An investigation of the treatment efficacy of permeable pavements for water quality performance in South Africa

Thesis submitted in fulfilment of the requirements for the degree of:

MSc in Environmental and Geographical Sciences

At:

The University of Cape Town

Submitted By:

René Schieritz

February 2016

DECLARATION

I, René Schieritz, hereby declare that the work on which this dissertation/thesis is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university.

I empower the university to reproduce for the purpose of research either the whole or any portion of the contents in any manner whatsoever.

René Schieritz

19A Draper Road

Claremont, 7708

Cape Town

15 February 2016

ABSTRACT

Stormwater pollution has been recognised as a leading cause of ecological degradation of urban streams. Sustainable Drainage Systems (SuDS) attempt to address stormwater impacts by flow attenuation and pollutant treatment, simultaneously providing amenities such as water for use in irrigation or other suitable uses. Permeable pavements are a form of SuDS that provide on-source treatment and storage of stormwater while retaining the functionality of hardened surfaces. They have been studied extensively in the international literature but no studies in a South African context have been published. This study investigated the water quality performance of a recently constructed permeable pavement at the University of Cape Town. Effluent quality was assessed against the South African Water Quality Guidelines and an ecosystem assessment tool. The results showed that, while the pavement had been constructed with unwashed aggregate and therefore exported suspended solids, effluent still met the standards required for irrigation and some industrial uses. However, the effluent did not meet desirable nutrient standards for discharge into the aquatic ecosystem. The performance of the pavement was similar to values reported in the international literature, suggesting that the quality ranges can be extrapolated to other permeable pavements.

The newly constructed pavement displayed noteworthy inter-event progression, as well as identifiable intra-event variation of pollutant concentrations. Further research into effluent toxicity, long-term impacts of unwashed aggregate and catchment-wide impacts of permeable pavements are recommended.

ACKNOWLEDGEMENTS

A number of people have supplied the necessary input, support, advice and encouragement for this thesis. Without the following, I would not have finished this thesis.

Firstly, Dr. Kevin Winter, my supervisor who has so patiently listened to my absurd ideas and steered me in the right direction. He can always be trusted to give encouragement when the end just doesn’t seem in sight, and will stand by his students all the way.

Secondly, Dr. Kirsty Carden, the project manager on this WRC-funded project. Kirsty managed project expenses, compiled reports, gave advice – basically, whatever needed doing, she did.

I would like to thank the entire Urban Water Management Group, for being a group where ideas flourish, as well as backing me financially, along with the University of Cape Town Postgraduate Funding Centre. Also, my thanks to the Water Resource Commission for funding the research (K5-2409) of which the research in this thesis is a part of.

Further, I would like to acknowledge Benjamin Biggs, who was with me for most of this project and an excellent source of engineering knowledge as well as a great sounding board. Also, Claire Lawrence-Naidoo and the Chemistry Department for allowing me access to their laboratory and Charles Nicholas from the Engineering Workshop for the construction of the weirs.

My parents have supported me throughout my studies; I dedicate this thesis to them and to my girlfriend Julie Campbell – for her patience, and her understanding; her encouragement and support and the endless hours of complaining she had to endure. She has always been the reason for me to keep trying.

CONTENTS

Declaration i

Abstract ii

Acknowledgements iii

Contents iv

List of Figures vii

List of Tables ix

Abbreviations 1-1

1 - Introduction 1-2

1.1 The need for Sustainable Stormwater Management 1-2
1.2 Water Management in South Africa 1-3
1.2.1 Stormwater management in Cape Town 1-4
1.3 Permeable Pavements 1-4
1.4 Performance 1-5
1.4.1 ‘Acceptable’ Water Quality 1-6
1.5 Aim 1-6
1.6 Thesis structure 1-7

2 - Literature review 2-9

2.1 Stormwater & Stormwater Management 2-9
2.1.1 Pre Development vs Post Development 2-10
2.1.2 Conventional drainage systems 2-11
2.1.3 Stormwater pollution 2-12
2.1.4 Impervious Areas and their impacts 2-14
2.1.5 The ‘Stormwater Management Dilemma’ 2-15
2.1.6 Temporal Variability: The ‘First Flush’ 2-16
2.1.7 Reporting Stormwater Pollution: EMCs & TMDL 2-17
2.1.8 Factors affecting EMC/loading 2-18
2.1.9 The Evolution of Stormwater Management 2-19
2.2 Implementing the new Paradigm: LIDs, SUDS, BMPs and others 2-20

2.3 SUDS 2-21
2.3.1 Overview of Sustainable Drainage Systems (SuDS) 2-21
2.3.2 Source Control Strategies 2-23
2.3.3 Source Control and Water Quality 2-23
2.3.4 Source Control and Flow 2-23
2.3.5 SuDS in Cape Town 2-24
2.4 Permeable pavement systems (PPS) 2-26
2.4.1 PPS design 2-27
2.4.2 Hydraulic and hydrological features 2-29
2.4.3 Drivers of Pollutant Removal 2-32
2.4.4 Pollutant removal capacity in literature 2-32
2.4.5 Stormwater Harvesting 2-33
2.5 Assessing PPS Performance 2-34
2.5.2 Pollutant Performance Metrics in the literature 2-36
2.5.3 Monitoring 2-37

3 - Methodology 3-39
3.1 Field Sampling 3-39
3.2 Site Descriptions 3-41
3.2.1 NEB PPS 3-41
3.2.2 Rondebosch Permeable Pavement (RPPS) 3-46
3.2.3 Rondebosch Train Station (RTS) 3-47
3.2.4 P8 3-48
3.3 Pilot Study Sampling 3-49
3.4 Parameter Selection 3-49
3.5 Full scale field sampling 3-50
3.6 Data Analysis 3-51
3.6.1 Rainfall Analysis 3-51
3.6.2 Inter event analysis 3-51
3.6.3 Intra Event Analysis 3-52
3.6.4 Correlation 3-52

4 - Results 4-53
4.1 Rainfall Characteristics 4-53

4.2 NEB-B 4-55
    4.2.1 Inter-Event Variability 4-56
    4.2.2 Intra-Event Variability 4-63
    4.2.3 Correlations 4-72
4.3 RPPS & RTS 4-76
4.4 NEB-I & P8 4-78
4.5 Summary Statistics 4-79
4.6 Heavy Metal Results 4-80
4.7 Results Summary 4-80

5 - Analysis 5-81

5.1 Water quality from NEB-B: ‘fit for use’? 5-81
    5.1.1 Total Suspended Solids 5-83
    5.1.2 Ammonia 5-84
    5.1.3 Orthophosphate 5-85
    5.1.4 Electrical Conductivity 5-85
    5.1.5 pH 5-86
    5.1.6 Heavy Metals 5-86
    5.1.7 Is NEB-B Effluent ‘fit-for-use’? 5-86
    5.1.8 Target Water Quality Ranges for Aquatic Ecosystems 5-87
5.2 Performance of NEB-B against other sites and Literature values 5-88
5.3 Summary of Analysis 5-91

6 - Discussion 6-92

6.1 PPS in Literature 6-92
    6.1.1 Performance Assessment of PPS 6-92
6.2 Assessing NEB-B 6-93
    6.2.1 Pollution Reduction 6-94
    6.2.2 Pollutant Progression 6-94
    6.2.3 Unwashed Stone 6-95
6.3 Outliers: Events 8, 9 & 10 6-96
6.4 Pilot Study: Findings, limitations and difficulties 6-97
6.5 Analysis of Methodology 6-98
    6.5.1 NEB-A 6-98

