape Town, South Africa. Retrieved August 10, 2015, from http://www.1stweather.com/regional/data/data_daily_rain.shtml
- Abbot, C. L., & Comino-Mateos, L. (2003). In-situ hydraulic performance of a permeable pavement sustainable urban drainage system. *Water and Environment Journal*, 17(3), 187–190.
- Al-Rubaei, A., Engström, M., & Viklander, M. (2015). Long-term hydraulic performance of stormwater infiltration systems—a field survey. *Urban Water Journal*, 12(8), 660–671.
- Alsubih, M., Arthur, S., Wright, G., & Allen, D. (2014). Influence of the Sediment on the Hydrological Performance of Permeable Pavements. In *13th International Conference on Urban Drainage* (pp. 1–8). Sarawak, Malaysia.
- Andersen, C. T., Foster, I. D. L., & Pratt, C. J. (1999). The role of urban surfaces (permeable pavements) in regulating drainage and evaporation: development of a laboratory simulation experiment. *Hydrological Processes*, 13(4), 597–609.
- Armitage, N., Carden, K., Winter, K., Naidoo, V., Spiegel, A., Mauck, B., & Coulson, D. (2014). *WSUD for South Africa Framework and Guidelines*. Report TT 558/14, Water Research Commission of South Africa, Pretoria, South Africa. ISBN: 9781431205301.
- Armitage, N., Vice, M., Fisher-jeffes, L., Winter, K., Spiegel, A., & Dunstan, J. (2013a). *Alternative Technology for Stormwater Management: Sustainable Drainage Systems – Report and South African Case Studies*. Report TT 1826/1/13, Water Research Commission of South Africa, Pretoria, South Africa. ISBN: 9781431204243.
- Armitage, N., Vice, M., Fisher-jeffes, L., Winter, K., Spiegel, A., & Dunstan, J. (2013b). *The South African Guidelines for Sustainable Drainage Systems*. Report TT 558/13, Water Research Commission of South Africa, Pretoria, South Africa. ISBN: 9781431204137.
- Aryal, R., & Beecham, S. (2014). Assessment of Suspended Solids and Their Fraction on Permeable Pavement Clogging. In *13th International Conference on Urban Drainage* (pp. 1–8). 7-12 September, Sarawak, Malaysia.
- Balades, J., Legret, M., & Madiec, H. (1995). Permeable pavements: pollution management tools. *Water Science and Technology*, 32(1), 49–56.
- Ball, J. E., & Rankin, K. (2010). The hydrological performance of a permeable pavement. *Urban Water Journal*, 7(2), 79–90. ISSN:1573-062X.
- Barbosa, a E., Fernandes, J. N., & David, L. M. (2012). Key issues for sustainable urban stormwater management. *Water Research*, 46(20), 6787–98. ISSN:1879-2448.
- Bean, E. Z., Hunt, W. F., Bidelspach, D. A., & Jonathan, T. S. (2004). *Study on the surface infiltration rate of permeable pavements*. Washington, DC.
- Beecham, S., Lucke, T., & Myers, B. (2010). Designing porous and permeable pavements for stormwater harvesting and reuse. In *1st European International Association for Hydro-Environment Engineering and Research (IAHR) Conference*. Edinburgh, UK.
- Beecham, S., Pezzaniti, D., & Kandasamy, J. (2012). Stormwater treatment using permeable

References

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

- pavements. *Proceedings of the ICE-Water Management*, 165(3), 161–170.
- Berndtsson, J. C. (2014). Storm water quality of first flush urban runoff in relation to different traffic characteristics. *Urban Water Journal*, 11(4), 284–296. ISSN:1573-062X.
- Bernot, M. J., Calkins, M., Bernot, R. J., & Hunt, M. (2011). The Influence of Different Urban Pavements on Water Chemistry. *Road Materials and Pavement Design*, 12(1), 159–176. ISSN:1468-0629.
- Bond, P. C. (1999). *Mineral Oil Biodegradation Within Permeable Pavements*. PhD Thesis, Coventry University, UK.
- Borgwardt, S. (2006). Long-term in-situ infiltration performance of permeable concrete block pavement. In *Proceedings of the 8th International Conference on Concrete Block Paving*. November 6-8, San Francisco, USA.
- Bosch, D., & Onstad, C. (1988). Surface seal hydraulic conductivity as affected by rainfall. *Transactions of the ASAE*, 31(4), 1120–1127.
- Bouwer, H. (2002). Artificial recharge of groundwater: hydrogeology and engineering. *Hydrogeology Journal*, 10(1), 121–142.
- Brattebo, B. O., & Booth, D. B. (2003). Long-term stormwater quantity and quality performance of permeable pavement systems. *Water Research*, 37(18), 4369–76. ISBN: 2066853836.
- Brown, J. N., & Peake, B. M. (2006). Sources of heavy metals and polycyclic aromatic hydrocarbons in urban stormwater runoff. *The Science of the Total Environment*, 359(1–3), 145–55. ISSN:0048-9697.
- Brown, R., Keath, N., & Wong, T. (2008). Transitioning to water sensitive cities: historical, current and future transition states. In *11th International Conference on Urban Drainage*. Edinburgh, Scotland, UK.
- Brown, R. R. (2005). Impediments to integrated urban stormwater management: the need for institutional reform. *Environmental Management*, 36(3), 455–68. ISSN:0364-152X.
- Brundtland, G. H. (1987). *Our Common Future: Report of the World Commission on Environment and Development*. Oxford: Oxford University Press.
- Burian, S., & Edwards, F. (2002). Historical perspectives of urban drainage. In *9th International Conference on Urban Drainage*. doi:10.1061/40644(2002)284.
- Butler, D., & Davies, J. W. (2004). *Urban Drainage* (3rd ed.). Spon Press. Oxon, UK.
- Buys, F., & Aldous, M. (2009). The perceived economic impact of the City of Johannesburg's storm water attenuation policy on private property developers. *Acta Structilia*, 16(2), 18–45.
- Carden, K. (2013). *A measure of sustainability in the context of urban water management in South Africa*. PhD Thesis, University of Cape Town.
- CDoT. (2004). Groundwater and Seepage. In *Drainage Design Manual*. CDoT. Colorado, USA.
- Charlesworth, S., Everett, M., McCarthy, R., Ordóñez, A., & De Miguel, E. (2003). A comparative study of heavy metal concentration and distribution in deposited street dusts in a large and a small urban area: Birmingham and Coventry, West. *Environment International*, 29(5), 563–573.

References

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

- Charlesworth, S. M., Nnadi, E., Oyelola, O., Bennett, J., Warwick, F., Jackson, R., & Lawson, D. (2012). Laboratory based experiments to assess the use of green and food based compost to improve water quality in a Sustainable Drainage (SUDS) device such as a swale. *The Science of the Total Environment*, 424(May), 337–43. ISSN:1879-1026.
- Chowdhury, R. K., & Beecham, S. (2013). Characterization of rainfall spells for urban water management. *International Journal of Climatology*, 33(4), 959–967. ISSN:08998418.
- CoCT. (2009). *Management of Urban Stormwater Impacts Policy*. chment, Stormwater and River Management Branch, Cape Town, South Africa.
- Collins, K. A., Hunt, W. F., & Hathaway, J. M. (2010). Side-by-Side Comparison of Nitrogen Species Removal for Four Types of Permeable Pavement and Standard Asphalt in Eastern North Carolina. *Journal of Hydrologic Engineering*, 15(6), 512–521. ISSN:1084-0699.
- Concrete Manufacturers Association. (2003). *Concrete Block Paving – Cost Comparison between Concrete Block Paving and Premix Asphalt*. Portland Park, Pretoria, South Africa.
- Coombes, P. J., Kuczera, G., Kalma, J. D., & Argue, J. R. (2002). An evaluation of the benefits of source control measures at the regional scale. *Urban Water*, 4(4), 307–320. ISBN: 1462-0758.
- Coupe, S. J. (2004). *Oil biodegradation and microbial ecology within permeable pavements*. PhD dissertation, University of Coventry.
- Coupe, S. J., Nnadi, E. O., & Charlesworth, S. (2010). Multiple Benefits Derived from the Installation of Permeable Pavement System. *Novatech*, 1–10. ISBN: 2476888370.
- CSIR. (2000). Chapter 6: Stormwater Management. In *Guidelines for Human Settlement Planning and Design*. Council for Scientific and Industrial Research (CSIR). Pretoria, South Africa.
- Das, B., & Sobhan, K. (2013). *Principles of Geotechnical Engineering* (8th ed.). Cengage Learning. Stamford, USA. ISBN: 1133108660.
- Debo, T. N., & Reese, A. (2003). *Municipal stormwater management* (2nd ed.). Lewis Publishers of CRC Press. Florida, USA. ISBN: 9781420032260.
- Deletic, A. (1998). The first flush load of urban surface runoff. *Water Research*, 32(8), 2462–2470. ISSN:00431354.
- Dhalla, S., & Zimmer, C. (2010). *Low Impact Development Stormwater Management Planning and Design Guide*. Stormwater Guide. Toronto: Toronto and Region Conservation Authority.
- Dietz, M. E. (2007). Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. *Water, Air, and Soil Pollution*, 186(1–4), 351–363. ISSN:0049-6979.
- Donovan, I., & Naji, F. (2003). *Water Sensitive Planning Guide for the Sydney Region*. Sydney, Australia.
- Drake, J. a. P., Bradford, A., & Marsalek, J. (2013). Review of environmental performance of permeable pavement systems: state of the knowledge. *Water Quality Research Journal of Canada*, 48(3), 203. ISSN:1201-3080.
- Duncan, H. (1999). *Urban stormwater quality: a statistical overview*. CRC for Catchment

References

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

Hydrology. Melbourne, Australia.

- DWAF. (1996a). *South African Water Quality Guidelines: Volume 4 Agricultural Use: Irrigation*. (S. Holmes, Ed.) (2nd ed., Vol. 4). Department of Water Affairs (DWAF). Department of Water Affairs and Forestry (DWAF), Pretoria, South Africa. ISBN: 0798853387.
- DWAF. (1996b). *South African Water Quality Guidelines. Volume 2: Recreational Water Use. Second Edition*. (S. Holmes, Ed.) (2nd ed., Vol. 2). CSIR Environmental Services. Department of Water Affairs and Forestry, Pretoria, South Africa. ISBN: 0798853387.
- DWAF. (1996c). *South African Water Quality Guidelines: Volume 1 - Domestic Use*. (S. Holmes, Ed.) (2nd ed., Vol. 1). CSIR Environmental Services. Department of Water Affairs and Forestry (DWAF), Pretoria, South Africa. ISBN: 0798853387.
- DWAF. (1996d). *South African Water Quality Guidelines: Volume 3 - Industrial Use*. (S. Holmes, Ed.) (2nd ed., Vol. 3). CSIR Environmental Services. Department of Water Affairs and Forestry (DWAF), Pretoria, South Africa. ISBN: 0798853387.
- DWAF. (2004). *National water resource strategy*. Department of Water Affairs and Forestry (DWAF), Pretoria, South Africa.
- DWAF. (2013). *National Water Resource Strategy (NWRS2): Water for an Equitable and Sustainable Future* (Vol. NWRS2). Department of Water Affairs and Forestry (DWAF), South Africa.
- Ellis, J. (1977). The characterisation of particulate solids and quality of water discharged from an urban catchment. *IAHS-AISH Publication, 123*, 283–291.
- Ellis, J., Deutsch, J., Legret, M., Martin, C., Revitt, D. M., Scholes, L., H. Seiker, & Zimmerman, U. (2006). The DayWater decision support approach to the selection of sustainable drainage systems: A multi-criteria methodology for BMP decision makers. *Water Practice Technology, 1*(1). doi:10.2166/WPT.2006002.
- Fach, S., & Geiger, W. (2005). Effective pollutant retention capacity of permeable pavements for infiltrated road runoffs determined by laboratory tests. *Water Science & Technology, 51*(2), 37–45.
- Fassman, E. A., & Blackbourn, S. (2010). Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils. *Journal of Hydrologic Engineering, 15*(6), 475–485. ISBN: 1084-0699(15:6L.475;1.
- Ferguson, B. (1994). *Stormwater infiltration*. Lewis Publishers, CRC Press. London, UK. ISBN: 0-87371-987-5.
- Ferguson, B. K. (2006). Progress in Porous and Permeable Pavements. In *Proceedings of the StormCon Conference*. Denver, Colorado.
- Field, R., & Sullivan, D. (2002). *Wet-weather flow in the urban watershed: technology and management*. Lewis Publishers, CRC Press. Florida, USA. ISBN: 1566769167.
- Fisher-Jeffes, L. (2011). *Development of the Simple Economic Model (SEM) for stormwater management*. MSc. Eng. Dissertation, University of Cape Town.
- Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D., & Viklander, M. (2014a). SUDS, LID, BMPs, WSUD and more –

References

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

- The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, 12(7), 525–542. ISSN:1573-062X.
- Fletcher, T. D., Vietz, G., & Walsh, C. J. (2014b). Protection of stream ecosystems from urban stormwater runoff: The multiple benefits of an ecohydrological approach. *Progress in Physical Geography*, 1–13. ISSN:0309-1333.
- Fletcher, T., & Deletić, A. (2008). Volume 1 in Urban water series. In *Data requirements for integrated urban water management*. The United Nations Educational, Scientific and Cultural Organization (UNESCO) Publishing and Taylor & Francis, Taylor & Francis Group. Paris, France. ISBN: 1749-0790.
- Formpave, & Hanson. (2010). *Formpave product directory*.
- German, J., & Svensson, G. (2002). Metal content and particle size distribution of street sediments and street sweeping waste. *Water Science & Technology*, 46(6), 191–198.
- Göbel, P., Dierkes, C., & Coldewey, W. G. (2007). Storm water runoff concentration matrix for urban areas. *Journal of Contaminant Hydrology*, 91(1–2), 26–42. doi:10.1016/j.jconhyd.2006.08.008. ISSN:0169-7722.
- González-Angullo, N., Castro, D., Rodríguez-Hernández, J., & Davies, J. W. (2008). Runoff infiltration to permeable paving in clogged conditions. *Urban Water Journal*, 5(2), 117–124. ISSN:1573-062X.
- Goodland, R., & Daly, H. (2008). Environmental Sustainability : Universal and Non-Negotiable. *Ecological Applications*, 6(4), 1002–1017.
- Goonetilleke, A., Thomas, E., Ginn, S., & Gilbert, D. (2005). Understanding the role of land use in urban stormwater quality management. *Journal of Environmental Management*, 74(1), 31–42. ISSN:0301-4797.
- Hach Company. (2014). *Ammonia Nitrogen, Salicylate Test Method*. USA.
- Hamel, P., Daly, E., & Fletcher, T. D. (2013). Source-control stormwater management for mitigating the impacts of urbanisation on baseflow: A review. *Journal of Hydrology*, 485(January), 201–211. ISSN:00221694.
- Hamel, P., & Fletcher, T. D. (2014). The impact of stormwater source-control strategies on the (low) flow regime of urban catchments. *Water Science and Technology : A Journal of the International Association on Water Pollution Research*, 69(4), 739–45. ISSN:0273-1223.
- Haselbach, L. M., Valavala, S., & Montes, F. (2006). Permeability predictions for sand-clogged Portland cement pervious concrete pavement systems. *Journal of Environmental Management*, 81(1), 42–9. ISSN:0301-4797.
- Hatt, B., Deletic, A., & Fletcher, T. (2006). Integrated treatment and recycling of stormwater: a review of Australian practice. *Journal of Environmental Management*, 79(1), 102–13. doi:10.1016/j.jenvman.2005.06.003.
- Hatt, B. E., Fletcher, T. D., & Deletic, A. (2007). Treatment performance of gravel filter media: implications for design and application of stormwater infiltration systems. *Water Research*, 41(12), 2513–24. ISSN:0043-1354.
- Heal, K., McLean, N., & D'arcy, B. (2004). SUDS and Sustainability. In *26th Meeting of the Standing Conf. on Stormwater Source Control*. September 2004, Dunfermline, UK.