6.5.2 Using sequential bottle samplers 6-98
6.5.3 Using Automatic Samplers 6-99
6.5.4 Monitoring Permeable Pavements 6-100
6.5.5 pH measurement difficulties 6-100
6.6 Study Observations 6-101
6.6.1 Pavement Clogging 6-101
7 - Conclusion 7-103
8 - Reference List 8-106

Appendix A

Appendix B

LIST OF FIGURES

Figure 2-1: Effects of urbanisation on the water cycle (Chocat et al., 2007) *2-10*
Figure 2-2: Typical hydrograph associated with pre- and post-development with the conventional approach to stormwater management (Armitage et al., 2013) *2-11*
Figure 2-3: Typical pre- and post-development scenarios with the conventional approach to stormwater management (Armitage et al., 2013) *2-12*
Figure 2-4: The evolution of the stormwater paradigm (Roy et al., 2009) *2-19*
Figure 2-5: The Stormwater Design Hierarchy (Armitage et al., 2013) *2-22*
Figure 2-6: Concept of a Clogging Front (Beecham et al., 2010) *2-30*
Figure 2-7: Monitoring stormwater processes (Barbosa et al., 2012) *2-38*
Figure 3-1: Sequential bottle sampler in the background, with first bottle containing sample shown in the foreground *3-40*
Figure 3-2: Original consultants drawing for design of NEB PPS parking lot *3-41*
Figure 3-3: Schematic of the NEB PPS surface layout, including monitoring chambers. *3-42*
Figure 3-4: Layer works design diagram for the NEB PPS. Note that the top layer of geotextile was omitted for NEB-A *3-43*
Figure 3-5: Picture of the NEB PPS. Note the ground beam separating PPS sections in the middle of the picture 3-44
Figure 3-6: ISCO 6712 Sampler with 24 bottle arrangement *3-45*
Figure 3-7: Active low switching circuit used with float switch to enable the sampling program at a suitable water level *3-46*
Figure 3-8: Image of RPPS. The PPS covers the parking bays only, while the remainder of the pavement is impervious *3-47*

Figure 3-9: Picture of RTS, a public parking lot for a train station 3-48

Figure 3-10: Picture of P8 shortly after rainfall. Runoff discharges into an open culvert on the left of this picture 3-49

Figure 4-1: Rainfall event dates during study period. Black bars indicate the sampled events during the main study; sampled event numbers are shown above the bars. 4-55

Figure 4-2: Image of filters after TSS test. From left to right are RTS, NEB-B and RPPS. Note the fine brown layer of sediment on the filter from NEB-B, whereas RPPS is almost indistinguishable from the deionised water blank 4-57

Figure 4-3: Average TSS concentrations for each event, along with total event rainfall. Initially, TSS appears to increase linearly from event to event. 4-58

Figure 4-4: Average Orthophosphate concentrations for each event, along with total event rainfall. Similarities in progression with TSS are evident. 4-59

Figure 4-5: Average Ammonia concentrations for each event, along with total event rainfall 4-60

Figure 4-6: Average EC for each event, along with total event rainfall. 4-61

Figure 4-7: Average pH for each event, along with total event rainfall. 4-62

Figure 4-8: TSS concentrations shown at relative sampling time per event. 4-63

Figure 4-9: Event-standardised TSS concentrations aggregated according to sampling time. R^2 value shown on graph suggests negative linear correlation between TSS concentration and event progression. The data point at hour one is an average of the sample at enable and the 'first' program sample. 4-64

Figure 4-10: EC shown at relative sampling time per event. Event numbers displayed on the right border. 4-65

Figure 4-11: Event-standardised EC aggregated according to sampling time 4-66

Figure 4-12: Orthophosphate concentration shown at relative sampling time per event. Event numbers displayed on the right border 4-67

Figure 4-13: Event-standardised Orthophosphate concentrations aggregated according to sampling time 4-68

Figure 4-14: Ammonia concentration shown at relative sampling time per event. Event numbers displayed on the right border. 4-69

Figure 4-15: Event-standardised Ammonia concentrations aggregated according to sampling time 4-70

Figure 4-16: pH shown at relative sampling time per event 4-71

Figure 4-17: Event-standardised pH aggregated according to sampling time. A smooth 'saturation curve' pattern is evident. 4-72

Figure 5-1: Ecosystem health criteria categories and thresholds from Nel et al. (2013) 5-82

Figure 5-2: Bar graph depicting the distribution of NEB-B sample concentrations as categorised against criteria outlined by Nel et al, (2013). 5-87

Figure 5-3: As Figure 5-2 above, for RPPS 5-88

Figure 6-1: RPPS during rainfall. Note the ponding in the centre of the pavement 6-101

Figure 6-2: NEB Pavers nearer the centre remain clear after one rainfall season (left). However, pavers near the rain garden are filled with sediment (right) 6-102

Figure A-8-1: Pilot study EC results show decreasing EC with each event II

Figure A-8-2: Pilot study pH results .... *II*
Figure A-8-3: Pilot study Orthophosphate results are relatively high, with most error bars overlapping .... *III*
Figure A-8-4: Pilot study Ammonia results show initially high ammonia, with significant variabil .... *III*

LIST OF TABLES

Table 3-1: Analysis methods followed, along with their EPA equivalent methodologies and concentration ranges *3-50*
Table 4-1: Sampled Rainfall Event dates, with sites sampled and event duration *4-54*
Table 4-5: Cumulative rainfall per event before sampler was triggered shown with antecedent dry weather days for that event. Note missing event 4, as it was only automated by event 5 .... *4-56*
Table 4-2: Correlation coefficients for each water quality parameter and selected rainfall characteristics. Bold numbers indicate a level of significance of above 0.1, underlined bold number indicate a significance level above 0.05 .... *4-72*
Table 4-3: Levels of Significance for correlation coefficients at six degrees of freedom (Siegle, 2015) *4-73*
Table 4-4: Rank correlation matrix between parameters. Note significant correlation between TSS, O-Phosphate and TSLME *4-74*
Table 4-6: Average values and standard error for samples collected from RPPS and RTS 1 and 2 .... *77*
Table 4-4: Water quality values from P8 .... *4-78*
Table 4-5: Water quality values from NEB-I *4-79*
Table 4-6: Summary averages across all sampling sites (excluding pilot). Results reported with Standard Error of the Mean (SEM). *4-79*
Table 4-7: Heavy metal concentrations for Pb and Cu. Note the highest concentrations evident in NEB-I, which generally showed low results for other parameters. Average and standard error for each are shown. *4-80*
Table 5-1: Comparison of results from this study with results summarised by Newman et al., 2013 .... *5-90*
Table A-4: Summary statistics of results from RPPS Pilot Study .... *I*

ABBREVIATIONS

ADWP: Antecedent Dry Weather Period
BMP: Best Management Practice
IUWM: Integrated Urban Water Management
LID: Low Impact Development
NEB: New Engineering Building – building at UCT
P8: Impervious parking lot at UCT
PPS: Permeable Pavement Systems
RPPS: Rondebosch Permeable Pavement System – PPS in The Rondebosch
RTS: Rondebosch Train Station –A parking lot
SAWQ/G: South African Water Quality Guidelines
SuDS: Sustainable Drainage Systems
TAN: Total Ammonia Nitrogen
TSLME: Time Since Last Measured Event
UCT: University of Cape Town
WSUD: Water Sensitive Urban Design

1 - INTRODUCTION

Stormwater pollution has been recognised as a key environmental stressor since the 1970s (Roy *et al.*, 2008). Traditional stormwater management structures are solely designed for the rapid abstraction of stormwater away from urban areas and into natural streams (Taebi & Droste, 2004; Goonetilleke *et al.*, 2005; Roy *et al.*, 2008; Burns *et al.*, 2012). While effective at reducing localised flood risk, this approach had, and continues to have, negative environmental impacts (Paul & Meyer, 2001; Goonetilleke *et al.*, 2005; Burns *et al.*, 2012; Walsh *et al.*, 2012). Burns *et al.* (2012) have defined this traditional method of abstraction and discharge as the 'drainage efficiency approach'.

In the last decade, a thorough body of literature has also described stormwater pollution from urban areas as one of the primary threats to downstream aquatic ecosystems (Paul & Meyer, 2001; Taebi & Droste, 2004; Gnecco *et al.*, 2005; Goonetilleke *et al.*, 2005; Bernhardt *et al.*, 2008; Luo *et al.*, 2009). Increasingly, recommendations for managing stormwater suggest a move away from the drainage efficiency approach towards Sustainable Drainage Systems (SuDS) which mimic natural hydrological processes and reduce pollutant loadings (Heal *et al.*, 2004; Mitchell, 2005; Armitage *et al.*, 2013).

The remainder of this introduction will focus on the SuDS philosophy and introduce permeable pavements as a sustainable urban drainage system. This study investigates the performance of permeable pavements in the South African context, and includes discussion of local stormwater policies, regulations and management guidelines. This contextualises the aims and objectives of the study.

1.1 The need for Sustainable Stormwater Management

In the international literature, stormwater is widely recognised as one of the most significant contributing factors towards the degradation of downstream rivers (Walsh, 2000; Paul & Meyer, 2001; Burns *et al.*, 2012; Walsh *et al.*, 2012). Impervious surfaces interrupt the natural progress of infiltration, evapotranspiration and groundwater recharge, thereby converting rainfall into runoff which is then commonly discharged into a nearby drainage system (Roy *et al.*, 2008; Armitage *et al.*, 2013; Burns *et al.*, 2013). Stormwater networks act as hydraulically efficient shortcuts from the stormwater source to the nearest urban river, preventing processes of retention and attenuation that smooth flood peaks and provide the opportunity for the removal of suspended solids by settling and nutrients by biodegradation and plant uptake (Walsh & Kunapo, 2009; Burns *et al.*, 2012). Not only does the hydrological shift cause significant increases in erosion (Chocat *et al.*, 2007) and reduction in base flows (Hamel & Fletcher, 2014), but anthropogenic activities can deposit significant amounts of pollutants on impervious areas (Brown & Peake, 2006; Göbel *et al.*, 2007). These are readily washed off, and the lack of processes such as filtration and biodegradation results in their direct discharge into streams (Walsh, 2000)).

Stormwater can also be a significant resource (Fletcher *et al.*, 2014a). Many countries are plagued by chronic water scarcity, including South Africa. Increasingly, alternative sources are required for fit-for-use water, and lateral benefits can be derived from using nutrient-enriched stormwater (Mitchell *et al.*, 2006; Nnadi *et al.*, 2008).

The confluence of these two concepts, the need to maintain ecological function in aquatic ecosystems and the need for new water sources, lead to the inevitable conclusion that conventional stormwater management is unsustainable and undesirable (Burns *et al.*, 2012). An emerging paradigm of stormwater management is contained within the concepts of Water Sensitive Urban Design (WSUD) and Integrated Urban Water Management (IUWM), and expressed in practices such as Low Impact Development (LID), Best Management Practices (BMP) and Sustainable Drainage Systems (SuDS) (Fletcher *et al.*, 2014a). This paradigm is one of holistic management of stormwater (Mitchell, 2006) which aims to produce processes that promote sustainability (Heal *et al.*, 2004). These processes simulate natural hydrology and water quality characteristics to protect and maintain urban aquatic ecosystems (Heal *et al.*, 2004; Burns *et al.*, 2012; Armitage *et al.*, 2013; Hamel *et al.*, 2013)

1.2 Water Management in South Africa

Stormwater management in South Africa is still mostly reliant on the drainage efficiency approach. While some SuDS implementations have been constructed, resistance to their uptake has resulted in very little knowledge about their efficacy (Armitage *et al.*, 2013). However, some municipalities have begun to adapt policies and regulations to include WSUD principles, and recommend SuDS implementations, including the City of Cape Town (City of Cape Town, 2009; Haskins, 2012). Furthermore, as a water scarce country, South Africa may need to find alternative sources of suitable water, especially in the face of potential climate change (Mwenge Kahinda *et al.*, 2010).

1.2.1 Stormwater management in Cape Town

Cape Town is South Africa's oldest colonial formal urban settlement, dating back to the arrival of the first Dutch settlers. The first phase of Cape Town's stormwater network was constructed in 1899. Since then, continued expansion of concrete canals, river modification, infilling and removal of wetlands and catchment hardening have contributed to significant alteration of Cape Town's hydrograph, which now mimics that of most urban centres (Haskins, 2012). With the establishment of the Catchment Management Branch in 1997, the City expanded on the requirement to provide adequate stormwater infrastructure by including river, lakes and wetlands as part of the formal stormwater network. Haskins (2012) argues that these natural water features are recognised as an important and valuable asset for the city as they provide environmental goods and services which are highly valued by the inhabitants.

The first move towards integrated catchment management is evident in the Stormwater Management Planning and Design Guidelines for New Developments released by the Transport, Roads and Stormwater Directorates Catchment, Stormwater and River Management Branch in 2002. These guidelines were aimed at new developments, but also intended to apply to stormwater upgrade and rehabilitation projects (Transport Roads & Stormwater Directorate, 2002). The management objectives were to minimise flooding risk, protect receiving water bodies, promote the multifunctional use of stormwater management systems and develop sustainable environments. The policy was largely adhered to for peak flow reductions, but other impacts were not mitigated as successfully (City of Cape Town, 2009). The City of Cape Town stormwater by-law issued in 2005 provided regulatory support for stormwater management, but did not set water quality standards for stormwater discharge.

In 2009, the City of Cape Town included Water Sensitive Urban Design (WSUD) principles in their development policy. The Management of Stormwater Impacts Policy laid out specific objectives of sustainable drainage:

- Improve quality of stormwater runoff
- Control quantity and rate of runoff
- Encourage groundwater recharge. (City of Cape Town, 2009: Section 6.1, p.8)

1.3 Permeable Pavements

Permeable pavement surfaces (PPS) are a form of source control sustainable drainage systems. These pavements allow water to infiltrate through their structure, discharging either into the subgrade or into a downstream drainage system (Scholz & Grabowiecki, 2007; Drake *et al.*, 2013). They provide attenuation and temporary storage, thereby reducing the effective imperviousness of the catchment in which they have been implemented (Ball & Rankin, 2010). Voids within the paving layer permit infiltration into the aggregate while processes of sedimentation, adsorption and biodegradation enable the removal of pollutants (Newman *et al.*, 2002; Scholz & Grabowiecki, 2007; Drake *et al.*, 2013).