References

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

- Hedden, S., & Cilliers, J. (2014). Parched prospects: The emerging water crisis in South Africa. *African Futures*, (September).
- Hjorth, P., & Bagheri, A. (2006). Navigating towards sustainable development: A system dynamics approach. *Futures*, 38, 74–92. doi:10.1016/j.futures.2005.04.005. ISBN: 0016-3287. ISSN:00163287.
- Jacobsen, M., Webster, M., & Vairavamoorthy, K. (Eds.). (2013). *The Future of Water in African Cities - Why waste water?* World Bank Publications. Washington DC. ISBN: 9780821397213.
- James, W., & Gerrits, C. (2003). *Maintenance of Infiltration in Modular Interlocking Concrete Pavers with External Drainage Cells. Practical modeling of urban water systems*. CHI monograph 11. Guelph, Canada.
- James, W., & Langsdorff, H. Von. (2003). The use of permeable concrete block pavement in controlling environmental stressors in urban areas. In *7th International Conference on Concrete Block Paving* (pp. 1–8). Sun City, South Africa. ISBN: 0958460914.
- Jefferies, C., Duffy, A., Berwick, N., McLean, N., & Hemmingway, A. (2008). SUDS treatment train assessment tool. In *Proceedings 11th International Conference on Urban Drainage*. IAHR/IWA. Edinburgh, Scotland, UK.
- Kazemi, F., & Hill, K. (2015). Effect of permeable pavement basecourse aggregates on stormwater quality for irrigation reuse. *Ecological Engineering*, 77, 189–195. doi:10.1016/j.ecoleng.2015.01.020. ISSN:09258574.
- Kim, L., Ko, S., Jeong, S., & Yoon, J. (2007). Characteristics of washed-off pollutants and dynamic EMCs in parking lots and bridges during a storm. *The Science of the Total Environment*, 376(1), 178–84. ISSN:0048-9697.
- Kjeldsen, T. ., Smithers, J. ., & Schulze, R. . (2002). Regional flood frequency analysis in the KwaZulu-Natal province, South Africa, using the index-flood method. *Journal of Hydrology*, 255(1), 194–211. ISSN:00221694.
- Kresin, C., James, W., & Elrick, D. (1996). Observations of Infiltration Through Clogged Porous Concrete Block Pavers, 5. ISBN: 0969742274.
- Lariyah, M. S., Mohamed Roseli, Z., Zulkefli, M., & Hanim, A. (2014). Application of Porous Pavement System for MSMA Stormwater Management Ecohydrology : Comparison of Asphalt , Interlocking and Turf Pavement. In *13th International Conference on Urban Drainage* (pp. 1–10). Sarawak, Malaysia.
- Legret, M., & Colandini, V. (1999). Effects of a porous pavement with reservoir structure on runoff water: water quality and fate of heavy metals. *Water Science and Technology*, 39(2), 111–117.
- Legret, M., Colandini, V., & Le Marc, C. (1996). Effects of a porous pavement with reservoir structure on the quality of runoff water and soil. *Science of The Total Environment*, 189/190, 335–340. ISSN:00489697.
- Lems, P. (2008). The values of urban water. In *Proc. 11th International Conference on Urban Drainage* (pp. 1–14). Edinburgh, Scotland, UK.
- Loayza, N., Rigolini, J., & Llorente, G. (2012). Do middle classes bring about institutional

References

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

- reforms? *Economics Letters*, 116(3), 440–444.
- Lucke, T., & Beecham, S. (2011). An investigation into long-term infiltration rates for permeable pavements on sloping sub-catchments. In *12th International Conference on Urban Drainage, Porto Alegre/Brazil, 11-16 September 2011* (pp. 1–8). Porto Alegre, Brazil.
- Lucke, T., Beecham, S., Boogaard, F. C., & Myers, B. (2013). *Are Infiltration Capacities of Clogged Permeable Pavements Still Acceptable?* GRAIE, Lyon, France (FRA).
- Mammon, N. (2005). Cape Town 2025: Urban Form and Infrastructure. In *Cape Town 2025 Conference* (pp. 14–15). Isandla Institute. Cape Town, South Africa.
- Marsalek, J. (2000). Evolution of urban drainage: from cloaca maxima to environmental sustainability. In *The National Conference of Urban Hydraulics* (pp. 28–30). Sant'Angelo di Sorrento, Italy.
- Marsalek, J., Barnwell, T. O., Geiger, W., Grottker, M., Huber, W. C., Saul, A. J., Schilling, W., & Torno, H. C. (1993). Urban Drainage Systems: Design and Operation. *Water Science & Technology*, 27(12), 31–70.
- Marsalek, J., Jimenez-Cisneros, B. E., Karamouz, M., Malmquist, P., Goldenfum, J., & Chocat, B. (2008). *Urban Water Cycle Processes and Interactions*. IHP Technical Documents in Hydrology, UNESCO. Paris, France.
- Martine, G., McGranahan, G., Montgomery, M., & Fernandez-Castilla, R. (2008). Introduction. In *The New Global Frontier: Urbanization, Poverty and the Environment in the 21st century* (pp. 1–16). Earthscan. London, UK.
- Melbourne Water Corporation. (1999). *Urban Stormwater: Best Practice Environmental Management Guidelines*. Environment Protection Authority – Melbourne Water Corporation, CSIRO Publishing, Collingwood.
- Milandri, S., Winter, K., Chimphango, S., Armitage, N., Mbui, D., Jackson, G., & Liebau, V. (2012). The performance of plant species in removing nutrients from stormwater in biofiltration systems in Cape Town. *Water SA*, 38(5), 655–662. ISSN:0378-4738.
- Minnesota Highway Department. (2014). *Minnesota Pavement Design Manual*. Minnesota, USA.
- Minton, G. R. (2002). *Stormwater Treatment: Biological, Chemical, and Engineering Principles*. Resource Planning Associates. Seattle, USA.
- Mitchell, V. (2006). Applying Integrated Urban Water Management concepts: A review of Australian experience. *Environmental Management*, 37(5), 589–605.
- Mukheirbir, P. (2005). Local water resource management strategies for adaptation to climate induced impacts in South Africa. In *Proceedings, workshop on rural development and the role of food, water & biomass: opportunities for development and climate*. Energy Research Centre, University of Cape Town. Cape Town, South Africa.
- Mullaney, J., Jefferies, C., & Mackinnon, E. (2011). The performance of block paving with and without geotextile in the sub-base. In *12th International Conference on Urban Drainage*, 11-16 September, Porto Alegre, Brazil.
- Myers, B., Beecham, S., & van Leeuwen, J. A. (2011). Water quality with storage in permeable pavement basecourse. *Proceedings of the ICE - Water Management*, 164(7), 361–372.

References

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

ISSN:1741-7589.

- Nel, N., Parker, a, & Silbernagl, P. (2013). Improving water quality in stormwater & river systems: an approach for determining resources. *Journal of the South African Institution of Civil Engineering*, 55(1), 22–35.
- Newman, A., Coupe, S., Henderson, J., Morgan, J., Puehmeier, T., & Pratt, C. (1996). Oil Retention and Microbial Ecology in Porous Pavement Structures. In *European Forum of Environmental Research Laboratories* (Vol. 9). Rennes, France.
- Newman, A. P., Coupe, S. J., Puehmeier, T., Morgan, J. A., Henderson, J., & Pratt, C. J. (2002). Microbial Ecology of Oil Degrading Porous Pavement Structures. In *Global solutions for urban drainage. Proc. 9th Int. Conf. on Urban Drainage*. Portland, Oregon.
- Newman, A., & Pratt, C. (2002). Oil bio-degradation in permeable pavements by microbial communities. *Water Science and Technology*, 45(7), 51–56.
- Nieswand, G. H., Hordon, R. M., Shelton, T. B., Chavooshian, B. B., & Blarr, S. (1990). Buffer Strips to Protect Water Supply Reservoirs: A Model and Recommendations. *American Water Resource Bulletin*, 26(6), 959–966.
- Nnadi, E. O. (2009). *An evaluation of modified pervious pavements for water harvesting irrigation purposes*. PhD Thesis, Coventry University, UK.
- Nnadi, E. O., Coupe, S. J., Sañudo-Fontaneda, L. a., & Rodriguez-Hernandez, J. (2014). An evaluation of enhanced geotextile layer in permeable pavement to improve stormwater infiltration and attenuation. *International Journal of Pavement Engineering*, 15(10), 925–932. ISSN:1029-8436.
- Nnadi, E. O., Ph, D., Asce, M., Newman, A. P., Sc, M., Duckers, L., Coupe, S. J., & Charlesworth, S. (2012). Design and Validation of a Test Rig to Simulate High Rainfall Events for Infiltration Studies of Permeable Pavement Systems. *Journal of Irrigation and Drainage Engineering*, 38(6), 553–557. doi:10.1061/(ASCE)IR.1943-4774.
- Novotny, V., & Brown, P. (2007). The fifth paradigm of urbanization. In *Cities of the future: towards integrated sustainable water and landscape management*. IWA Publishing. London, UK.
- O’Neill, S., Adhikari, A. R., Gautam, M. R., & Acharya, K. (2013). Bacterial contamination due to point and nonpoint source pollution in a rapidly growing urban center in an arid region. *Urban Water Journal*, 10(6), 411–421. ISSN:1573-062X.
- O’Regan, B., & Moles, R. (1997). Applying a Systems Perspective to Environmental Policy. *Environmental Planning and Management*, 40(4), 535–538.
- Page, J. L., Winston, R. J., & Hunt III, W. F. (2014). Retrofitting With Urban Street Trees for Stormwater Management Using the Silva Cell™ Suspended Pavement System. In *13th International Conference on Urban Drainage* (pp. 1–9). Sarawak, Malaysia.
- Pagotto, C., Legret, M., & Cloirec, P. L. E. (2000). Comparison of the hydraulic behaviour and the quality of highway runoff water according to the type of pavement. *Water Research*, 34(18), 4446–4454.
- Partners in Development (Pty) Ltd. (2009). *Diocese of Natal: Upgrade of Cathedral Centre Parking Area PID (Pty) Ltd*. Pietermaritzburg, South Africa.

References

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

- Paul, M. J., & Meyer, J. L. (2001). Streams in the Urban Landscape. *Annual Review of Ecology and Systematics*, 32(2001), 333–365. ISBN: 978-0-387-73411-8.
- Petrucci, G., Rioust, E., Deroubaix, J. F., & Tassin, B. (2013). Do stormwater source control policies deliver the right hydrologic outcomes? *Journal of Hydrology*, 485, 188–200. ISBN: 0022-1694.
- Pieterse, E. (2008). “Urbanisation Trends and Implications.” In *City Futures: Confronting the Crisis of Urban Development*. London, UK. ISBN: 1842775413.
- Pitt, R., Clark, S., Parmer, K., Field, R., & Connor, T. P. O. (1990). *Groundwater contamination from stormwater infiltration*. U.S.EPA, Cincinnati, Ohio.
- Pitt, R., Field, R., Lalor, M., & Brown, M. (1995). Urban stormwater toxic pollutants: assessment, sources, and treatability. *Water Environment Research*, 67(3), 260–275.
- Pratt, C. J. (1999). Use of permeable, reservoir pavement constructions for stormwater treatment and storage for re-use. *Water Science and Technology*, 39(5), 145–151.
- Pratt, C. J., Mantle, J. D. G., & Schofield, P. A. (1995). UK research into the performance of permeable pavement, reservoir structures in controlling stormwater discharge quantity and quality. *Water and Science*, 32(1), 63–69.
- Pratt, C. J., J.D.G. Mantle, & Schofield, P. A. (1989). Urban Stormwater Reduction and Quality Improvement Through the Use of Permeable Pavements. *Water Science & Technology*, 2(8–9), 769–778.
- Pratt, C. J., Newman, A. P., & Bond, P. C. (1999). Mineral Oil Bio-degradation within a Permeable Pavement: Long term observations. *Water Science and Technology*, 39(2), 103–109.
- Pratt, C. J., Newman, A. P., Platje, L., Puehmeier, T., Morgan, J., & Henderson, J. (2002a). Recent studies on oil degrading porous pavement structures. In *Standing Conference on Stormwater Source Control*. Coventry University. Coventry, UK.
- Pratt, C., Wilson, S., & Cooper, P. (2002b). *Source control using constructed pervious surfaces*. London, UK.
- Roads and Stormwater Department. (2009). *Management of Urban Stormwater Impacts Policy*. Cape Town, South Africa.
- Rossi, L., Krejci, V., Rauch, W., Kreikenbaum, S., Fankhauser, R., & Gujer, W. (2005). Stochastic modeling of total suspended solids (TSS) in urban areas during rain events. *Water Research*, 39(17), 4188–96. ISSN:0043-1354.
- Rushton, B. T. (2001). Low-Impact parking Lot Design Reduces Runoff and Pollutant Loads. *Journal of Water Resources Planning and Management*, 127(3), 172–179.
- SABC News. (2016). Eight provinces declared drought disaster areas. Retrieved June 14, 2016, from <http://www.sabc.co.za/news/a/1446f1804d145859b06af293fd523eaa/Eightundefinedprovincesundefineddeclaredundefineddroughtundefineddisasterundefinedareas-20161006>
- Salmore, A. K., Hollis, E. J., & McLellan, S. L. (2006). Delineation of a chemical and biological signature for stormwater pollution in an urban river. *Journal of Water and Health*, 4(2), 247–262. doi:10.2166/wh.2006.006.

References

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

- Sansalone, J., & Teng, Z. (2004). In Situ Partial Exfiltration of Rainfall Runoff. I: Quality and Quantity Attenuation. *Journal of Environmental Engineering*, 130(9), 990–1007. ISSN:0733-9372.
- Scholz, M., & Grabowiecki, P. (2007). Review of permeable pavement systems. *Building and Environment*, 42(11), 3830–3836. ISSN:03601323.
- Scholz, M., & Grabowiecki, P. (2009). Combined permeable pavement and ground source heat pump systems to treat urban runoff. *Journal of Chemical Technology & Biotechnology*, 84(3), 405–413. ISSN:02682575.
- Schwab, G. O., Fangmeier, D. D., Elliot., W. J., & Frevert, R. K. (1994). *Soil and Water Conservation Engineering* (4th ed.). John Wiley & Sons, Inc. New York. ISBN: 0-471-57490-2.
- Senge, P., Seville, D., Lovins, A., & Lotspeich, C. (2000). *Systems Thinking Primer for Natural Capitalism: The Four Basic Shifts, Society for Organisational Learning*.
- Shackel, B., Kaligis, J. O., Muktiarto, Y., & Pamudji. (1995). Infiltration and structural tests of permeable eco-paving. In *Highways and the Environment, Conference*. Sydney, New South Wales, Australia.
- Siriwardene, N., Deletic, A., & Fletcher, T. (2007). Clogging of stormwater gravel infiltration systems and filters: Insights from a laboratory study. *Water Research*, 41(7), 1433–40.
- Smithers, J. C., & Schulze, R. E. (2004). The estimation of design rainfalls for South Africa using a regional scale invariant approach. *Water SA*, 30(4), 435–444.
- Smolek, A. P., Hunt III, W. F., & Anderson, A. R. (2014). Permeable Pavement Retrofits : Water Quality and Hydrologic Performance in a Treatment Train with a Flow-Through Filter Over Sandy Soils and as a Standalone Over Impermeable Soils. In *13th International Conference on Urban Drainage* (pp. 1–8). 7-12 September, Sarawak, Malaysia.
- Suárez, J., & Puertas, J. (2005). Determination of Cod, Bod, and Suspended Solids Loads During Combined Sewer Overflow (CSO). *Ecological Engineering*, 24(3), 199–217.
- Taebi, A., & Droste, R. (2004). Pollution loads in urban runoff and sanitary wastewater. *Science of the Total Environment*, 327(1), 175–184.
- Taylor, A., & Fletcher, T. (2007). Estimating life cycle costs of stormwater treatment measures. *Australian Journal of Water Resources*, 11(1), 79–92.
- Thompson, D. B. (2006). *The Rational Method*. Civil Engineering Department, Texas Tech University. Texas, USA.
- Todes, A. (2009). New Directions in Spatial Planning? Linking Spatial Planning and Infrastructure Development. *Journal of Planning Education and Research*, 32(4), 400–414.
- Tota-Maharaj, K. (2010). *Geothermal Paving Systems for Urban Runoff Treatment and Renewable Energy Efficiency*. The University of Edinburgh. Retrieved from <http://hdl.handle.net/1842/4909>
- Tota-Maharaj, K., Grabowiecki, P., & Babatunde, A. (2012). The performance and effectiveness of geotextiles within permeable pavements for treating concentrated stormwater. In *16th Int. Water Technology Conference*. Turkey.
- Tota-Maharaj, K., Grabowiecki, P., Scholz, M., & Coupe, S. J. (2009). Hybrid urban runoff

References

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

- treatment system incorporating permeable pavement and geothermal heat pumps. In *National Telford Institute Workshop, Sustainable Water Management* (pp. 1–6). 2-3rd April, Edinburgh, Scotland.
- Tota-Maharaj, K., & Scholz, M. (2010). Efficiency of permeable pavement systems for the removal of urban runoff pollutants under varying environmental conditions. *Environmental Progress & Sustainable Energy*, 29(3), 358–369. ISSN:19447442.
- UNDESA. (2012). *World Urbanization Prospects: The 2011 Revision*. United Nations Department of Economic and Social Affairs. New York. Retrieved from <http://esa.un.org/unpd/wup/Documentation/highlights.htm>.
- UNDP. (2006). *Human Development Report (HDR): Beyond scarcity: power, poverty and the global water crisis*. United Nations Development Programme (UNDP). New York.
- UNEP. (2010). *Africa Water Atlas*. United Nations Environment Programme (UNEP). Nairobi; Kenya. ISBN: 978-92-807-3110-1.
- UN-Habitat. (2010). *State of the world's cities 2010/2011: bridging the urban divide*. (E. L. Moreno, O. Oyeyinka, & G. Mboup, Eds.). Nairobi, Kenya.
- United Nations. (2005). *World Urbanisation Prospects: The 2005 Revision*. Department of Economic and Social Affairs, United Nations Publication, United Nations.
- US EPA. (1983). *Results of the Nationwide Urban Runoff Program Volume I - Final Report. WH-554*. US Environmental Protection Agency (EPA). Washington, DC.
- US EPA. (1999). *Method 160.2: Total Suspended Solids*.
- Vaze, J., & Chiew, F. H. . (2002). Experimental study of pollutant accumulation on an urban road surface. *Urban Water*, 4(4), 379–389. ISSN:14620758.
- Vice, M. A. (2011). *Century City as a case study for Sustainable Drainage Systems (SuDS) in South Africa*. MSc. Eng. Dissertation, University of Cape Town.
- Voogt, T. (2011). Permeable Concrete Block Paving. In *Road Pavements Forum, 22nd Meeting, CSIR International Convention Centre, 8-9 November*. Pretoria, South Africa. Retrieved from http://www.csir.co.za/Built_environment/Transport_Infrastructure/22RPF/15_T_Voogt.pdf
- Walker, M. (2013). Pervious, Permeable and Porous Pavers – Are they really the same? *Stormwater Report, Water Environment Federation*. Retrieved June 18, 2016, from <http://stormwater.wef.org/2013/10/pervious-permeable-porous-pavers-really/>
- Walsh, C. J. (2000). Urban impacts on the ecology of receiving waters : a framework for assessment , conservation and restoration. *Hydrobiologia*, 431(2), 107–114.
- Water Research Commission. (1999a). *A Framework for Implementing Non-Point Source Management Under the National Water Act*. Department of Water Affairs and Forestry (DWAF), Pretoria, South Africa.
- Water Research Commission. (1999b). *Managing the Water Quality Effects of Settlements – 1st edition*. Department of Water Affairs and Forestry (DWAF), South Africa.
- Wilson, S., Shuttleworth, A., Newman, A. P., & Puehmeier, T. (2003). Performance of an oil interceptor incorporated into a pervious pavement. *Proceedings of the ICE - Engineering Sustainability*, 156(1), 51–58. ISSN:1478-4629.