Permeable pavements have received considerable attention in the literature, and are popular as they are able to retain their core function as a load bearing surface while contributing to sustainable stormwater management (Balades *et al.*, 1995; Shackel *et al.*, 2003; Scholz & Grabowiecki, 2007; Drake *et al.*, 2013; Imran *et al.*, 2013). PPS have been identified as having significant environmental benefits, as they reduce peak flows, effectively remove certain pollutants and in many cases contribute to groundwater recharge (Balades *et al.*, 1995; Legret *et al.*, 1996; Rushton, 2001; Abbot & Comino-Mateos, 2003; Brattebo & Booth, 2003; Scholz & Grabowiecki, 2007; Ball & Rankin, 2010; Drake *et al.*, 2013). Simultaneously, they have been found to have other direct benefits such as a reduction of the heat island effect and increased surface grip due to elimination of hydroplaning (Scholz & Grabowiecki, 2007). Other benefits which can be exploited are their potential for treating and storing stormwater for reuse as well as integrating the pavements with ground source heat pumps (GSHP) for renewable energy harvesting (Grabowiecki *et al.*, 2008; Nnadi *et al.*, 2008; Scholz & Grabowiecki, 2009; Tota-Maharaj, 2010).

While well-studied, their use is fairly recent in South Africa; the oldest reported PPS is a parking lot constructed at the University of Witwatersrand in 2007 (Water Sensitive Urban Design (WSUD) | WITS Parking Lot, n.d.). No studies focussing on the use of PPS in South Africa have been published, and with increasing acceptance by practitioners, it is important that the performance of PPS within the South African context is understood.

1.4 Performance

Performance of a sustainable drainage system is defined by how well it meets its goals for stormwater that flows through the structure (Strecker *et al.*, 2001). These goals generally include pollutant reduction, peak flow reduction, groundwater recharge and opportunities for stormwater harvesting (Ball & Rankin, 2010; Beecham *et al.*, 2010, 2012; Hamel & Fletcher, 2014). This study will focus on the performance of permeable pavements with regards to water quality of the effluent and, consequently, stormwater harvesting and reuse.

Water quality performance for PPS is commonly reported as percentage reduction of pollutant concentrations of influent versus effluent (e.g. Rushton, 2001; Scholz & Grabowiecki, 2007; Tota-Maharaj & Scholz, 2010). The Management of Stormwater Impacts Policy similarly prescribes a performance criterion for SuDS based on this metric, whereby it requires Suspended Solids and Phosphates from brownfield sites to be reduced by 85% and 45% respectively (City of Cape Town, 2009). However, the use of percentage reduction as a performance metric is not recommended (USEPA, n.d.; Wright Water Engineers and Geosyntec Consultants, 2007). Rather, it is recommended that the absolute water quality of SuDS be investigated under a variety of environmental conditions and compared to respective guidelines and regulations (Heal *et al.*, 2009). This is more meaningful to downstream aquatic ecosystems, as pollutant concentrations are the final determinant of ecosystem health (Walsh, 2000). Similarly, stormwater harvesting and reuse relies on the 'fit-for-use' quality of water, which is guided by national guidelines.

1.4.1 'Acceptable' Water Quality

Water quality is a relative concept, and what concentrations of various quality constituents are acceptable is dependent on the type of use. While most anthropogenic uses have set standards for water quality, aquatic ecosystems have requirements which are ecosystem-specific. Water quality guidelines for most 'natural' pollutant constituents such as nutrients and suspended solids suggest that levels should not deviate from background levels by more than a specified percentage (Department Of Water Affairs And Forestry, 1996).

Water quality performance for PPS will be determined by the absolute pollutant concentrations of effluent. 'Performance' will vary depending on the intended use, whether it is for harvesting and re-use, or discharge into the aquatic ecosystem. As there are no universal standards for acceptable water quality for receiving aquatic ecosystems, performance for this purpose needs to assessed locally.

1.5 Aim

The aim of this study was to investigate the water quality performance of permeable pavements in Cape Town. As described above, 'performance' suggests goals or targets, which were drawn from the South African Water Quality Guidelines (SAWQG). By comparing the effluent water quality from PPS throughout a rainy season to the water quality targets for various potential uses, it was possible to identify the potential of effluent water quality for harvesting and reuse. A local study which assigned water quality categories for natural ecosystem was used to categorise water for discharge into the environment.

The first research question posed was: “Is the water quality of PPS effluent of acceptable quality, both for re-use and discharge into the aquatic environment?”

The following objectives were set for the study:

- Thoroughly investigate the water quality of effluent from a newly constructed PPS at the University of Cape Town, and compare the water quality against the South African Water Quality Guidelines
- Contextualise the results with water quality estimates from nearby impervious surfaces as well as other existing PPS

Additionally, this study intended to investigate the temporal variability of pollutant concentrations in the effluent of PPS. Temporal variability within a storm event can significantly impact the representativeness of monitoring efforts which in turn can skew measures of performance. The PPS under investigation was newly constructed, and exploring the variability between event means was a way of investigating the performance progression of the PPS. While some studies had previously assessed pollutant progression throughout a PPS life cycle in a laboratory simulation, little information is available about the progression of a recently constructed field site. This led to the dual research questions of: “Do PPS exhibit significant intra-event variability?” and “Does a newly constructed PPS show a progression in effluent water quality throughout its first rain season?”

It should be noted that this study only investigates PPS with an impermeable layer that does not permit water to infiltrate into the subgrade.

1.6 Thesis structure

This report begins with a literature review outlining the background of stormwater management, and the context around PPS. The review highlights the strengths and weaknesses and common issues around PPS implementation and use. The main findings of the literature review were that PPS are good performing interventions, but that construction, design and maintenance are a concern. The study focussed mainly on a single pavement for high temporal and spatial resolution data, and this is reflected in the results. Results from the PPS agree largely with literature values, and the water quality constituents measured meet most water quality guidelines for appropriate reuse, but the newly constructed pavement shows some trends that suggest that a longer study period would be beneficial. While the analysis proposes some putative agents for these trends, few conclusive statements can be made.

The discussion reviews some points of the literature review and discusses some key findings from the study. It continues to analyse the methodology, and remarks on some study observations around pavement clogging. The study concludes that most findings with results from the literature, and gives recommendations for future research.

2 - LITERATURE REVIEW

Increased urbanisation rates coupled with unsustainable stormwater practices have placed considerable pressure on the urban water cycle (Adewumi et al., 2010; Armitage et al., 2013). Internationally, various alternatives to the drainage efficiency approach have been implemented. One such approach which is seeing increasing use in South Africa is the Sustainable Drainage Systems, or SuDS approach (Armitage *et al.*, 2013). SuDS are structural and non-structural interventions which manage stormwater impacts by mimicking the natural hydrological cycle, often incorporating consecutive interventions to form a 'treatment train' (Jefferies *et al.*, 2008; Armitage *et al.*, 2013; Fletcher *et al.*, 2014a)

Permeable Pavement Systems (PPS) fall into the source control category of SuDS (Beecham *et al.*, 2012). Source controls aim to reduce runoff and pollutant loads that enter into the drainage system by on-site stormwater systems and practices (Barbosa *et al.*, 2012; Fletcher *et al.*, 2014a). PPS functionally replace asphalt and concrete surfaces, allowing water to infiltrate either into the groundwater, be stored for reuse or attenuated and released into the downstream drainage system. Primary benefits of permeable surfaces are runoff attenuation and pollutant retention, but may also include the retention of stormwater for potential reuse, increased groundwater recharge, increased surface grip during rainfall events and an overall reduction of the urban heat island effect (Scholz & Grabowiecki, 2007). Limited research has been undertaken on the performance of, and the harvesting of rainwater from PPS within a South African context, and little or no data is available on the maintenance requirements for PPS sites exposed to South African conditions.