References

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

- Wium, P. (2015). Personal communication. Cape Town, South Africa.
- Wong, T., & Brown, R. (2008). Transitioning to water sensitive cities: Enduring resilience through a new hydro-social contract. In *11th International Conference on Urban Drainage* (p. 10). September, Edinburgh, Scotland.
- Woods-Ballard, B., Kellagher, R., Martin, P., Jefferies, C., Bray, R., & Shaffer, P. (2007). *The SUDS Manual*. CIRIA 697. London, UK.
- World Bank. (2009). *Urbanization and Growth*. (M. Spence, P. C. Annez, & R. M. Buckley, Eds.). World Bank Publications. Washinton DC. ISBN: 0821375741.
- World Bank. (2010). *Report on the Status of disaster risk reduction in the sub-Saharan Africa region*. Washinton DC. Retrieved from . <http://www.gfdrr.org/gfdrr/sites/>
- World Bank. (2011). *Water Resources Management in an Urban Context in Africa*. Washington DC.
- Yong, C., Deletic, A., Fletcher, T. D., & Grace, M. R. (2008). The clogging behaviour and treatment efficiency of a range of porous pavements. In *11th Int. Conference on Urban Drainage* (pp. 1–12). Edinburgh, Scotland, UK.
- Yong, C. F., Deletic, A., Fletcher, T. D., & Grace, M. R. (2009). Porous pavements: Evaluation of clogging in two accelerated laboratory studies in Melbourne. In *6th Int. Water Sensitive Urban Design Conf. and Hydropolis* (pp. 388–395). Australian Water Association. Perth, Australia.

References

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

Appendix A: Urbanisation and emerging water Challenges

A1. Urbanisation

The urban landscape is transforming more rapidly in the 21st Century than at any stage in history. Many water challenges facing cities globally have been associated with high current rates of urban expansion, termed the ‘second wave of urbanisation’ (Pieterse, 2008; UN-Habitat, 2010; Jacobsen *et al.*, 2013). The ‘second wave of urbanisation’ (graphically depicted in Figure A-1) is defined as the radical global urban growth from 1950 to the present, in contrast to the ‘first wave of urbanisation’ that took place in Europe and North America between 1750 and 1950. The total global urban population (developed and developing city urbanites) surpassed the rural population for the first time in history by the end of 2007, as seen in Figure A-2. The relevance of this rapid urbanisation, according to Pieterse (2008), is that an effective societal transition towards sustainability is demanded to ensure human existence. Therefore, the issue of sustainable cities is high on the international agenda and water plays a critical role in this (Carden, 2013).

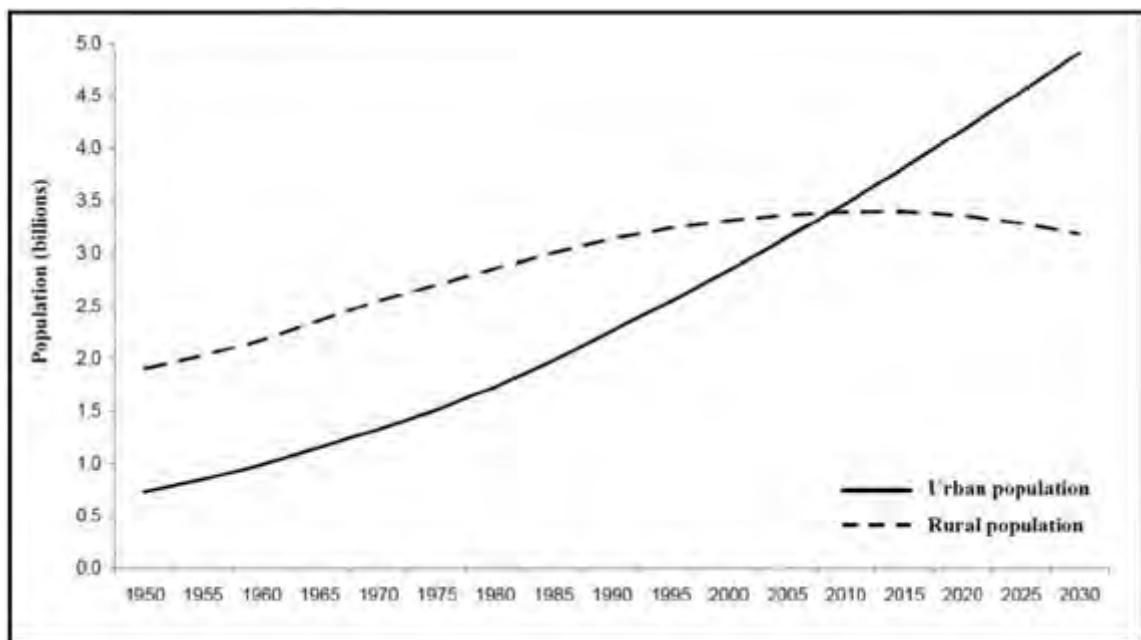


Figure A-1: Second wave of urbanisation
(After United Nations, 2005)

Sub-Saharan Africa is urbanizing particularly rapidly and has urban population growth rates that remain the highest in the world at 3.9% (UN-Habitat, 2010). The urban population of Sub-Saharan Africa (from this point onwards referred to as ‘Africa’), accounting for approximately 320 million Africans (37%) as shown in Figure A-2, is predicted to double in the next 20 years (UN-Habitat, 2010). Africa’s urban population, which lags the global urban expansion trends, is predicted to exceed the continent’s rural population by 2030. The implication is that city planners

Appendix A: Urbanisation and emerging water crisis

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

have a unique opportunity to prepare for predicted substantial increases in urban population in addition to merely retrofitting existing infrastructure.

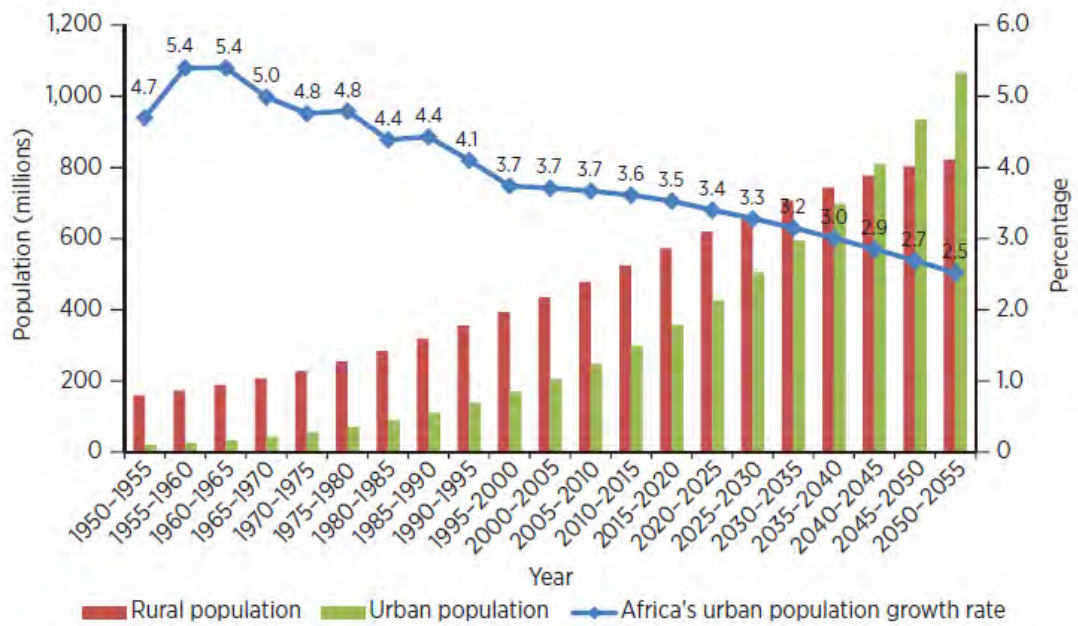


Figure A-2: Trend in urbanisation in Sub-Saharan Africa
(UNDESA, 2012)

The rapid urban growth has affected cities in the Southern Hemisphere considerably, shaping many of the environmental challenges faced (Martine *et al.*, 2008). Pieterse (2008) further asserted that urbanisation is characterised by ‘intense social and political struggles over water’ in the developing world in particular.

In South Africa similar urbanisation trends are emerging. The South African urban population has doubled since 1950 to comprise roughly 65% of the total population (Hedden & Cilliers, 2014). The sprawling of urban landscapes in South Africa, commonly acknowledged to have originated from modernist planning approaches and spatial planning framework policies (Mammon, 2005), has profoundly affected the urban water systems, in particular the drainage system (Lems, 2008; Todes, 2009).

A2. Emerging urban water challenges

The 2006 Human Development Report (UNDP, 2006) noted that the world may be approaching a ‘global water crisis’, not only in terms of water shortages, but also as a result of power struggles,

Appendix A: Urbanisation and emerging water crisis

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

inequality in distribution and poverty. South Africa experiences unique water challenges. Hedden & Cilliers (2014) summarized the current water situation in South Africa as follows:

'South Africa is over-exploiting its freshwater resources and water could be a large constraint on the implementation of the National Development Plan... The authors' research finds that the gap between demand and supply increases and that the solutions proposed by the Department of Water Affairs and Sanitation will not close the gap without additional, aggressive measures.'

A2.1 Water demand increases

The growing chasm between water supply and demand is not only found in South Africa (Figure A-3) but is a common phenomenon in Africa in general. In Africa, water demand continues to rise at a faster rate than population growth while water supplies shrink as a result of over competition between sectors and deteriorating water quality (Jacobsen *et al.*, 2013). Climate change further intensifies the uncertainty of the African water crisis.

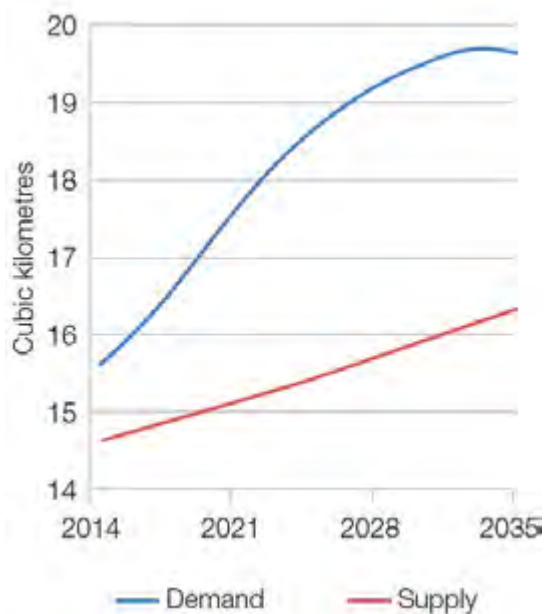


Figure A-3: South Africa's increasing gap between water demand and supply
(Hedden & Cilliers, 2014)

Africa is struggling to match its water demand increases. In fact, the water demand is increasing significantly faster than its population growth. World Bank (2009) predicted a 283% increase in Africa's water demand between 2005 and 2030, triple that of any other region, as shown in Figure A-4, and 92 billion m³ (20%) of this new demand will be generated by the domestic and municipal sectors. The agriculture sector is predicted to account for the majority of this demand increase at 320 m³ (72 %). Loayza *et al.*, (2012) proposes a number of factors that explain the

Appendix A: Urbanisation and emerging water crisis

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

urban water demand increases, the most notable being an increase in industrial and commercial demand.

South Africa depends almost solely on surface water for much of its urban, industrial, and agricultural requirements (DWAF, 2004). However, South Africa is a semi-arid country and the scarcity of fresh water is intensified by the increasing urbanisation rates, spatial distribution and highly variable nature of rainfall across the country. Mukheirbir (2005) noted that climate change may further exacerbate water shortages. Climate change, such as the El Nino and La Nina may increase the frequency of climate change but more generally, there is no scientific consensus on how/if climate change may affect the El Niño-Southern Oscillation (ENSO).

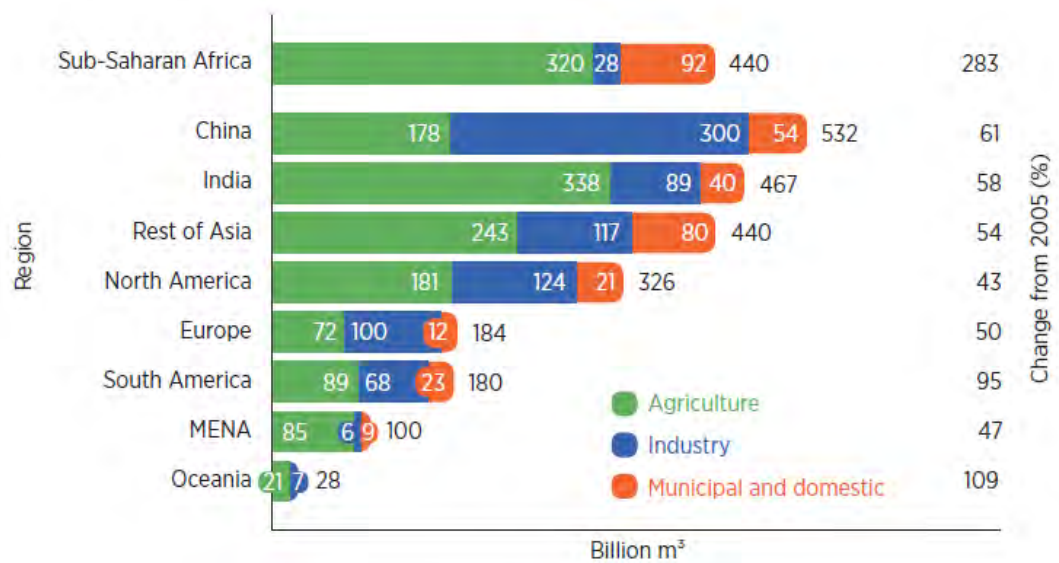


Figure A-4: Increase in Annual Water Demand (2005 to 2030)
(World Bank 2009)

Over-exploitation of surface water resources increases the water risk and exacerbates water shortages, particularly in times of drought (Hedden & Cilliers, 2014), such as the 2015-2016 drought which occurred in South Africa (SABC News, 2016). If there is not a reliable supply of water, whatever the source, then communities and industries that rely on rainfall will experience water shortages

A2.2 The quality and quantity of available water supply

Appendix A: Urbanisation and emerging water crisis

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

As the water demand continues to grow in Africa, water availability is shrinking and availability of water per capita in Africa (4 000 m³) is well below the worldwide average (6 000 m³) (UNEP, 2010).

Although Africa controls a large portion of the world's fresh water resources, its abstraction of this water is poorly managed in most catchments. Downstream users are affected by irrigation extraction in upstream basins, diminishing flows. The result is altered hydrographs, reducing perennial flows for cities in dry months and intensifying flooding during the wet season. In South Africa, the only way to sustain the rising demand may be to reallocate some of the water used for irrigating to other areas (Hedden & Cilliers, 2014). A viable alternative that could be used to supplement the country's over-stretched surface water resources is stormwater. Poorly managed solid waste and wastewater produced in cities places additional pressure on water quality in stormwater drainage systems in these areas which degrades a potential water resource.

A2.3 Climate variability and future considerations

Water is the primary medium through which the impact of climate change is going to be felt in South Africa (DWAF, 2013). Africa's water challenges are exacerbated by natural climate variability as African climates are typically unpredictable from year to year. However, African climate data suggests more variability is being experienced than in the past. The intensity and frequency of natural hazards currently faced in African cities are likely to increase into the future with climate change as shown in Figure A-5. Some climatic change models predict an increased duration or frequency of dry periods in parts of Southern Africa. For example, Hedden & Cilliers, (2014) developed a model which produced an integrated forecast of 1,9% average decline in rainfall for South Africa up to 2030 and 2,1% by 2035 (as compared to 1990 levels). The impact of climate change will also differ across the country – the arid interior (the Karoo region in particular) is expected to experience larger increases in temperature than the coastal regions (DWAF, 2013). Therefore, climate change for South Africa is likely to have a negative impact on the availability of both surface and groundwater, and diminish reliable yield over time (Hedden & Cilliers, 2014). Many African cities do not possess sufficient water storage facilities to accommodate climatic variation associated with these increased dry periods and therefore cannot reduce peak run-off flows and supplement low-season flows in changing hydrological systems (World Bank, 2011). Possibly the largest threat facing urban environments into the future is uncertainty (Jacobsen *et al.*, 2013).

A2.4 Alternative water sources

Some cities in South Africa are attempting to adapt to these challenges by seeking alternative water sources which could increase security and reliability of supply. For example, the CoCT, together with the Department of Water Affairs, is currently investigating potential future water

supplies for CoCT, including further surface water schemes, the desalination of sea water, water re-use and groundwater. Other sources such as stormwater have also been identified as potential options. While there have been some examples of successful stormwater harvesting schemes implemented in South Africa, such as in Atlantis, CoCT – where stormwater is used to recharge a ground water aquifer for harvesting purposes – more attention needs to be given it as a suitable resource. Stormwater harvesting may increasingly become a viable option to help combat South Africa’s water challenges.

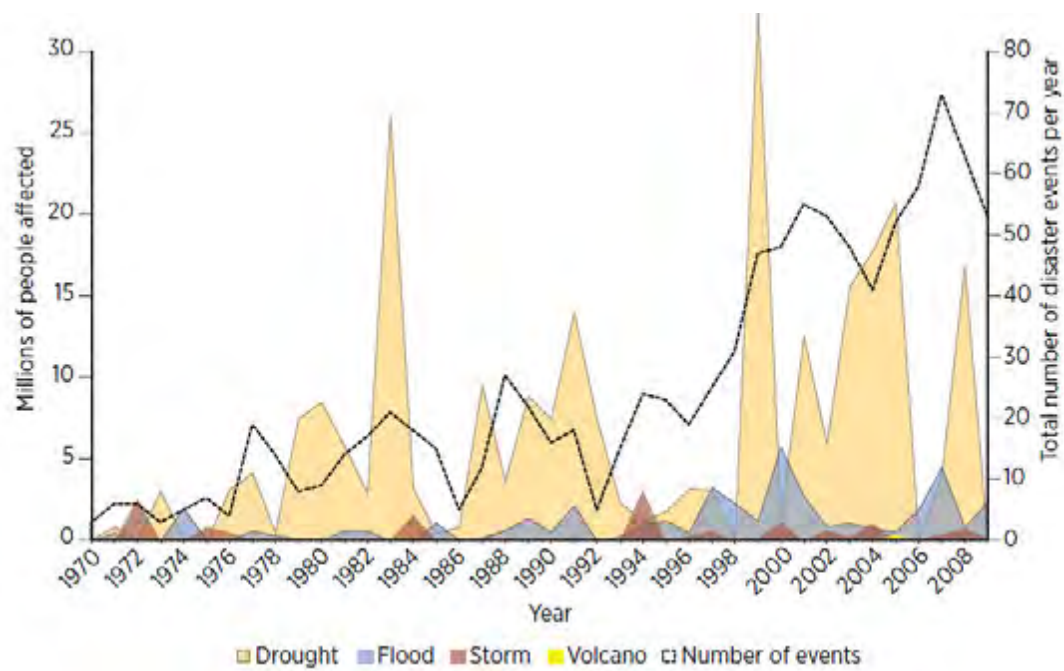


Figure A-5: Increased Frequency and Impact of Reported Disasters in Africa
(The World Bank, 2010)

Appendix A: Urbanisation and emerging water crisis

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

**Appendix B: Stormwater management: past, present
and looking forward**

B1. Urban stormwater

The definition of urban drainage includes both wastewater and stormwater disposal systems either as combined or separate sewers (Butler & Davies, 2004). The need to manage these fluids effectively led to the creation of various urban drainage designs. A separate system is designed to carry wastewater and stormwater in two different systems; wastewater is carried to the treatment plant and stormwater is disposed of to the receiving waters. However, in a combined sewer system, both wastewater and stormwater are carried in the same set of pipes. In South Africa, separate sewer systems are generally used. There is continued debate among researchers, drainage engineers and regulatory agencies on the best system of conveyance of stormwater in relation to quantity and treatment costs (Butler & Davies, 2004; Suárez & Puertas, 2005) .

B2. Stormwater management historically

Historically, the design of urban drainage systems have been driven at different time periods by different objectives and influenced by climate, topography, geology, engineering and construction capabilities, scientific knowledge, societal values and religious beliefs, among other factors (Burian & Edwards, 2002).

A short history of stormwater management according to Debo & Reese (2003). They suggest that stormwater management has developed through a number of paradigms to the present which may be summarised as follows:

- i) ***‘Run it in ditches’*** – everything of liquid form and any objects generally transported by those liquids were designed to run into ditches. This was apparent from the start of the ‘first wave’ of urbanisation where rural practices were prevalent in urban areas.
- ii) ***‘Run it in pipes’*** – Liquid waste from streets, flush toilets and kitchens was piped to the nearest watercourse (Lems, 2008). This piped infrastructure was increasingly used from the 1850s onward.
- iii) ***‘Run it in stormwater pipes’*** – this transition came about soon after World War II and was the first of many ‘urban’ based stormwater design paradigms (Thompson, 2006).
- iv) ***‘Keep it from stormwater pipes’*** – from the early 1970s, detention ponds were frequently used to attenuate high flood peaks. However, the successful implementation of detention ponds however requires complex and time-consuming input data and considerations. These requirements were rarely met (Novotny & Brown, 2007).
- v) ***‘Do not allow flooding’*** – The first mainframe hydraulics and hydrology models were geared for use on computers in the late 1970s and became commonly available in the 1980s. This software became increasingly easy to use and was relatively effective for large scale stormwater quantity master-planning with a focus on the prevention of flooding.

Appendix B: Stormwater management: past, present and looking forward

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

- vi) ***‘Do not pollute’*** – This shift was aided by improved stormwater, which placed more emphasis on pollution control software, that became available from the 1980’s (Water Research Commission, 1999a,b).
- vii) ***‘It is the ecology’*** – From the early 1990s new programmes aimed at improving river health became popular (Water Research Commission, 1999b), using macro-invertebrates and fish in the receiving waters as indicators of the quality of stormwater runoff.
- viii) ***‘Water is Watershed’*** – Recent organisational convergence in the USA has established the reorganisation of federal agencies to be watershed-focused causing local governments to be operating in terms of holistic watershed planning. However, a major impediment to this approach is that it is too complex for most citizens to understand and relate to.
- ix) ***‘Green and bear it’*** – There has been a growing acceptance of sustainable development amongst local municipalities and governments globally – including the control of stormwater runoff (Ellis *et al.*, 2006). Novotny & Brown (2007) comment, *‘A new paradigm is emerging from the successes and failures of efforts to control pollution that offers the promise of adequate amounts of clean water for all beneficial uses. Urban waterways are the historic core of our cities’ economies and have the potential to be rich sources of biological diversity, contributing to the quality, economy and health of urban life.’* Additionally, Novotny & Brown (2007) advocates that urban elements such as ‘energy’ and ‘environment’ are over taking other elements such as ‘economic growth’ and ‘mobility’ in regards to their importance to the global public.

Until recently South African stormwater authorities have been mainly concerned with the management of storm runoff and reducing flood risk. However, Armitage *et al.*, (2013b) remarks that a growing number of local authorities are adopting more advanced stormwater management approaches with CoCT arguably the most advanced with their *Management of Stormwater Impacts Policy* (CoCT, 2009).

B3. Conventional Separated Drainage Systems

Conventional separated (hereafter referred to ‘conventional’) stormwater systems have traditionally been used to manage urban drainage in South Africa. A conventional urban water system design keeps the water streams largely separate – unless wastewater and stormwater are combined – resulting in a separation of the urban water cycle (and stormwater surface drainage). This separation has caused stormwater, water supply and wastewater to be managed separately, creating a silo effect rather than an integrated system. This typically leads to an oversimplification of the water cycle and its underlying structure causing important inter-relationships to be neglected. Consequently, the complexities of urban stormwater systems and how they interact with the urban water cycle and their surrounding environment are often misunderstood.

Appendix B: Stormwater management: past, present and looking forward

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

Conventional separated drainage systems are primarily concerned with minimising inconvenience (during a minor storm event) and mitigating flood risk (during a major storm event), often using concrete pipes and channels to divert surface runoff into the nearest watercourse as quickly and efficiently as possible (Armitage *et al.*, 2013b). Water quality management and the associated aspects of amenity and biodiversity are often ignored (Woods-Ballard *et al.*, 2007; Armitage *et al.*, 2013b). It is now widely accepted that the conventional approach to urban water management is a major contributor to the degradation of urban waterways that facilitates wastage and does not reflect the values of the environmental society (Debo & Reese, 2003; Brown, 2005). Additionally, conventional systems have been shown to cause erosion, siltation and pollution of urban waterways (Armitage *et al.*, 2013b; Fletcher *et al.*, 2014a).

The impact of urbanisation and development on stormwater runoff flows is illustrated in Figure B-1 and Figure B-2. Pre-development runoff is minimal as precipitation is typically evaporated, transpired or infiltrated into the ground. Post-development runoff volumes and flows are however considerably increased, foreshortening the time to peak flows in the drainage system, due to the hardened surfaces and underground pipe networks that swiftly convey surface drainage to the nearest watercourse. Intensified flows and associated velocities in turn increase sediment transport capacity of the overland flow, increasing the polluting risk to receiving waters as surface runoff may collect pollution it intercepts along the way. The likelihood of downstream flooding and channel erosion is also greatly increased as these issues are transferred from source to receiving waters, which make rivers and other receiving waters more susceptible to the effects of high intensity short duration storms (CSIR, 2000). Furthermore, less infiltration of surface runoff into the soil strata decreases the recharge of the subsurface aquifers, lowering the base flow discharges to receiving waters. Rain that would usually form ponds and wetlands is diverted directly to nearby stormwater drains and rivers (Minton, 2002; Armitage *et al.* 2013). Waterways that were once a natural part of the urban landscape are sometimes hidden from the public and removed as a feature of the townscape, reducing the associated amenity and biodiversity of a riverine system. All these factors ultimately damage receiving waters, reduce biodiversity and amenity, and have a negative impact on the ability of the system to cope with future challenges (Ashley *et al.*, 2010).

B4. The need for alternative stormwater management systems

Conventional stormwater engineering used in South Africa has resulted in a numerous unintended adverse side effects. Although some South African local municipalities have made stormwater policy changes to reduce peak runoff through implemented mechanisms such as detention ponds, very little effort has been made to improve other associated aspects such as runoff quality, biodiversity and amenity (Armitage *et al.*, 2013b).

Appendix B: Stormwater management: past, present and looking forward

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

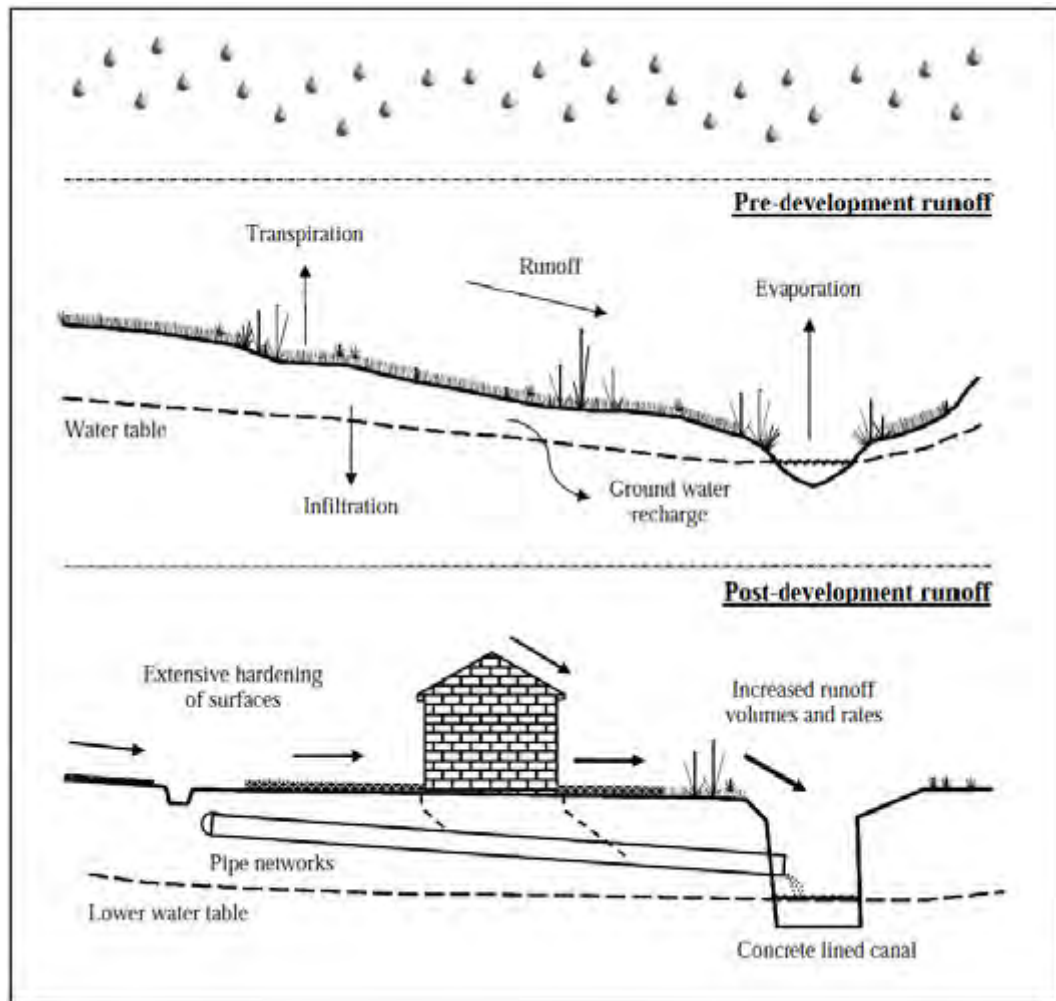


Figure B-1: Typical pre- and post-development scenarios with the conventional approach to stormwater management (Armitage *et al.*, 2013b)

There is growing international support for alternative stormwater management approaches in addressing drainage challenges. This includes a call for technology that mimics natural ways of draining urban areas thereby allowing the quality, amenity and biodiversity as well as quantity aspects of stormwater to be managed more sustainably. Ashley *et al.* (2010) and Armitage *et al.* (2014) stress that urban stormwater forms one part of the urban water cycle and therefore, should be treated as such. Stormwater management should be integrated with other urban services, such as water supply and groundwater systems, so that stormwater can be transformed into an asset rather than a waste product disposed of as quickly as possible. In so doing, stormwater will be viewed as a valuable resource to be protected and harvested, encouraging the stormwater management approach to emphasise stormwater pollution reduction and associated biodiversity and amenity, thereby lowering the risk of pollution to receiving waters from stormwater sources. Consequently, the urban environment may be enhanced, water security could be increased and an interdisciplinary environment to address stormwater management will be fostered.

Appendix B: Stormwater management: past, present and looking forward

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

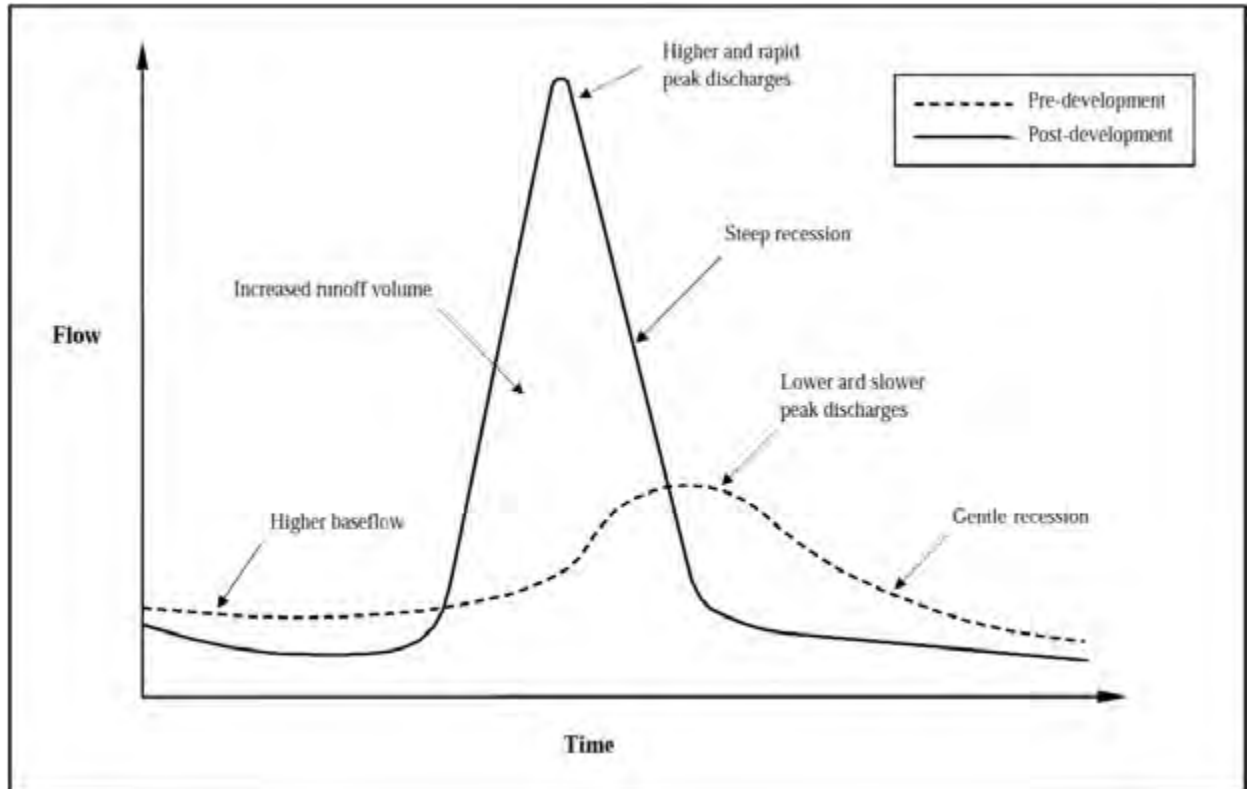


Figure B-2: Typical hydrograph associated with pre- and post-development with the conventional approach to stormwater management (Armitage *et al.*, 2013b)

The integration of urban water cycle constituents and the interactions that take place between them are illustrated in Figure B-3, modified from Fletcher & Deletić (2008). Figure B-3 also predicts where the impacts of human activity are most likely experienced. Effective management of urban water should be based on a scientific understanding of these impacts, in conjunction with planning strategies for the mitigation of these impacts (Marsalek *et al.*, 2008).