2.1 Stormwater & Stormwater Management

As human development within the built environment seals off naturally pervious soils and removes vegetative cover that transpires water, runoff from rainfall increases dramatically. This increased runoff in urban areas poses a significant risk to human welfare, as local flooding presents a hazard to property and human health (Burns *et al.*, 2012). Stormwater also has significant adverse environmental impacts, the recognition of which has only come about in the latter 20th Century (Roy *et al.*, 2008). This section of the literature review will highlight the progression of stormwater management from a nuisance-based approach to the emerging integrated management paradigm.

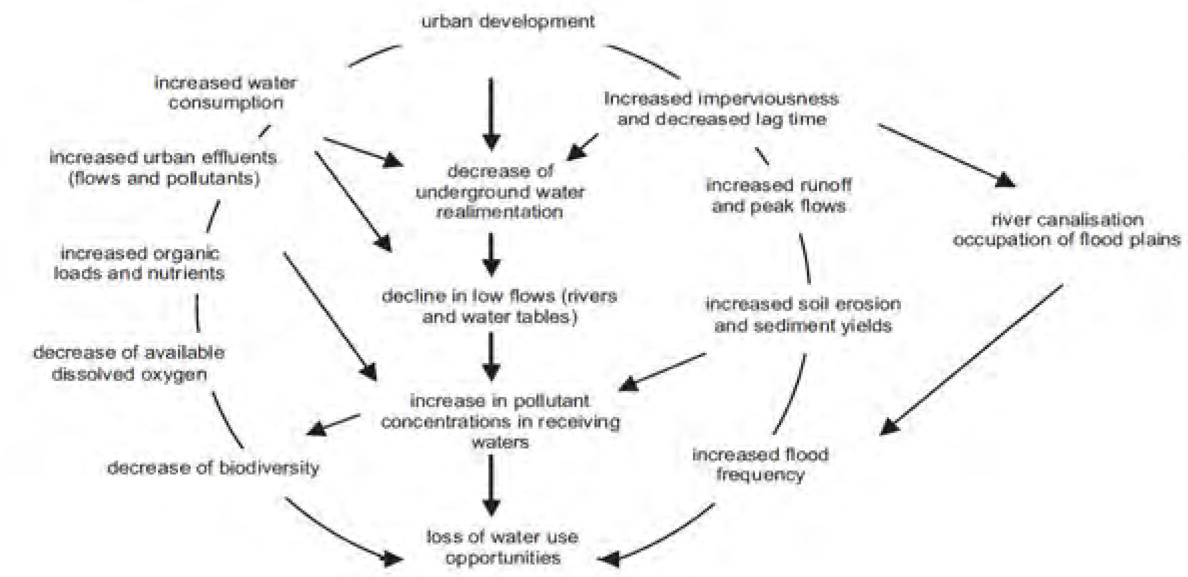


Figure 2-1: Effects of urbanisation on the water cycle (Chocat *et al.*, 2007)

Figure 2-1 summarises how urban development leads to negative impacts in the aquatic ecosystem, increased flood risks and loss of water use opportunities. SuDS processes are intended to mitigate all of the negative impacts by promoting natural hydrological processes.

2.1.1 Pre Development vs Post Development

Pre-development and post-development hydrology are two terms common in stormwater literature, and some clarification on these terms is warranted. Pre-development hydrology or flows describes a natural flow regime whereby rainfall infiltrates pervious soils and recharges groundwater; runoff only occurs when the amount of rainfall has exceeded the saturation point of the soil. A significant portion of water is lost due to evapotranspiration, driven by plant cover and soil characteristics. Water that infiltrates the soil recharges groundwater, which is slowly released into perennial river systems. Base flow in downstream aquatic ecosystems is maintained (Armitage *et al.*, 2013).

Post development hydrology is driven by an increased impermeable surface area and reduced vegetative cover. Runoff occurs once the surface area depression storage is filled, groundwater recharge is prevented and evapotranspiration is minimised. Most of the rainfall is converted into runoff, which is directed into nearby streams. These streams experience significantly magnified flow peaks which occur much faster after the start of rainfall due to reduced interception and storage. During dry seasons, a lower groundwater table results in significantly altered base flows (Shuster *et al.*, 2005; Burns *et al.*, 2012; Petrucci *et al.*, 2013).

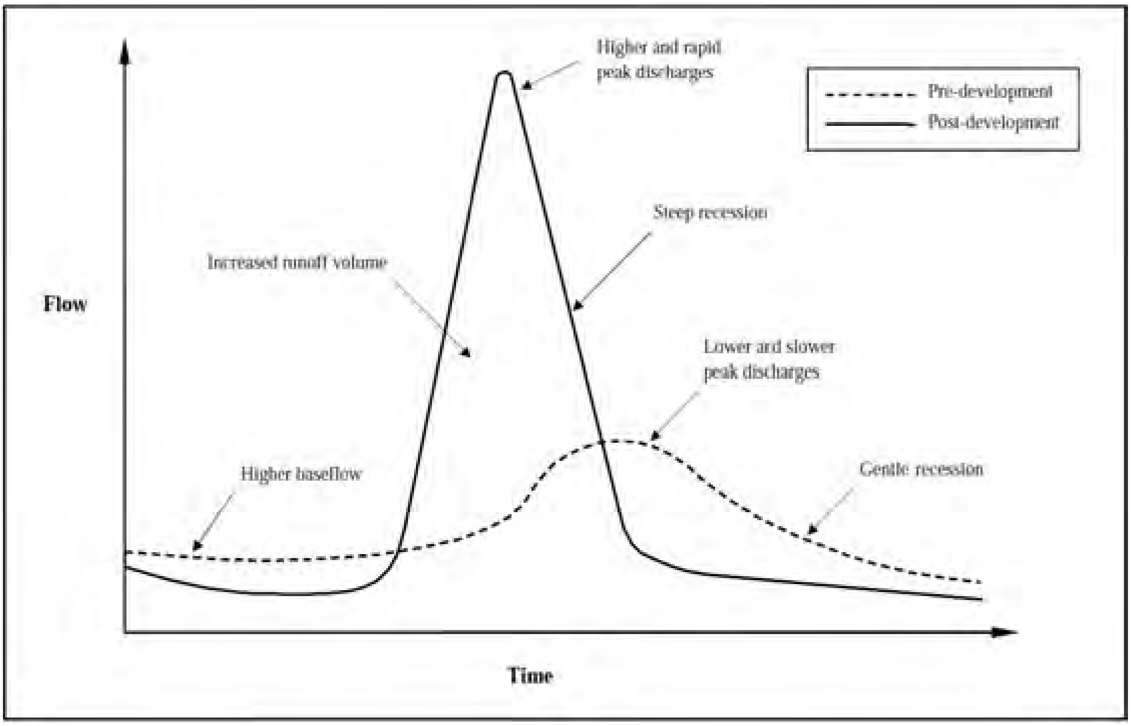


Figure 2-2: Typical hydrograph associated with pre- and post-development with the conventional approach to stormwater management (Armitage *et al.*, 2013)

2.1.2 Conventional drainage systems

Managing the stormwater risk has led to systems which prioritise the removal of stormwater from urban areas via hydraulically efficient conduits which discharge their effluent directly into nearby water bodies. These systems are termed ‘conventional’ stormwater management systems or ‘drainage-efficiency’ systems and promote flow efficiency from source to sink (Burns *et al.*, 2012; Armitage *et al.*, 2013).

There are inherent difficulties with the drainage-efficiency approach. Conventional systems are associated with high costs, significant modification of urban stream flow quantity, quality and pattern and an increased risk of downstream flooding due to increased flow quantity and peak flows (Walsh, 2000; Goonetilleke *et al.*, 2005; Burns *et al.*, 2012; Walsh *et al.*, 2012).