In some parts of the world the integration of urban design with the water cycle (and stormwater) is becoming known as Water Sensitive Urban Design (WSUD). This term, however, has not been universally accepted, for example, ‘Green Infrastructure’ has been adopted in the USA while WSUD remains virtually unknown. Fletcher *et al.* (2014a) cover the evolution of terminology such as LID, WSUD, SuDS, BMP and others, summarised as follows:

- LID (Low Impact Development) is a term commonly used in North America and New Zealand and in stormwater management refers to practices that aim to reproduce natural hydrological processes in development design. LID distinguishes itself from more conventional stormwater management practices such as retention ponds by not only reducing peak flows but aiming to recreate a ‘pre-development’ flow regime (Dietz, 2007). LID is impact-oriented, and also not a paradigm exclusive to water management (Fletcher *et al.*, 2014a).

Appendix B: Stormwater management: past, present and looking forward

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

- SuDS (Sustainable Drainage Systems) is a term that have arisen in the UK, and refers to technologies aimed at draining water in a more sustainable manner than conventional systems (Heal *et al.*, 2004; Jefferies *et al.*, 2008; Scholz & Grabowiecki, 2009; Tota-Maharaj *et al.*, 2009). The term ‘Sustainable Urban Drainage Systems’ (SUDS) is no longer the generally accepted name, the ‘Urban’ reference having been removed so as to accommodate rural stormwater management practices. The flow management principles of LID are implicit in SuDS – in fact the terms are effectively identical. Both involve systems designed for infiltration, attenuation and treatment (Tota-Maharaj *et al.*, 2009) and encourage a series of technologies to act together as a ‘treatment train’.
- BMP (Best Management Practice) is a term historically used in North America – but seems to be gradually falling out of fashion, and refers to such practices or interventions (technological and non-technological) that prevent or reduce pollution. BMP is a widespread term, and may refer to a particular technology or set of practices which prevent pollution, but also to a set of guidelines which may inform ‘best practice’ within a particular practice (e.g. design guidelines for permeable pavements). However, BMPs are not subject to a general performance standard, which may raise some contention about the use of the word ‘best’.
- Water Sensitive Urban Design (WSUD) is an overarching paradigm with aims and objectives related to the sustainable use and management of water resources in the urban context and refers specifically to the integration of urban design with the water cycle (and stormwater). WSUD as a paradigm is very similar to Integrated Urban Water Management (IUWM) – a term historically used in South Africa, however, there are differences: WSUD (the newer, Australian derived term) adds the Urban Design profession (architectural and town planning fields) to the IUWM (the older term) mix. In South Africa, ‘Water Sensitive Urban Design’ has been reduced to ‘Water Sensitive Design’ (WSD) to avoid alienating rural communities. Other equivalent terms to WSD are used internationally including, *inter alia*, Total Water Cycle Management (TWCM) and Integrated Water Resource Management (IWRM). The WSD and IUWM frameworks inform design and management principles, and provide guidelines and direction for other principles (such as SuDS) to operate holistically – SuDS is the stormwater component of the WSD framework.

Appendix B: Stormwater management: past, present and looking forward

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

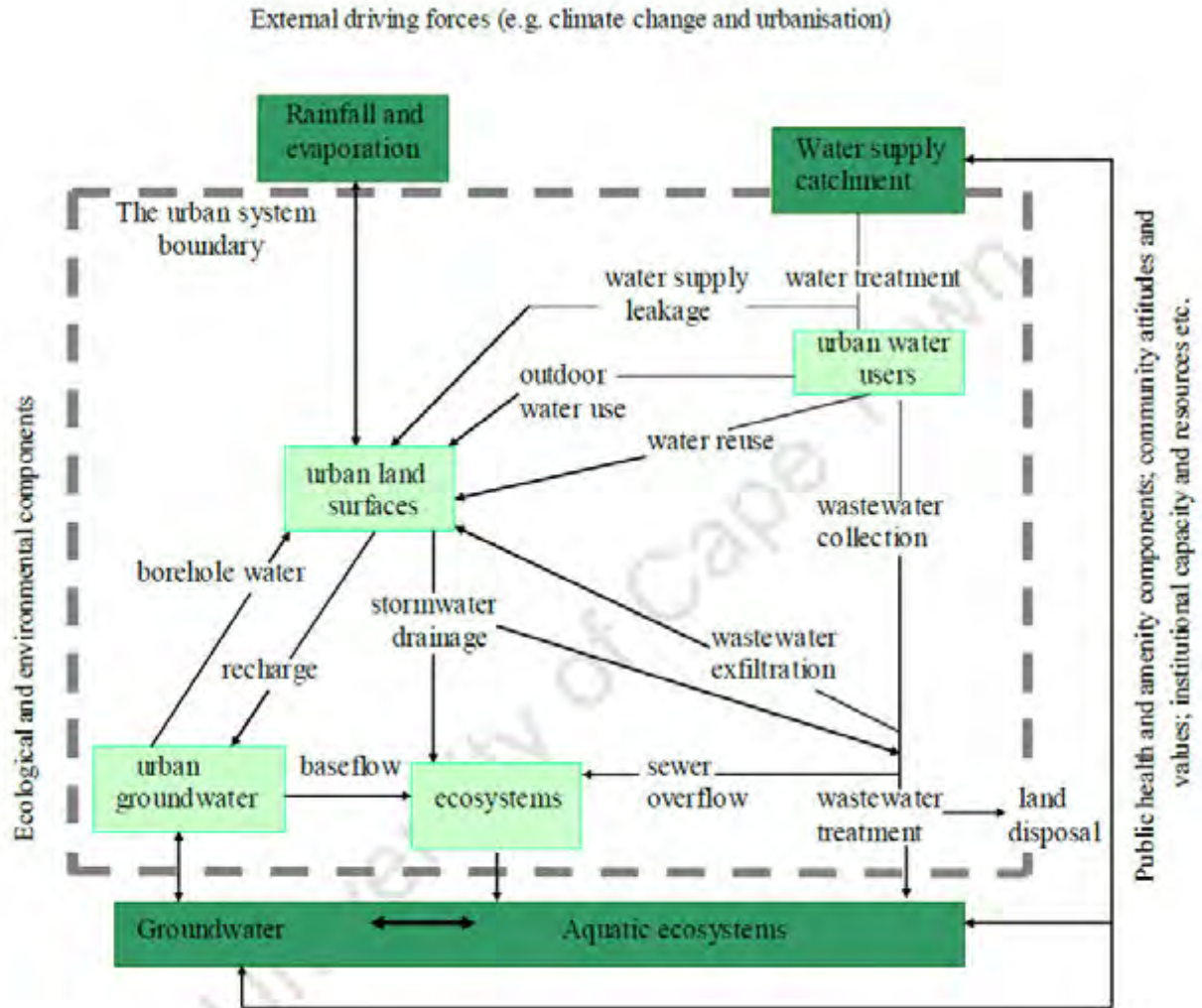


Figure B-3: Integration of urban water cycle components
(after Fletcher & Deletić 2008)

In South Africa, WSD seeks to develop efficient, flexible urban water systems by adopting a holistic view of all components of the urban water cycle (water supply, sanitation, and stormwater management) in the context of the wider watershed (Jacobsen *et al.*, 2013), whilst acknowledging that the system exists within an organisational framework as well as in the larger natural landscape (Mitchell, 2006). In other words, the social equity, economic efficiency and environmental sustainability drive what happens in cities rather than the natural inputs from the larger catchment, particularly in a developing nation context (Carden, 2013). Integrated solutions are required across scales (households, neighbourhoods, cities, catchments, trans-boundaries); domains (economic, social, environmental); and institutions (government, private sector and civil society).

South African urban communities facing the impacts of climate change – although some dispute this phenomenon – and population growth (there are exceptions in South Africa where

Appendix B: Stormwater management: past, present and looking forward

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

communities are shrinking) are looking to promote resilience, specifically with respect to future uncertainties with water supplies. The concept of WSD (a South African term) has therefore been taken a step further with the idea of ‘water sensitive’ settlements – developed from CRC concept for ‘Water Sensitive’ Cities in Australia by Monash University, which may be accorded three key characteristics: provision of ecosystem services for the built and natural environment; access to a diversity of water sources underpinned by a diversity of centralised and decentralised infrastructure; and socio-political capital for sustainability (Wong & Brown, 2008). The transformation of cities to include these sustainable urban water management concepts necessitates not only the integration of the components of IUWM / WSD and the various disciplines connected with the provision of water services, but also a paradigm shift in urban design so as to bring in aspects of ‘sensitivity to water’ and create landscapes that have ‘*intrinsic ecological functions related to the community and environment*’ (Wong & Brown, 2008). This shift in thinking is summarised in the transitions framework shown in Figure B-4 (Brown *et al.*, 2008).

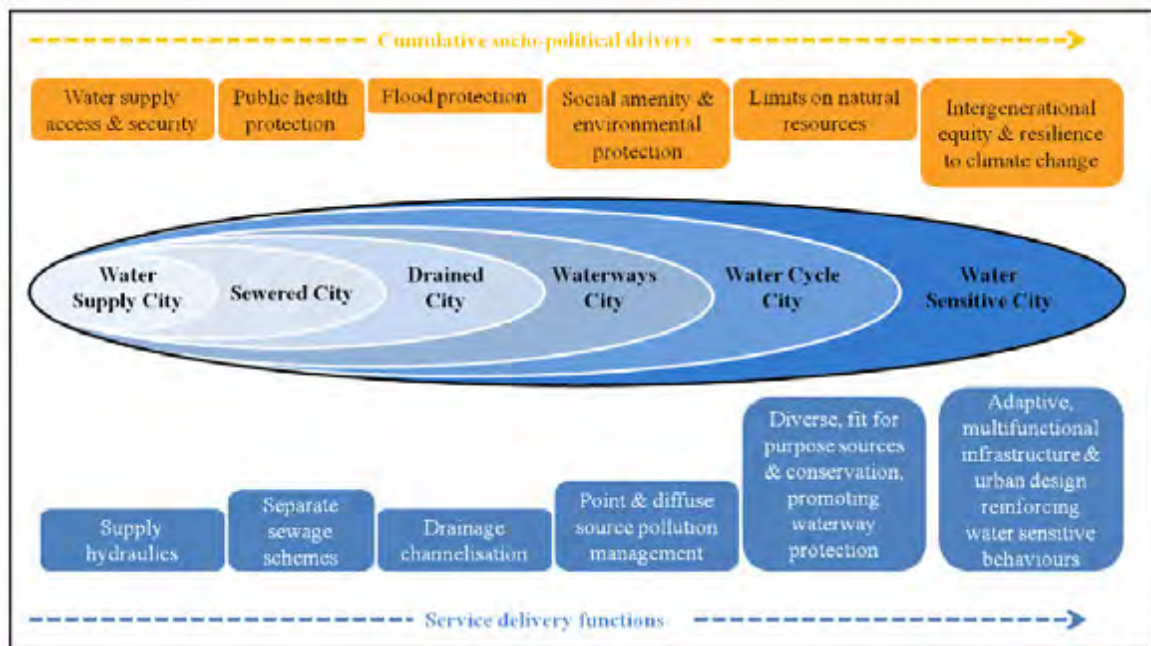


Figure B-4: Urban water management transition framework
(Brown *et al.*, 2008)

B5. ‘Sustainability’ and ‘Sustainable development’ defined

To better understand how SuDS improves sustainability within the stormwater sector, the definitions of sustainability and sustainable development have been provided. The term sustainability is derived from the Latin *sustenerere* (*sus* – up, *tenere* – hold), which basically means ‘the capacity to endure’. In ecological terms, it relates to how biological systems remain diverse

Appendix B: Stormwater management: past, present and looking forward

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

and productive; in social or human terms, it is the potential for long-term maintenance of well-being, and depends on the responsible use of natural resources (Carden, 2013). Goodland & Daly (2008) defined ‘sustainability’ as the maintenance of social, economic, and environmental (natural) capital by individually monitoring source and sink capacities of each capital and ensuring that these capacities are not exceeded.

A widely accepted definition for sustainable development is provided by the Brundtland Commission Report (1987) as ‘*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*’. Goodland and Daly (1996) developed this definition further to incorporate the terms ‘growth’, ‘regenerative’ and ‘absorptive’ capacities to make it more precise, stating that sustainable development is ‘development without growth in throughput of matter and energy beyond regenerative and absorptive capacities’.

Hjorth & Bagheri (2006) and Senge *et al.* (2000) stated that a true understanding of the sustainability and sustainable development requires an understanding of the underlying structure, sources and solutions to complex problems. This necessitates a change from linear, mechanistic thinking to non-linear organic thinking, often referred to as ‘systems thinking’. O’Regan & Moles (1997) further introduced system thinking into the equation of sustainable development and proposed that many conventional practices that enforce misguided theories and models in environmental management occur because the complexities of environmental systems are underestimated.

B6. Overview of Sustainable Drainage Systems (SuDS)

Armitage *et al.* (2013) defines SuDS as follows:

‘SuDS attempt to manage surface water drainage systems holistically in line with the ideals of sustainable development by mimicking the natural hydrological cycle, often through a number of sequential interventions in the form of a “treatment train”.’

SuDS promote the natural drainage processes to effectively manage stormwater runoff quantity (flow and volume); water quality; and the associated amenity and biodiversity of the urban drainage system (Figure B-5) (Armitage *et al.*, 2013a). SuDS are technological solutions designed for more sustainable drainage solutions which can be arranged to form a ‘treatment train’ as illustrated in Figure B-6. While these solutions have a myriad of forms such as bio-swales, constructed wetlands, rain gardens and permeable pavements (Dietz, 2007), they can be broadly categorised into four scales of intervention (Heal *et al.*, 2004; Armitage *et al.*, 2013b):

- i) **Good Housekeeping** refers to practices that minimize the release of pollutants to the environment where they are available for transport by stormwater.
- ii) **Source Control** refers to methods which deal with stormwater as close to the source as possible. These can be further subcategorized into infiltration type systems (such as

Appendix B: Stormwater management: past, present and looking forward

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

permeable pavements and soakaways) and harvesting type systems which divert stormwater for eventual reuse (such as rain harvesting).

- iii) **Local Controls** are methods which manage stormwater at a small catchment scale level. These may take the form of bioretention areas, swales or filter strips.
- iv) **Regional Controls** are larger controls which manage the runoff from an entire catchment, such as constructed wetlands or retention ponds.

Permeable pavements, the focus of this study, fall within the source control category and therefore, the majority of the discussion in this section on SuDS will focus on source control. Source and local control strategies aim to address stormwater management at the source and have been increasingly used to reduce hydrological or water quality disturbances to urban waterways and to harvest stormwater for appropriate use (Hamel *et al.*, 2013). This decentralised form of SuDS implementation has numerous benefits for both water quality and flow management.

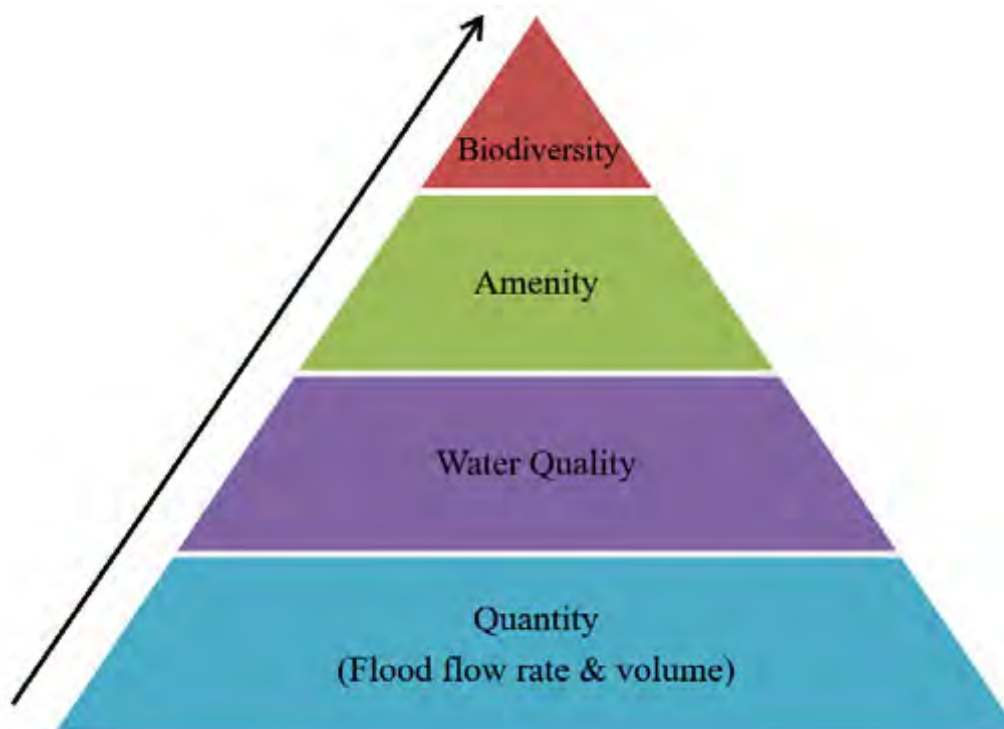


Figure B-5: The Stormwater design hierarchy
(Armitage *et al.*, 2013b)

The categorization of SuDS into the respective scale of treatment highlights the intention of these measures to be utilised in conjunction with each other – as it is common to utilise more than one option (unit input) per site and arranged options sequentially – to create a ‘treatment train’ from source to sink. Table B-1 explains the different SuDS intervention devices in a treatment train.

Appendix B: Stormwater management: past, present and looking forward

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

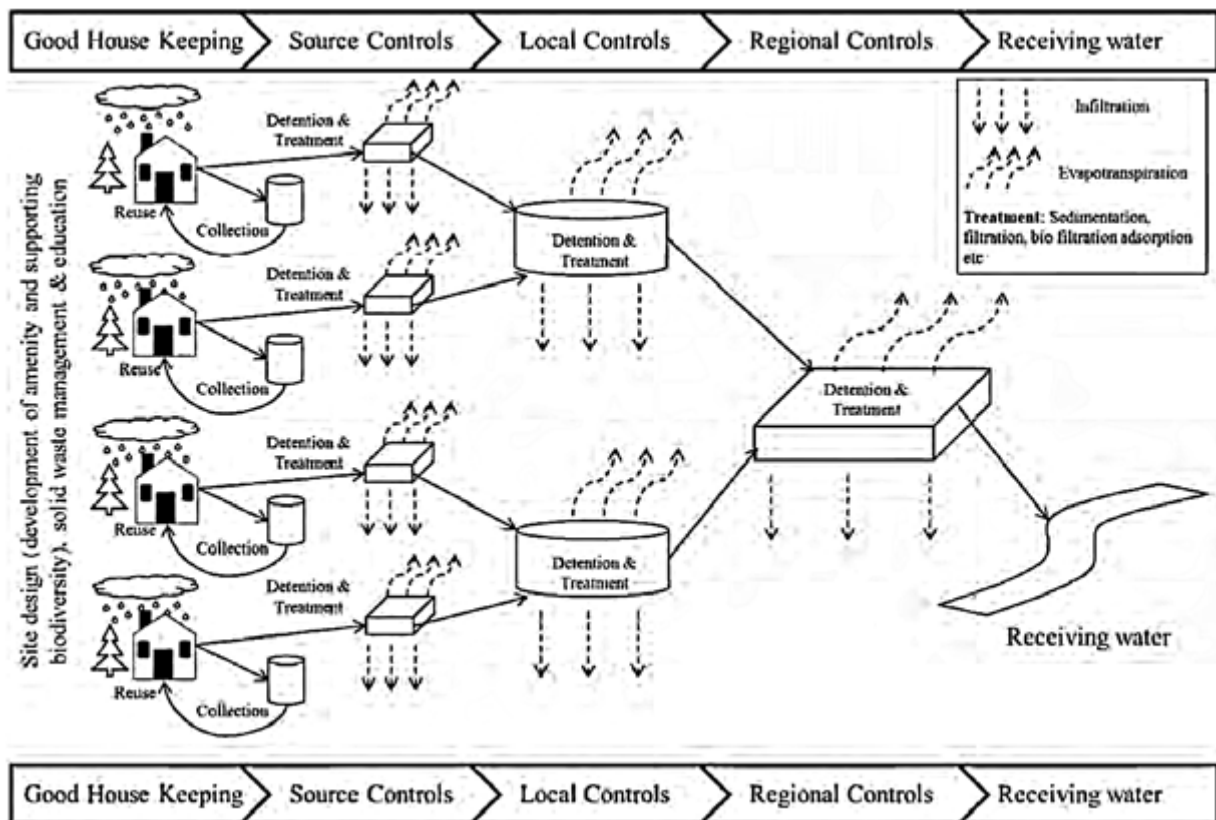


Figure B-6: The SuDS treatment-train
(Fisher-Jeffes, 2011)

Like all SuDS, source controls try to mimic natural hydrology patterns. Infiltration-oriented systems do so by infiltrating and disposing of water or infiltrating to groundwater. These systems are likely to be the preferred candidates for achieving a ‘natural’ flow regime, as they contribute to maintaining natural low flows and base flows as well as achieving peak flow reduction (Hamel *et al.*, 2013; Fletcher *et al.*, 2014b; Hamel & Fletcher, 2014). However, in some instances infiltration systems such as permeable pavements are used for storage, with the intention to harvest stormwater, where infiltration i.e. to groundwater must be prevented. Preventing infiltration in such cases could be a drawback if maintaining high water table levels (e.g. in San Francisco) is an objective. Additionally, source control measures with the intention to harvest stormwater can have a significant direct benefit in reducing on-site water demand, which can upscale to regional economic benefits (Coombes *et al.*, 2002). However, careful design and implementation is required if source controls should have positive catchment-wide impacts. A study from France (Petrucci *et al.*, 2013) has shown that source control techniques, when flow timing is not considered, can actually increase runoff peaks at a catchment scale due to the superposition of peak flows. Furthermore, they can significantly disturb downstream low-flows if the entire hydrology is not taken into consideration.

Appendix B: Stormwater management: past, present and looking forward

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

B7. A brief legal context for stormwater management in South Africa

A number of policies and guidelines bear influence on the management of stormwater and the environment in South Africa. In the engineering and built environment, these legal requirements and guidelines have played an important role in shaping the stormwater management approach (Buys & Aldous, 2009). The national legislation concerning urban drainage heavily favours conventional drainage practices. Additionally, this concept is also extensively supported by building codes and guidelines.

Internationally, there is extensive experience in the implementation of SuDS options and their performance, however, in South Africa SuDS approaches have not been explored to the same extent. Despite the benefits of its application, there have been few practical implementations of SuDS interventions in South Africa. Although useful, international case studies cannot always be applied to the South African context without modification.

In 2009, however, the CoCT issued policies in support of the notion of WSD which recognised the potential of SuDS in the urban landscape. The CoCT's Management of Urban Stormwater Impacts Policy (Roads and Stormwater Department, 2009) is arguably the most progressive stormwater management policy in the country, being the only accessible policy that fully supports principles of WSD and SuDS practices. Furthermore, it was the first policy to place value on stormwater in the context of the national water crisis and 'climate change'. This is a positive step in the right direction and it is hoped that other provinces in the country will follow suit and begin adopting water management policies that are in line with sustainable development principals, such as WSD and SuDS.

B8. Positive impacts of SuDS

The implementation of SuDS in cities, if carried out carefully, should positively impact all four objectives: stormwater runoff quantity (flow and volume); quality; associated amenity and biodiversity. By actively incorporating the SuDS philosophy, these unsustainable aspects of conventional stormwater management can be corrected.

Ashley *et al.* (2010) and Armitage *et al.* (2013) mention a number of additional SuDS 'greening' sustainability benefits over conventional drainage. These include amenity, biodiversity, carbon capture and reduced heat island effects as well as contributing towards addressing the challenges of climate change. An important practical benefit which further promotes use of SuDS is its ability to be installed incrementally with innate adaptability and flexibility to combat climate change knowledge advances (Armitage *et al.*, 2013b). Conventional drainage systems have worked well in the past to preserve public safety but do not generally provide the other benefits now expected.

Table B-1: SuDS options comprising the ‘treatment train’
(Armitage *et al.*, 2013b)

	Example	Description
Source Control	Rainwater Harvesting	Temporary storage and reuse of rooftop and/or surface runoff (Melbourne Water Corporation, 1999).
	Green Roofs	Vegetated roofs (Wanielista <i>et al.</i> , 2008; Stahre, 2006).
	Permeable Pavements	Load-bearing, durable and pervious surfaces such as concrete block pavers (CBPs) laid on top of granular or stone base that can treat and temporarily store stormwater runoff.
	Soakaways	Excavated pits that are packed with coarse aggregate and other porous media and are used to detain and infiltrate stormwater runoff from a single source.
	Filter strips	Vegetated areas of land that are used to manage shallow overland stormwater runoff through filtration (Debo & Reese, 2003).
Local Control	Swales	Shallow grass-lined channels with flat and sloped sides that are used to convey stormwater from one place to another. They typically remain dry between rainfall events (Mays, 2001; Parkinson & Mark, 2005).
	Infiltration	Trenches are excavated trenches which are lined with a geotextile and backfilled with rock or other relatively large granular material (Hobart City Council, 2006). They are typically designed to receive stormwater runoff from residential properties.
	Bio-retention areas	Landscaped depressions used to manage stormwater runoff through several natural processes such as filtration, adsorption, biological uptake and sedimentation (Debo & Reese, 2003).
	Sand filters	Underground sedimentation chamber connected to a filtration chamber in which stormwater runoff is temporarily stored before being filtered through a sand filter (Woods-Ballard <i>et al.</i> , 2007).
Regional Controls	Detention ponds	Relatively large depressions that temporarily store stormwater runoff in order to reduce the downstream flood peak (Woods-Ballard <i>et al.</i> , 2007).
	Retention ponds	Also known as ‘retention basins’ – are formed by excavating below the natural ground water level and/or lining the base to retain stormwater runoff (Debo & Reese, 2003; Mays 2001).
	Constructed wetlands	Attempt to mimic the characteristics of natural wetlands through the use of marshy areas and aquatic-resilient plants (NCDWQ, 2007; Woods-Ballard <i>et al.</i> , 2007).

Appendix B: Stormwater management: past, present and looking forward

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

Appendix C: Rainfall data

Table C-1: Monthly rainfall data for the Cape Town International Airport
(1stWeather.com, 2002)

Month	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	AVE
Jan	14.0	5.8	1.4	4.7	14.6	9.9	2.2	9.6	9.7	1.2	12.6
Feb	31.2	10.9	29.5	38.0	0.7	1.0	34.7	2.0	0.3	0.9	14.9
Mar	0.7	10.6	13.0	3.8	3.6	5.8	26.5	1.9	14.1	0.4	18.1
Apr	142.1	25.4	85.8	178.9	35.0	17.9	33.0	40.5	35.4	57.2	43.8
May	69.2	89.9	51.2	136.9	39.5	68.0	55.3	74.4	120.2	34.8	68.5
Jun	110.1	151.4	145.1	78.5	229.4	109.8	131.4	105.6	52.8	83.3	100.8
Jul	124.3	167.6	91.7	142.5	68.9	96.7	85.0	14.9	99.7	40.7	82.2
Aug	43.8	31.1	43.3	63.2	30.9	75.1	106.5	81.7	46.0	105.2	71.9
Sep	27.5	72.5	62.3	9.1	39.5	19.7	100.4	8.3	30.9	98.2	42.0
Oct	3.5	48.3	77.1	3.8	14.1	88.9	69.2	24.6	15.0	1.4	32.8
Nov	18.2	11.2	10.7	2.3	7.9	23.1	34.0	47.8	47.1	15.6	17.0
Dec	18.8	7.5	1.8	29.4	3.4	34.5	28.3	11.5	45.4	2.6	17.3
Total	603.4	632.2	612.9	691.1	487.5	550.4	706.5	422.8	516.6	441.5	531.4
Max	142.1	167.6	145.1	178.9	229.4	109.8	131.4	105.6	120.2	105.2	
Min	0.7	5.8	1.4	2.3	0.7	1.0	2.2	1.9	0.3	0.4	
% Ave	113	118	115	130	91	103	132	79	97	83	

Appendix C: Rainfall data

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

Table C-2: Daily rainfall data in 2002 (mm) recorded at Cape Town International Airport

2002	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0	0	0	0	0	0	0	4.2	0	0	0	0
2	0	0	0	0.6	1.6	0	0	3.6	0	15.5	0	0
3	0	0	0	0.8	0	0	0	0.2	0	0	11.4	0
4	0	0	0	2.8	4.4	0	0	0	0	0.3	0.2	0
5	5.2	10	0	0	11.8	10.8	0	0.2	0	0.6	0	0
6	13.7	1.1	0	0	1.6	0	0	0	0	0	0	0
7	0	0	0	0	0	14.3	2	0	0	0	0	0
8	0	0	0	1.4	0	0	13.8	0	5.4	0	3	0.2
9	0	0	0	4.6	0	0.2	0	0	3.8	0	0	0
10	7.6	0	0	0	0	0	0	0	0	0	0	0
11	19.8	0.2	0	0	0	0	0	7.5	0	0.2	0	0
12	1	0	0	0	0	1	0	5.6	0	0	0	0
13	0	0	2.6	0	0.2	4.9	0.2	2	0	0	0	0
14	0	2.8	0.2	0	0	0	12.6	0	0	0	0	0
15	0	0	0	0	0	6.2	7.5	0	0	0	0	0
16	12	0	0	0	1.4	0	0.5	0	0	0	0.4	9.4
17	1.6	0	0	0	0	2	0	0	0	11.7	0	0
18	0	0	0	0	0	3	0	0	0	1	0	0
19	0	0	0	0	0	0	0	0	0	0	6.4	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0.7	0	0	0	0	0	0	0	0	4.8
22	0	0	0.4	1.8	17.4	1	0.2	4.5	0	3.2	0.6	0.6
23	0	0	0	0.8	1.4	0.4	26	1	0	0	0	0
24	0	0	0.2	2.4	2.8	0	2	0	0.8	0	0	0
25	0	0	0	0	7.6	0	0	0	0.2	0	0	0
26	0	0	3	0	0	11	8.6	0	0	0	0	0
27	0	0.4	1.8	0	0	8.8	1.8	0	1.4	0	1.6	0
28	0	0.4	0.4	8.8	7.6	7.9	18.4	0	2	0	0	0
29	0	0	0	4	2.4	4.9	3.6	34	0	0	0	0
30	0	0	0	0	0	0	1	2.9	12.5	0	0	0
31	0	0	0	0	11.7	0	0	0	0	0	0	0
TOT	60.9	14.9	9.3	28	71.9	76.4	98.2	65.7	26.1	32.5	23.6	15
AVE	12.6	14.9	18.1	43.8	68.5	100.8	82.2	71.9	42	32.8	17	17.3
% AVE	483	100	51	63	104	75	119	91	62	99	138	86
Rain days	15	9	9	14	14	16	19	14	11	13	10	5

Appendix C: Rainfall data

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

Table C-3: Rainfall application and corresponding sample collection

Event	Rainfall (mm)	Volume (l)	Sample No.			
			Structure A	Structure B	Structure C	Structure D
1	1.6	2.1				
2	4.4	5.8				
3	11.8	15.6	1 and 2	1		
4	1.6	2.1		2	1	
5	0.2	0.3				
6	1.4	1.8	3		2	1
7	17.4	23.0	4	3	3 and 4	2 and 3
8	1.4	1.8	5	4		
9	2.8	3.7				
10	7.6	10.0		5	5	4
11	7.6	10.0	6	6	6	5 and 6
12	2.4	3.2				
13	11.7	15.4	7	7	7	7
14	10.8	14.3	8	8	8	8
15	14.3	18.9	9	9	9	9
16	0.2	0.3				
17	1	1.3				
18	4.9	6.5	10	10	10	10
19	6.2	8.2				
20	2	2.6				
21	3	4.0				
22	1	1.3				
23	0.4	0.5				
24	11	14.5	11	11	11	11
25	8.8	11.6				
26	7.9	10.4	12	12	12	12
27	4.9	6.5				
28	2	2.6				
29	13.8	18.2				
30	0.2	0.3				
31	12.6	16.6				
32	7.5	9.9				
33	0.5	0.7				
34	0.2	0.3				
35	26	34.3				
36	2	2.6				
37	8.6	11.4				

Appendix C: Rainfall data

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

Table C-3: Rainfall application and corresponding sample collection (cont.)

Event	Rainfall (mm)	Volume (l)	Sample No.			
			Structure A	Structure B	Structure C	Structure D
38	1.8	2.4				
39	18.4	24.3				
40	3.6	4.8				
41	1	1.3				
42	4.2	5.5				
43	3.6	4.8				
44	0.2	0.3				
45	0.2	0.3				
46	7.5	9.9				
47	5.6	7.4				
48	2	2.6				
49	4.5	5.9				
50	1	1.3				
51	34	44.9				
52	2.9	3.8				
Total	312.2	412.1				

Appendix C: Rainfall data

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

Appendix D: New Engineering Building parking area

D1. New Engineering Building (NEB) parking area

This section outlines the design and construction method of a permeable pavement field test site at the University of Cape Town's (UCT) New Engineering Building (NEB) for long-term quality and quantity monitoring. The design of UCT's NEB permeable parking area, which still acts a working parking area, was adapted slightly during construction to allow samples of the drainage to be taken for further analysis. A description of the NEB parking area project was included in the appendices, even though I was not directly responsible for the results, because it was informative from the perspective of the laboratory project as a whole and provided the rationale for why unwashed aggregate in the investigation was used.

The construction of the NEB PPS provided a convenient opportunity to set up a long-term monitoring facility for an in-situ pavement. This test site enabled monitoring of stormwater quality and quantity after implementation through differently designed sections of permeable pavement, as well as from a section that does not have permeable pavers. The test site was also intended to be used to test infiltration rates through a newly constructed PPS, to monitor its performance over time, as well as the impact of maintenance activities. The investigation process of the NEB PPS site was also used to inform and refine tune the assessment methodology used in the laboratory investigation. This was intended to better equip future PPS studies and to allow for representative data to be collected. It also provided an opportunity to monitor the construction activity – this has been documented in some detail in this section. After construction of the NEB parking area an independent MSc. student, Rene Schieritz, monitored the quality and quantity of effluent exiting from this site.

D2. NEB parking area site description

The PPS was designed with three separate sections – partly because of the slope. Leaving the area un-compartmentalised would have severely limited the storage capacity of the parking area. This provided a convenient opportunity to modify the sections to form a test site suitable for long-term experimental monitoring of the PPS (Figure D-1). The typical pavement layerworks is shown in Figure D-2 and the underdrain design for the PPS is shown in Figure D-3 – courtesy of Sutherland Engineers Consultants. The first section of pavement receives considerable volumes of runoff from the roof surface of the NEB building. This runoff discharges directly into the base-course layer of the PPS, and a catchpit was specially constructed to sample some of the 'natural' runoff from this area in the absence of infiltration.