Furthermore, the drainage-efficiency approach does not provide opportunities for stormwater harvesting. In an environment where water security is increasingly concerning and alternative water sources are sought after, stormwater harvesting has the potential for increasing water supply for fit-for-purpose use and thereby reducing the strain on water supply networks (Mitchell *et al.*, 2006; Nnadi *et al.*, 2008; Beecham *et al.*, 2010; Petrucci *et al.*, 2012).

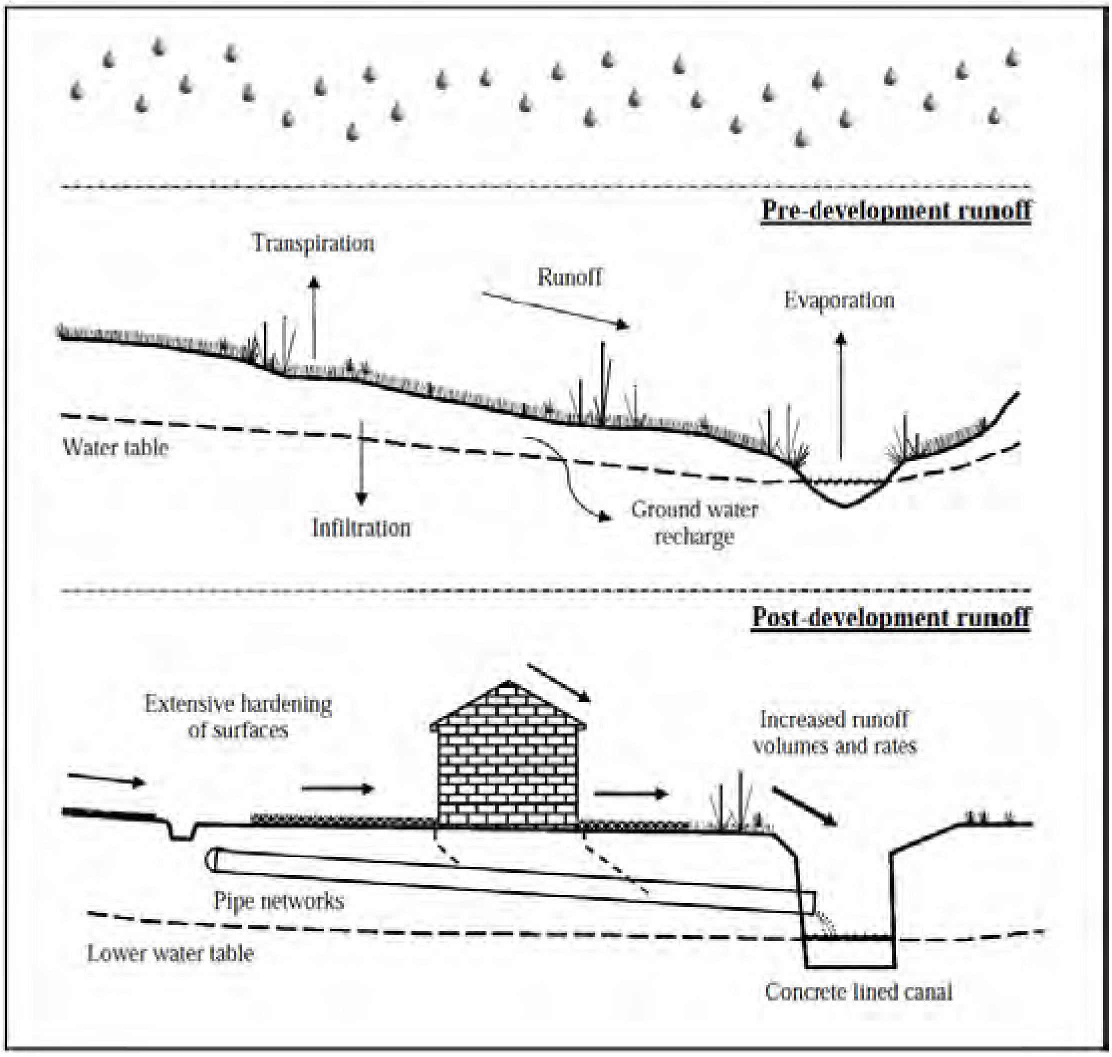


Figure 2-3: Typical pre- and post-development scenarios with the conventional approach to stormwater management (Armitage et al., 2013)

2.1.3 Stormwater pollution

Until the 1970s, stormwater pollution was not well understood. The fact that stormwater is inherently polluted due to wash-off from urban surfaces was masked by pollution via sewage contamination (Walsh, 2000). Indeed, stormwater contamination is a significant contributor to overall urban stream pollution. Stormwater runoff has been identified as the second biggest contributing factor to stream pollution in the USA (Paul & Meyer, 2001) and non-point source pollutants in stormwater may provide a more significant pollutant 'shock' than secondary treated wastewater (Taebi & Droste, 2004; Goonetilleke *et al.*, 2005).

Stormwater has also been associated with significant risks to human health. A study in the USA identified urban runoff as being responsible for 47% of pathogen contamination of Long Island Sound and Stormwater management was proposed as a cost-effective means of protecting human health (Gaffield *et al.*, 2003). Stormwater has been found to have an elevated level of faecal coliform indicators, to the point that it may be the primary source of bacterial contamination in surface waters (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).

Along with being a significant source of microbial contamination, stormwater also 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). Originating from a variety of sources, the final makeup depends largely on the type and intensity of land use.

Probably the most universal source of potential pollutants is atmospheric deposition. Dust, aerosols and gases settle to the ground according to their mass. Dry atmospheric deposition forms a layer on surfaces, to be washed away by rainfall. Deposition varies according to the atmospheric composition; furthermore, local wind patterns may create distinct spatial variation (Göbel *et al.*, 2007).

Paved areas and roads act as an important source for stormwater pollution. They are highly impervious, so accumulated pollutants are washed off readily. Further, the high vehicular activity results in the deposition of heavy metals, oil, grease and particulates. These are caused by road surface abrasion, brake pad abrasion, tyre abrasion, drip loss and corrosion, and vary with the type and intensity of vehicle activity, traffic technology and rainfall and deposition characteristics (Brown & Peake, 2006; Göbel *et al.*, 2007; Kim *et al.*, 2007; Berndtsson, 2014). Along with being a conduit for pollutions wash-off, pavements themselves may contribute to stormwater pollutant loadings by leaching chemicals (Bernot *et al.*, 2011).

Roof areas can act as a receiving surface for pollutants from atmospheric deposition, before they are washed off by rainfall. They can be sources of pollutants themselves, depending on the types of materials used. Metal roof surfaces corrode to contribute metal ions to urban runoff (Gnecco *et al.*, 2005), but this process depends on the roof type and rainfall pH. Where acidic rainfall is prevalent, corrosion from roof surfaces is increased. Organic materials from leaves, animal matter and lichens and/or moss may also contribute towards organic matter in runoff (Göbel *et al.*, 2007).