Appendix D: New Engineering Building parking area

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

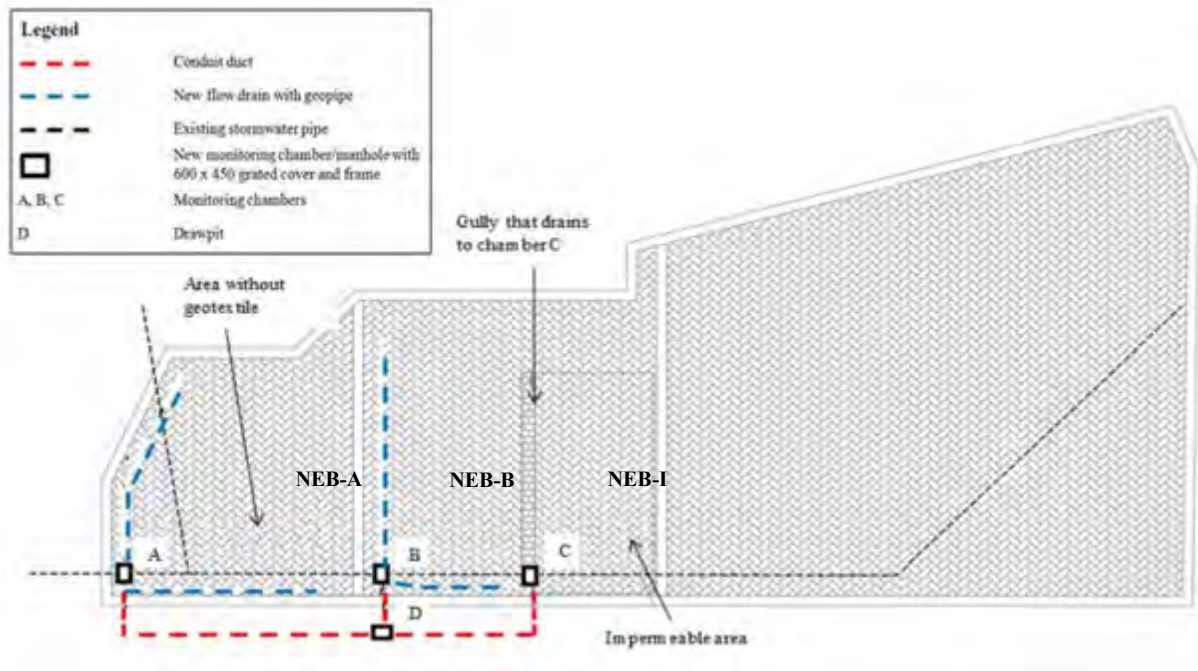


Figure D-1: Monitoring schematic of the NEB PPS

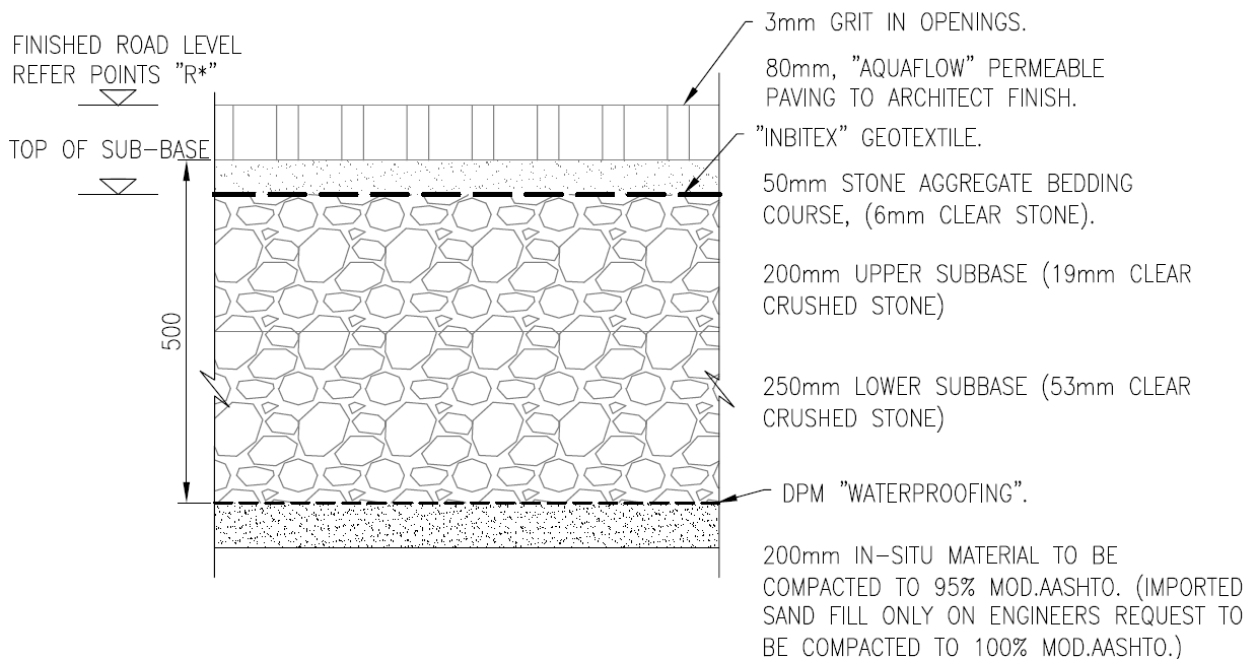


Figure D-2: NEB permeable pavement layerworks (scale 1:10)

NEB-I (shown in Figure D-1: Monitoring schematic of the NEB PPS) is an area of pavement that was sealed off to provide surface runoff for comparison with the drainage from the permeable pavement areas. NEB-B is a normal PPS installation with a geotextile between the bedding

Appendix D: New Engineering Building parking area

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

medium and the sub-grade. NEB-A uses the same design, but lacks the geotextile. All of the sections are separated from one another via ground beams which prevent flow from spilling from one compartment to the next. Monitoring chambers A, B, C and D were placed for the sampling equipment installation, with each chamber having a conduit connection to the central monitoring chamber (D), which was initially intended to house all samplers and any other centralised monitoring system.

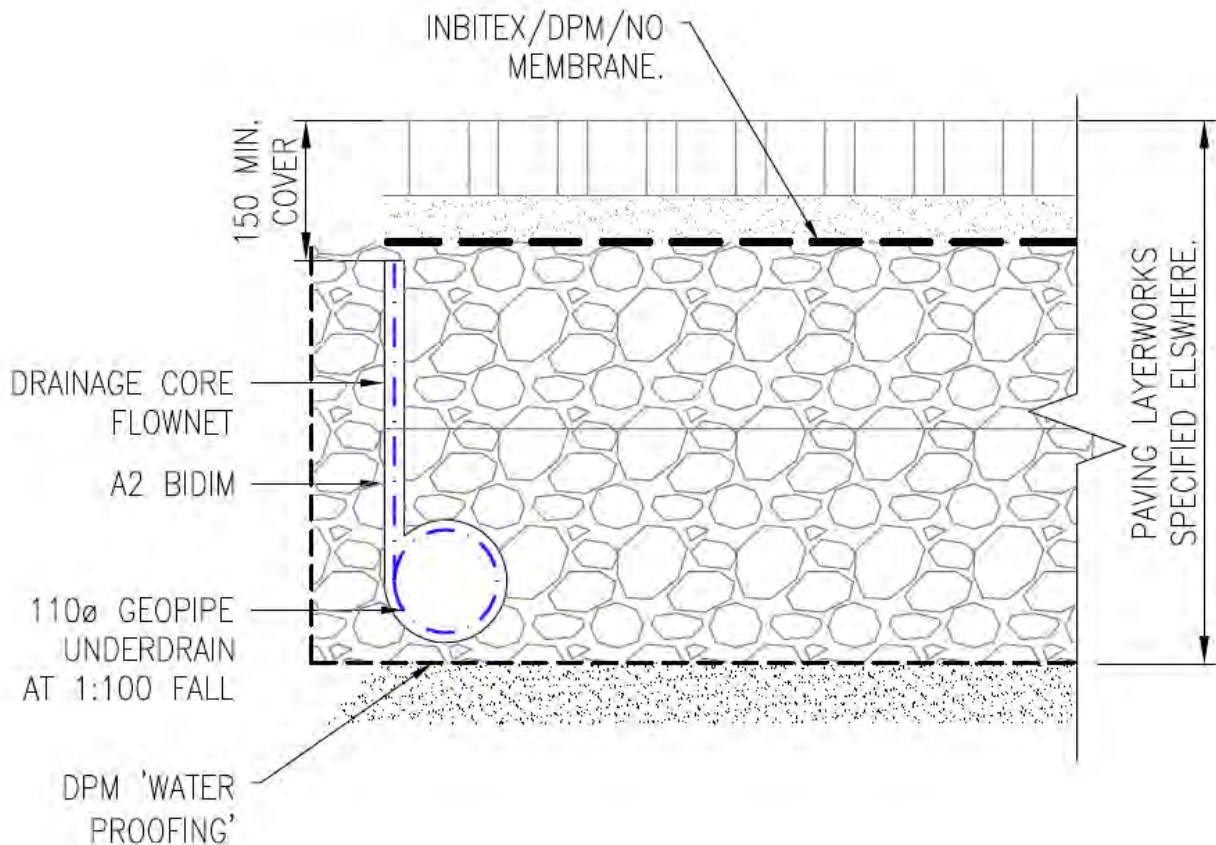


Figure D-3: NEB permeable pavement underdrain detail (scale 1:10)

While the monitoring chambers were intended to be accessible during working hours by being placed between parking lots, this was problematic, particularly for chambers A and C which, were mostly inaccessible owing to cars being parked there during the day. The problem was further aggravated by the fact that the instrumentation chamber (D) was too small to accommodate more than one automatic sampler.

This, coupled with the relative ease and cost-effectiveness of monitoring using a sequential bottle rig for sampling, led to the addition of another parking lot on UCT Upper Campus, being considered for the study. This is an impervious asphalt parking lot at UCT which receives little or no run-on from other land use sites and has sloped drainage which makes sampling without a

Appendix D: New Engineering Building parking area

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

pump possible. Due to the fact that it is a different surface i.e. asphalt, means that is it not representative of the surface runoff from a brick surface such as the NEB PPS.

D3. NEB monitoring chamber design and placement

The NEB parking area test site was initially designed, completely independently from this investigation, to – apart from operating as a car park – attenuate peak flows as well as improve the quality of stormwater runoff coming from the NEB roof area. The pavement design also incorporated an additional 100mm of 19mm crushed stone when compared with the standardised designs (Formpave & Hanson, 2010).

Once the agreement had been obtained from the University and the NEB construction team for this site to be used for long-term monitoring of the permeable pavement, the Urban Water Management (UWM) research unit proposed certain modifications to the original design. In particular, this involved separating the parking area into three different sections and incorporating varying designs allowing separate discharge from each section. If runoff from each section could be monitored then it was possible to compare the effluent from different PPS designs within the same site. To achieve this, the site was altered so that the infiltrated stormwater from the lower two compartments of the pavement, each with their own layerworks design, would drain to a separate catchpit or monitoring chamber. Here monitoring equipment could be installed after construction to monitor the treatment and hydraulic performance of the PPS of each section. Figure D-1 illustrates the additions which were incorporated into the final design to allow for the monitoring of the PPS.

The UWM research unit arranged for the construction of four additional chambers on the site, for the purposes of stormwater monitoring. The purpose of each monitoring chamber is for the installation of equipment that would allow monitoring of the quality and quantity of drainage from the PPS underdrain. Chambers A, B and C collect runoff from the site while Chamber D was included to house the data loggers for the monitoring equipment – connected via electrical cables to Chambers A, B and C. Chamber A monitors the infiltrated drainage through a PPS without a geotextile, representing one type of effluent drainage. Chamber B monitors the drainage exiting the underdrain of the PPS including the geotextile Inbitex, representing the effluent drainage from an alternate PPS design. Chamber C collects surface runoff from an impermeable section of the parking area, representing the ‘influent’ quality and quantity flows for the site. The necessary excavations down to the existing stormwater pipe are shown in Figure D-4. Figure D-5 shows one of the monitoring chambers during the construction phase.

Appendix D: New Engineering Building parking area

The impact of unwashed aggregate on the quality of water emanating from permeable pavements



Figure D-4: Excavation of monitoring chamber B down to the existing stormwater pipe

The chamber design required consideration of the installation of multi-parameter probes, flow meters, passive samplers and grab samples to be taken at regular intervals. The final designs for Chamber A (identical to Chambers B and C) and D are shown in Figure D-6 and Figure D-7, respectively. The chambers were designed to house probes to monitor flows and water quality exiting the underdrain. A 150mm extension of the pipe into the chamber was required as shown in Figure D-6a. The chambers needed an instrument base, no smaller than 400mm x 400mm, to facilitate a platform for placement of the passive samplers. The inclusion of this base allowed for a small baffle wall to be easily constructed should ponding within the chamber be needed for flow measurement in the future. To create space in the chamber for the base, the catchpits were positioned so that the existing stormwater pipe was off-centre as seen in Figure D-6a.

Passive samplers require a minimum space of 150mm between the bottom of the underdrain and the instrument base, thus the minimum required depth of the chamber from the pavement surface is 1260mm to accommodate each of the monitoring components. To allow adequate working room, the dimensions for Chambers A, B and C were selected to be 600mm x 800mm. Chamber D was eventually constructed as a circular chamber to make it easier to work in this space.

Care was also taken to position the monitoring chambers in between parking bays to enable access during working hours. To achieve this, the ground beams had to be shifted slightly. However, accessing the chambers still proved to be problematic.

Appendix D: New Engineering Building parking area

The impact of unwashed aggregate on the quality of water emanating from permeable pavements



Figure D-5: Construction of NEB parking area monitoring chambers

Piezometer tubes – two 160mm diameter x 580mm long uPVC pipes with small diameter holes drilled around the lower portion and a suitable cap to prevent rubbish falling in – were incorporated to measure the internal water depth in the south-east corners of each of the two monitored compartments (i.e. between the monitoring chamber and the corner of the kerb and the ground beam). To measure the water depth in the stone layer the cap can then be removed and a ‘dip-stick’ used to determine the water level.

Appendix D: New Engineering Building parking area

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

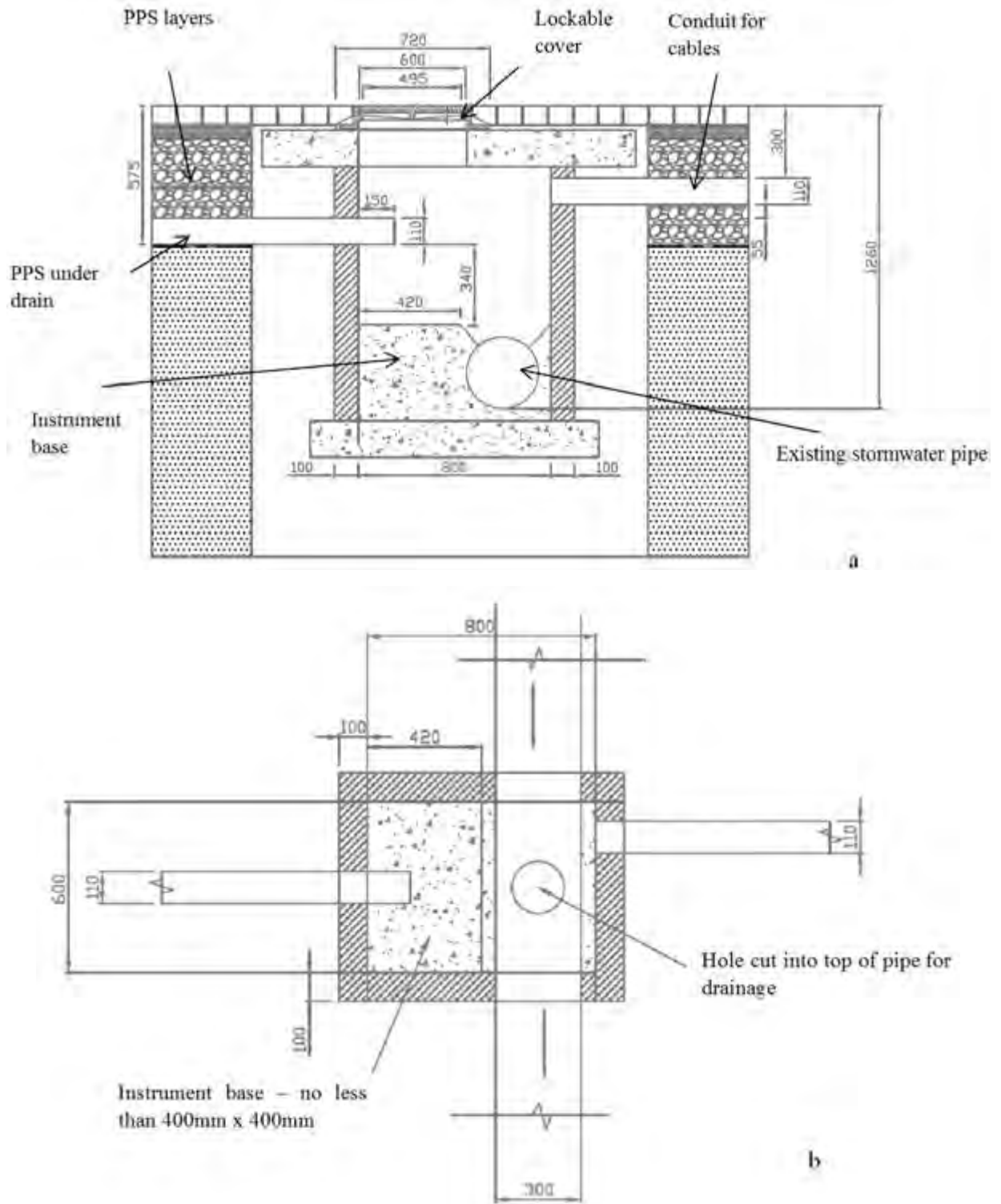


Figure D-6: Diagram showing in section (a) and plan (b) the proposed design for monitoring chamber A