2.1.4 Impervious Areas and their impacts

Since impervious areas are the key cause of urban stream degradation, predicting ecological impacts by catchment impervious area is intuitive. Impervious areas not only provide increased runoff and easier pollutant wash-off patterns, but they also act as a hydraulically efficient conduit for transport. Ecological function begins to rapidly decrease above a certain percentage impervious cover within a catchment. The threshold is generally accepted at being around 10-15% and may be as low as 2% for some areas, depending on catchment characteristics (Paul & Meyer, 2001; Rushton, 2001; Bernot *et al.*, 2011; Walsh *et al.*, 2012). While Total Impervious Area (TIA) may be a good indicator of the extent of development, it does not accurately reflect the impacts of surface elements that are topologically isolated from the stormwater drainage system (Shuster *et al.*, 2005). However, as the topographical distance of runoff from source to sink increases so does the potential for attenuation. Storm water infrastructure which efficiently conveys runoff effectively bypasses the potential for attenuation essentially acts as a 'runoff (Walsh & Kunapo, 2009). This means that impermeable areas that are directly connected to storm water infrastructure have a more significant impact on streams-leading to the concept of directly connected impermeability (DCI) or effective impermeability (EI). DCI has been found to be a reliable predictor of stream ecology impacts, especially for impacts on invertebrate (Hatt *et al.*, 2004; Walsh & Kunapo, 2009; Urrutiaguer *et al.*, 2012). In order to mitigate these impacts, recommendations for mitigation are the reduction of DCI via drainage disconnection (Urrutiaguer *et al.*, 2012) and storm water interception and storage (Hatt *et al.*, 2004). Reduction in DCI has been considered an efficient method for addressing both stormwater quality and quantity issues. Walsh (2000) argues that the conduits transporting pollutants are ultimately more detrimental than the source, and that drainage disconnection is a most effective method of reducing the ecological impacts of stormwater.

T.D. Fletcher *et al.* (2014) argue further that a focus on simple peak flow reduction results in large end-of-catchment management strategies which are insufficient to address ecological needs. They advocate an ecohydrological approach which considers the importance of the entire flow regime rather than a single dimension of it. For example, maintaining low flows and base flow of adequate quantity and quality is vital in the maintenance of ecosystem function (Hamel *et al.*, 2013).

2.1.5 The 'Stormwater Management Dilemma'

Goonetilleke *et al.* (2005) refer to a 'Stormwater Management Dilemma' which makes managing stormwater pollution inherently challenging. Whereas most authorities can effectively manage point-source pollution from wastewater treatment works or other single discharge points by monitoring, regulating and clearly identifying responsible parties or individuals, stormwater pollution is largely diffuse (Barbosa *et al.*, 2012). Due to the topographical and temporal uncertainties around concentrations and flows, pollutant loads can be difficult to estimate and extremely challenging to regulate as responsible individuals or parties cannot be identified. The variable loads, and often even the uncertain pollutant makeup of stormwater is also a challenge for management systems.

These factors combined make an argument against typical 'end-of-pipe' solutions where stormwater is treated directly before discharge into river systems, as upscaling estimates of pollutant loads from site to catchment scale increases the inherent uncertainty around the resulting stormwater pollutant loads and concentrations (Goonetilleke *et al.*, 2005).

2.1.6 Temporal Variability: The 'First Flush'

'First flush' refers to the phenomenon by which the first portion of stormwater from a rainfall event is significantly more polluted than the remainder. It enjoys a significant presence in the literature, but remains a fairly controversial topic. There are a multitude of varying definitions and methods for measuring the first flush. Furthermore, it seems to exhibit significantly different characteristics depending on the system under observation (Deletic, 1998)

Different methods of measuring and quantifying the first flush effect have attributed strongly to the controversy around the topic (Deletic, 1998). A commonly used variant involves calculating the cumulative pollutant load and cumulative runoff volume curves. If that curve (with cumulative pollutant load on the Y-axis) exceeds the bisector (45°), then the first flush effect is present. The degree of divergence between the curve and the bisector is then a measure of quantification of the effect (Bertrand-Krajewski *et al.*, 1998; Deletic, 1998; Lee *et al.*, 2002). More restrictive criteria were proposed by Saget *et al.* (1995) in Deletic (1998), where the first flush was defined as carrying 80% of the total pollutant load in 30% of the total runoff. However, it was found that such events were exceedingly rare (Gnecco *et al.*, 2005). Other researchers have defined the first flush simply as the relative pollutant load delivered by a set proportion of the runoff (e.g. portion of pollutant load carried by 20% of the runoff (Deletic, 1998)).

The first-flush concept is of obvious interest, as it influences the design of detention ponds and other runoff management methods (Bertrand-Krajewski *et al.*, 1998; Deletic, 1998). However, it appears to be a phenomenon with highly localised dynamics. The phenomenon may vary in significance due to catchment characteristics, but also display differential dynamics depending on the pollutant in question (Lee *et al.*, 2002).

2.1.6.1 First flush informing management

The first flush has been identified as a useful topic in storm water management, as it may influence the design of pollutant mitigation interventions. Most of the older studies focussed around using first flush characteristics to inform the design of retention basins. Bertrand-Krajewski *et al.* (1998) advocate the use of cumulative mass curves as they offer the advantage of elucidating a) the proportion of rainwater that should be intercepted and b) the timing at which said proportion occurs.

However, there is a problem with predicting the first flush effect by meteorological and catchment characteristics. For instance, Gupta & Saul (1995) suggested that first flush could be predicted using storm duration, peak inflow of the storm and the Antecedent Dry Weather Period. In a study of two catchments with similar catchment characteristics, Deletic (1998) found no reliable predictors for first flush. Gnecco *et al.* (2005) studied heavy metal concentrations in first flush due to rooftop contamination, and found the only good correlation of first flush to be maximum rainfall intensity. They found that 70% of rainfall events carried a strong first flush signature, supporting the concept of first flush for heavy metals.

Chinese researchers took a slightly different approach, and attempted to discern how much of the total pollution load would be captured in the first 30% of rainfall runoff (FF_{30}), for each of the studied pollutant types (Li *et al.*, 2007). They determined that FF_{30} contained 52.2% - 72.1% of total suspended solids, 53.0%-65.3% of chemical oxygen demand, 40.4%-50.6% of total nitrogen and 45.8%-63.2% of total phosphorous. Unfortunately, this study was conducted in only one catchment, and therefore the hierarchies cannot be generally applied.

Similarly, Korean researchers have found significant first flush signatures emerging from highways and bridges, specifically for oils and grease (Kim *et al.*, 2005, 2007). There have been several publications from Korea and China dealing with the first flush from single sources. Consistently, the first flush has been observed in these situations. Unfortunately, there is a dearth of literature on *in-stream* observations of the first flush effect.

While the concept of the first flush at a catchment scale is still under debate, there is considerable evidence for first flush at a single land-use scale (e.g. Kim *et al.*, 2005; *Kim et* al., 2007; Lee *et al,.* 2002; Berndtsson 2014). Therefore, on-site retention and treatment that is designed to remove the initial portion of flow should be more effective than similar interventions at a catchment scale.

2.1.7 Reporting Stormwater Pollution: EMCs & TMDL

There are two main ways in which stormwater pollution is measured, and the most prominent of those is the pollutant event mean concentration (EMC). This is the aggregate of the mass emissions divided by the total volume discharged throughout the rainfall event (Brezonik & Stadelmann, 2002; Taebi & Droste, 2004; Gnecco *et al.*, 2005; Kim *et al.*, 2007; Maniquiz *et al.*, 2010). The other applicable method is by using total pollution, which is the total mass emission of a pollutant throughout the rainfall event (Li *et al.*, 2007). The advantage of the latter is that it gives a more absolute picture of how much a potential source is contributing towards pollution in receiving waters. It also allows for the implementation of the Total Maximum Daily Load (TMDL), a regulatory threshold which limits the amount of total pollution that may be discharged (Roux *et al.*, 1999; Kim *et al.*, 2007).