Appendix D: New Engineering Building parking area

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

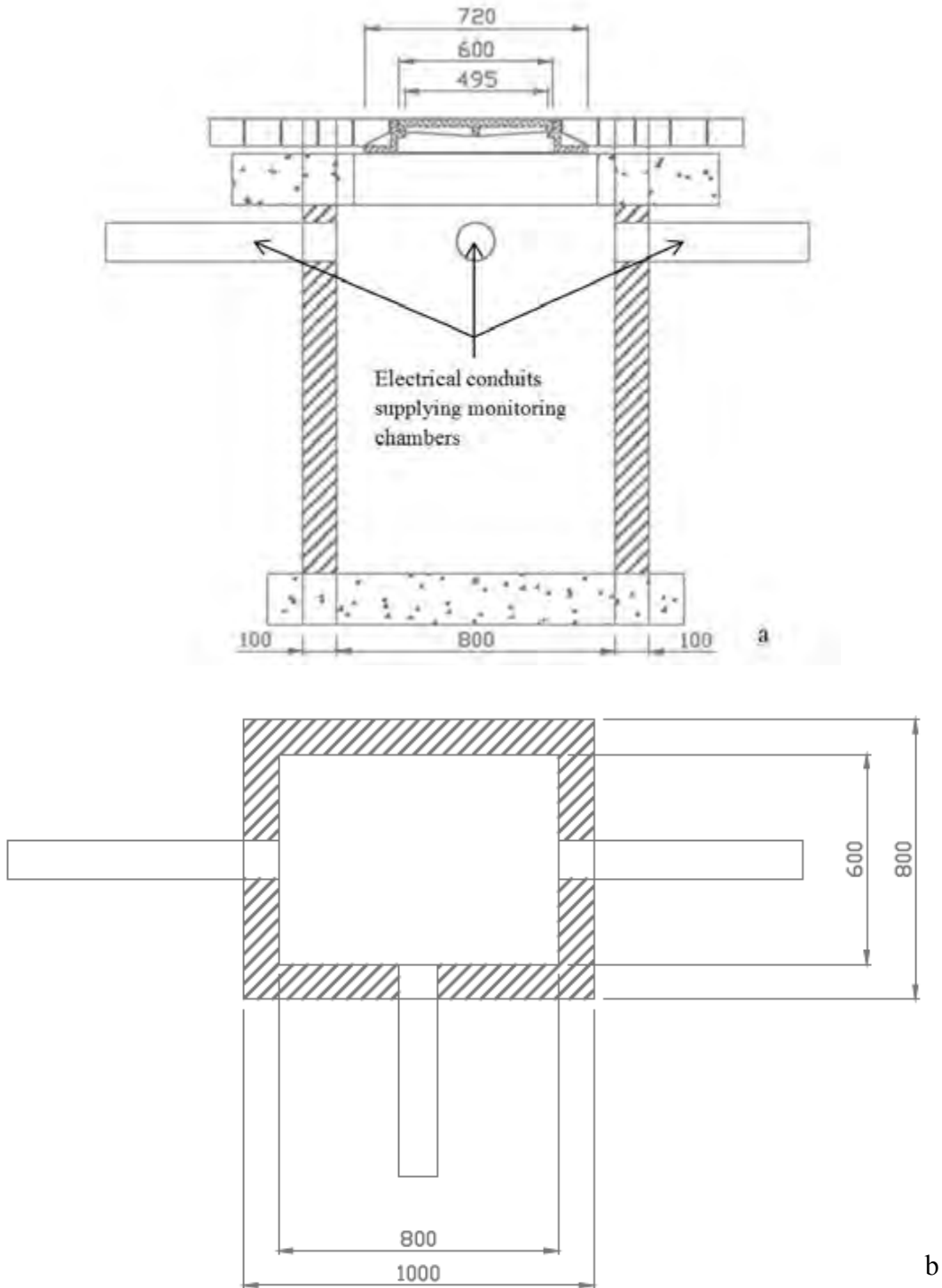


Figure D-7: Diagram showing in section (a) and plan (b) the proposed design for the drawpit - labelled as chamber D

Appendix D: New Engineering Building parking area

The impact of unwashed aggregate on the quality of water emanating from permeable pavements

D4. Lessons learnt from construction of NEB PPS

One objective of this research was to close the gap between the theory of implementing and managing PPS, and to determine what happens in practice. There is thus considerable value in the observation and monitoring of the construction and ongoing management of a site such as the NEB permeable pavement parking area, and relating these observations back to the literature.

D4.1 Inbitex geotextile

The inclusion of geotextiles in PPS is an area of particular interest, and was cause for discussion during the construction phase of the NEB PPS. At one point near the end of the construction process, concerns were raised with respect to the potential blocking of the geotextile as a result of fine material (dust and sediment) being generated on the site. However, recent research carried out in the UK suggests that if the gap between pavers and the size of ‘pea gravel’ – 2-4mm gritstone, are carefully controlled, fine silt material – which presents a clogging risk to the geotextile - will be trapped in the top 100mm of the pavement i.e. sediment will not migrate down far enough to reach the geotextile. This appears to tie in with observations by the paving contractors that clogging and blocking tends to happen in the top 50mm to 70mm – a ‘clogging zone’, in between the pavers. Maintenance should address the clogging in this top ‘clogging zone’ of the pavement by periodically removing the grit (and sediment) out from between the pavers and replace it if and when needed.

D4.2 Deposition of dust and fines on pavement

Another concern during the construction phase was the large amount of dust and fines generated and deposited on the sub-base stone layers and Inbitex during construction. Due to the tight space constraints of the site, the pavement had to be completed in two stages to allow for the movement of vehicles and machinery. Large machinery operated for considerable periods of time directly adjacent to the unfinished pavement as illustrated in Figures Figure D-8Figure D-10.

This method of construction increases the risk of sand, silt and fine material deposition onto the stone which, could potentially have a destructive effect on the drainage capacity and detention volume of the PPS (Armitage *et al.*, 2013a) and thus increases the likelihood of a premature failure of the pavement due to clogging of the pavement layers. Of particular concern was the potential clogging of the Inbitex geotextile which was left exposed for days on end during construction as shown in Figure D-9. The movement of large construction vehicles adjacent the PPS – creating considerable amounts of dust that could settle on the pavement, was continued after the paving blocks were laid and pea gravel swept in-between pavers (see Figure D-10), when the PPS is particularly vulnerable to clogging.



Figure D-8: Clearing of rubble with heavy machinery adjacent to sub-base stone layer

At one point during the construction, the contractors used the stone bedding on the west half of the site for storing construction material, introducing risk of contamination of the stone prior to completion. The paving consultant and project manager were notified of this risk and were requested to ensure that the stone be more carefully protected.

Appendix D: New Engineering Building parking area

The impact of unwashed aggregate on water quality emanating from permeable pavements



Figure D-9: Potential clogging risks are intensified by heavy machinery use



Figure D-10: Start of the second stage of construction

D4.4 Failed embankment causing pavement failure

The un-vegetated embankment on the north-west end of the site resulted in the deposition of a large amount of sediment directly onto the newly constructed pavement causing a section in the corner of the PPS to fail – noted by the ponding of water on the surface, before the construction of the rest of the site was completed. Due to the fact that the NEB PPS parking area had far more detention capacity for the roof runoff than needed, this failure did not raise major concerns. However, on other sites, which may require the optimal operation of the entire permeable area to effectively attenuate peak flows, this could become a critical issue.

Appendix D: New Engineering Building parking area

The impact of unwashed aggregate on water quality emanating from permeable pavements



Figure D-11: Failed embankment on the site causing pollution of the pavement

Observing the failure of this section of the pavement due to soil deposition from a raised embankment, raises yet another concern that local contractors have not familiarised themselves with the relevant literature on PPS in South Africa. Risk of this specific failure was emphasised in the SuDS Guidelines for South Africa (Armitage *et al.*, 2013a) and in the associated document, Sustainable Drainage Systems – Report and South African Case Studies (Armitage *et al.*, 2013b) which stated the following: *‘Permeable paving areas should be designed with particular consideration given to local landscaping to prevent fine material from embankments or planters washing onto the pavers and causing premature clogging. Ideally the paving should be higher than the abutting vegetated areas. Particular care needs to be taken during the establishment of the vegetation as this is when the risk is greatest.’*

D5. NEB Site Monitoring

D5.1 NEB monitoring site preparation and installation

The monitoring set-up was completed by Rene Scheritz. These are sections from the WRC Research Project K5/2409 report. Monitoring chambers A and B were designed to hold a 90° V-Notch weir box intended to serve as a flow measurement device as well as to provide sufficient head height for the peristaltic pumps of the samplers to operate. While both samplers were supposed to be placed into the instrumentation chamber (Chamber D, Figure 3-8), insufficient space resulted in the sampler for NEB-A being housed in monitoring chamber A itself.

Monitoring chamber B was linked to an IscoTM 6712 auto-sampler with a sequential setup consisting of 24 500mℓ HDPE bottles. The sampler was programmed to take distinct samples of 480mℓ at one-hour intervals from the onset of outflow. Due to the lack of a flow-monitoring device, the sampling programme was level-activated by a float switch placed in the weir. This setup had the distinct advantage that the sampler could be prepared well ahead of scheduled rainfall. As this sampler was placed in the instrumentation chamber, with a sampling hose running through the conduit to chamber B, access during parking hours was less problematic at this site. Regular access was still required to drain and clean the V-Notch weir box after each event, particularly to clean out any solids build-up in the chamber after storms – so that subsequent samples would not be contaminated.

Chamber A housed an ISCO GLS composite sampler, programmed to take a composite sample consisting of 49 samples of 150mℓ each, at 30 minute intervals. Since direct access to the chamber was required to set up and retrieve the sampler, several events were missed when this was not possible. Furthermore, this site showed effluent even during dry periods – potentially as a result of a nearby irrigation system, or perhaps the fact that draining the pavement takes an extended time. This made automated activation impossible for this site, further complicating sampler setup.

Chamber C measures runoff from an impermeable pavement surface constructed with the same pavers as the permeable pavement areas. The runoff is directed into it via a shallow channel and a stormwater grate. A passive sampling setup consisting of three interlinked PET bottles received samples directly from the stormwater grate. The first two bottles were self-sealing via a simple ball-float valve, allowing the initial portion of runoff (‘first flush’) to be segregated from the remainder. The last bottle was left open, allowing an aggregate sample of the storm event to form via mixing.

D5.2 NEB field sampling

Before each qualifying rainfall event, all monitoring pits were emptied and cleaned. Sample bottles were cleaned with a 1:5 mixture of 45% H₂SO₄ and distilled water as per standard sampling procedure. Samplers were programmed and tested. After each rainfall event, samples were retrieved and immediately analysed for pH and EC. Nutrient analyses were done immediately where possible, or within 24-48 hours. Retrieval was, in some cases, impaired by parked cars, but generally retrieval occurred within 4 to 10 hours of cessation of rainfall. When feasible, grab samples were also taken from the two other field sites – the Rondebosch PPS and train station parking lot – for comparison. These were analysed immediately for pH, EC, NH₃ and PO₄³⁻. In order to allow for the later testing for TSS, samples were preserved by addition of HNO₃ to reduce the pH to less than 2, and stored at below 4°C in PET bottle. TSS samples were performed more than 28 days after collection, due to equipment and laboratory availability; while this may compromise samples for EPA reporting, little impact is expected on actual TSS values.

Appendix D: New Engineering Building parking area

The impact of unwashed aggregate on water quality emanating from permeable pavements

Rainfall data was acquired from a weather monitoring station positioned at UCT. Data was supplied by the GEF (Global Environmental Fund) Fynbos Fire Project, Weather Station Network funded by The GEF Special Climate Change Fund (SCCF), <http://fynbosfire.org.za>. Access to the Weather Station Network is at <http://www.wmon.co.za>, UCT station ID is 16. The station records rainfall data at hourly intervals.

D6. Data analysis

D6.1 Rainfall analysis

Rainfall data was aggregated into total daily precipitation. Rainfall events were determined, where an event was defined as a sequence of contiguous rainy days. From this, the total event rainfall was calculated. The study period was defined to be from 01/11/2014 to 01/11/2015.

D6.2 Observations from NEB site

The following observations outline the main findings from monitoring of the NEB site by Rene Scheritz:

- Parts of the UCT PPS are already blocked due to runoff from a rain garden built on the road curb directly above it, and possibly also as a result of sand being stored on parts of the pavement during the construction process. Furthermore, runoff from the road spills into the first segment of the PPS, leading to rapid clogging in these areas. No infiltration tests were done on these areas, and there appears to be no hindrance in overall infiltration rates. However, this demonstrates how inappropriate land use characteristics around PPS could potentially lead to rapid clogging and impaired performance.
- It was not always possible to access the monitoring pits at UCT PPS as the manhole covers were often blocked by parked cars. For monitoring purposes, this type of design is unfavourable. Even though it is possible to place automatic samplers in a remote pit and draw samples through a conduit, the container used to draw samples from must be emptied and cleaned after each event, in order to prevent cross-contamination.
- Low-cost sequential samplers were used quite successfully. One of the biggest issues in their use is their limited volume, which resulted in the initial two bottles being filled very quickly. The other is that the ‘mixed’ sample at the terminal bottle is likely to be significantly enriched in TSS, as it settles out in the bottle. This low-cost sampling innovation could benefit from further implementation and experimentation, but may be a useful tool in monitoring plans constrained by budget implications.

Appendix D: New Engineering Building parking area

The impact of unwashed aggregate on water quality emanating from permeable pavements

D6.3 Water quality monitoring in the field study

Immediately apparent after sampling was that the PPS sub-grade at the NEB PPS was constructed with unwashed stone. TSS results were elevated above expected values compared to those obtained from RPPS. Furthermore, particulates could clearly be identified as construction material by appearance in suspension and after filtration.

Levels of PO_4^{3-} in NEB-B effluent rose throughout the winter season, rather than subsided as was the case with RPPS. This is either as a result of the pavement being flushed out and the PO_4^{3-} becoming more readily available for leaching or by microbial action; or because increasing amounts of PO_4^{3-} deposition are taking place on the surface of the pavement.

While the nutrient reduction of the PPS under test was not significant, nutrient concentration in the effluent is fairly consistent and does not reflect the vast variability shown in most impervious areas. Overall, nutrient levels emitted by PPS are lower than those from most impervious areas.

EC levels in PPS effluent are higher than those in effluent from impervious areas. This is likely due to the attenuation and potential for leaching of ions from the PPS subgrade material. EC levels seem to drop in PPS throughout a storm event, and EC levels are higher during the dry season.

pH is highly variable, ranging from 6.5 to about 9 in the PPS studied.

Intra-event variability showed the presence of a ‘first flush’ effect in terms of pollutant concentrations. The significance of this effect is unclear, but should be considered for future monitoring purposes. This may be a phenomenon present only in the newly constructed NEB-B, as entrained pollutants in the unwashed base-course are removed by influent. To make an accurate comparison, an existing PPS like RPPS would also need to be monitored with an auto-sampler.

Generally low intra-event variability and consistent readings suggest that PPS effluent will likely remain within a predictable range. This would be beneficial for managing downstream pollutant loads.

PPS water quality is generally compatible for use in Category 4 industrial processes and irrigation, and produces mostly acceptable water quality for downstream aquatic ecosystems. To meet PO_4^{3-} criteria, however, another SuDS technology with better phosphate removal capacity should be included in a SuDS treatment train.

D7. Observations from NEB site

The following observations outline the main findings from the various aspects of this NEB study:

- Parts of the UCT PPS are already blocked due to runoff from a rain garden built on the road curb directly above it, and possibly also as a result of sand being stored on parts of

the pavement during the construction process. Furthermore, runoff from the road spills into the first segment of the PPS, leading to rapid clogging in these areas. No infiltration tests were done on these areas, and there appears to be no hindrance in overall infiltration rates. However, this demonstrates how inappropriate land use characteristics around PPS could potentially lead to rapid clogging and impaired performance.

- It was not always possible to access the monitoring pits at UCT PPS as the manhole covers were often blocked by parked cars. For monitoring purposes, this type of design is unfavourable. Even though it is possible to place automatic samplers in a remote pit and draw samples through a conduit, the container used to draw samples from must be emptied and cleaned after each event, in order to prevent cross-contamination.
- In general though, the field tests conducted by Rene Scheritz showed that PPS water quality is generally compatible for use in Category 4 industrial processes (irrigation, washing, firefighting and dust control) and irrigation purposes, and produces mostly acceptable water quality for downstream aquatic ecosystems. Should PO_4^{3-} criteria need to be met, other SuDS technologies with better nutrient removal capacities should be included in a SuDS treatment train.

Appendix D: New Engineering Building parking area

The impact of unwashed aggregate on water quality emanating from permeable pavements

**Appendix E: Assessment of ethics in research
projects form**

EBE Faculty: Assessment of Ethics in Research Projects

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit to Ms Zulpha Geyer (Zulpha.Geyer@uct.ac.za; Chem Eng Building, Ph 021 650 4791). Students must include a copy of the completed form with the thesis when it is submitted for examination.

Name of Principal Researcher/Student:

Benjamin Eggs

If a Student:

Degree:

MSc. Eng.

Department: *Civil Engineering*

Supervisor: *Prof. Neil Arncliffe*

If a Research Contract indicate source of funding/sponsorship:

NRF scarce skills & Harry Crossley Fellowship

Research Project Title: *An investigation of the treatment efficacy of permeable pavements with a view to harvesting stormwater for use in South Africa.*

Overview of ethics issues in your research project:

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?	YES	<input checked="" type="radio"/> NO
Question 2: Is your research making use of human subjects as sources of data? If your answer is YES, please complete Addendum 2.	YES	<input checked="" type="radio"/> NO
Question 3: Does your research involve the participation of or provision of services to communities? If your answer is YES, please complete Addendum 3.	YES	<input checked="" type="radio"/> NO
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answer is YES, please complete Addendum 4.	YES	<input checked="" type="radio"/> NO

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate.

I hereby undertake to carry out my research in such a way that

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

Signed by:

	Full name and signature	Date
Principal Researcher/Student:		<i>23/01/2015</i>

This application is approved by:

Supervisor (if applicable):		<i>23/1/15</i>
HOD (or delegated nominee): Final authority for all assessments with NO to all questions and for all undergraduate research.		<i>23/1/15</i>
Chair: Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.		