2.1.8 Factors affecting EMC/loading

The main factors that seem to drive EMC have been identified as total precipitation, intensity and drainage area (Brezonik & Stadelmann, 2002; Kim *et al.*, 2007; Maniquiz *et al.*, 2010). EMCs were found to react to rainfall characteristics in a pollutant-specific manner, which is likely linked to the varied forms of pollutant generation (Brezonik & Stadelmann, 2002; Gnecco *et al.*, 2005). Pollutant EMCs were found to correlate weakly with Antecedent Dry Weather Period (ADWP) in two studies, which support the notion that longer dry weather periods allow for the building up of pollutants over time (Brezonik & Stadelmann, 2002; Kim *et al.*, 2007).

Furthermore, attempts at modelling EMC have revealed that site and event characteristics cause high uncertainty, thus suggesting that rainfall and catchment characteristics cannot be used as accurate universal predictors (Maniquiz *et al.*, 2010).

2.1.9 The Evolution of Stormwater Management

Roy *et al*. (2009) succinctly describe the evolution of stormwater management in Australia and the USA. Stormwater management practices have evolved separately in different geographical regions. In the USA and many parts of Europe, it was common practice to combine stormwater and sewer networks. This permits smaller rainfall events to be treated by sewage treatment works. However, larger rainfall events exceed the capacity of combined systems, leading to so-called Combined Sewer Overflows (CSOs) which discharge a mixture of raw sewage and stormwater into receiving water bodies. This phenomenon is often attributed to the misconception that stormwater pollution was due to CSOs alone, and that stormwater itself is not inherently polluted.

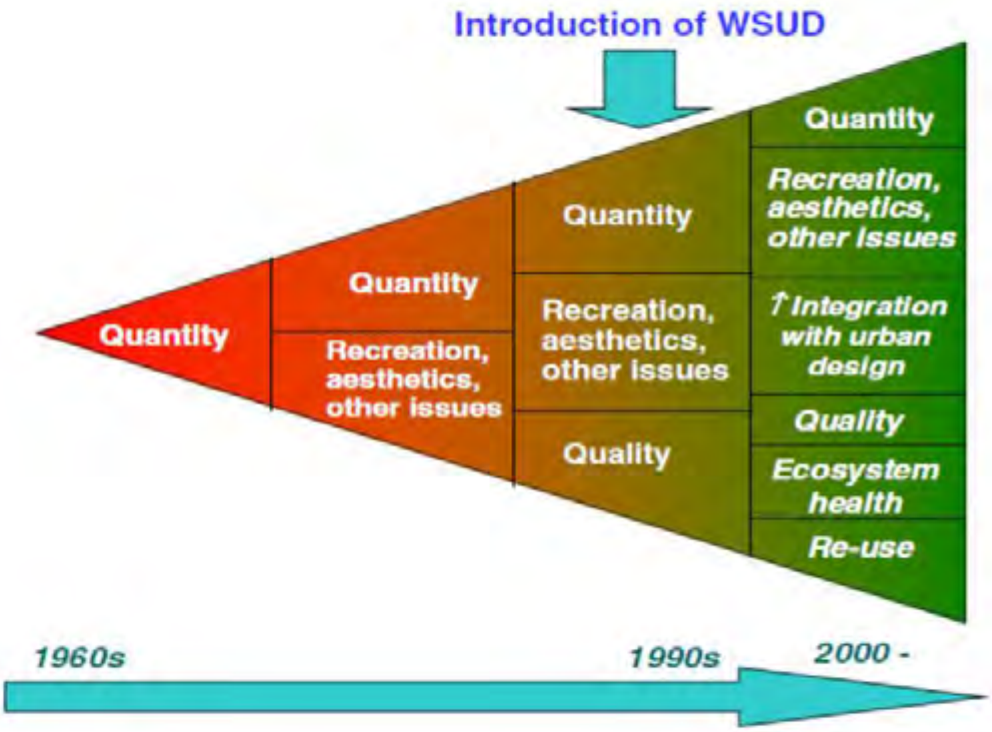


Figure 2-4: The evolution of the stormwater paradigm (Roy *et al*., 2009)

Figure 2-4: The evolution of the stormwater paradigm (Roy *et al*., 2009) shows how stormwater management evolved from a focus on only quantity management to managing multiple stormwater impacts. The movement from impact management to holistic, integrated management is seen with the introduction of WSUD.

2.2 Implementing the new Paradigm: LIDs, SUDS, BMPs and others

The previous section outlined the negative impacts of conventional stormwater management, as well as some of the difficulties inherent in managing stormwater and stormwater pollution due to the inherent uncertainties caused by temporal and spatial variation. This section will give a background on SuDS and related concepts, and describe how these systems address these concerns in a holistic manner.

Fletcher *et al. (*2014a) cover the evolution of terminology such as LIDs, WSUD, SuDS, BMPs and others. Many of these terms are extremely similar, with slightly differing connotations and different countries of origin. The explanations are summarized below, in accordance with Fletcher *et al. (*2014a).

- 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 not a paradigm exclusive to water management (Fletcher *et al.*, 2014a).
- SuDS or SUDS (Sustainable Drainage Systems/Sustainable Urban Drainage Systems) are terms that have arisen in the UK, and refer to structural and non-structural interventions 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 flow management principles of LID are implicit in SUDS, which are designed for infiltration, attenuation and (Tota Maharaj *et al.*, 2009) and SUDS are often designed as a series of technologies which act together as a 'treatment train'.
- BMPs (Best Management Practices) is a term commonly used in North America and refers to such practices or interventions (structural and non-structural) 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) and Integrated Urban Water Management (IUWM) are both overarching paradigms with aims and objectives related to the sustainable use and management of water resources in the urban context. These frameworks inform design and management principles, and provide guidelines and direction for other principles (such as SUDS) to operate holistically.

Most of the remainder of this literature review will focus on the implementation of SUDS in order to accomplish stormwater management objectives. SuDS and LID as terminologies will be used interchangeably where applicable, as the use of terminology is often more due to the geographical origin of the author than any conceptual differences. Most of the remaining paper will use the term SuDS instead of LIDs, as that is the prevalent terminology in the South African WSUD guidelines and policies.

2.3 SUDS

2.3.1 Overview of Sustainable Drainage Systems (SuDS)

SuDS increase natural drainage processes through the development of several unit processes (Armitage *et al.*, 2013); i.e. the effective management of stormwater runoff quantity (flow and volume); water quality; and the associated amenity and biodiversity of the urban drainage system.

SuDS are structural and non-structural interventions designed to recreate natural hydrological patterns while facilitating pollutant reduction for receiving waters. 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 categories (Heal *et al.*, 2004; Armitage *et al.*, 2013):

Good Housekeeping refers to practices that minimize the release of pollutants to the environment where they are available for transport by stormwater.

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 permeable pavements and soakaways) and harvesting type systems which divert stormwater for eventual reuse (such as rain harvesting) (Hamel & Fletcher, 2014).

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.

Regional Controls are larger controls which manage the runoff from an entire catchment, such as constructed wetlands or retention ponds.

.All of the structural innovations (2-3 above) are designed for treatment via flow infiltration or retention, or a combination of the two. Note that there is some confusion around the definition 'source control'. Source control is in some cases used to describe a catchment-wide strategy as opposed to a specific infrastructure (Petrucci *et al.*, 2013). For the purpose of this paper, source controls will refer to such infrastructure or design alterations which form a part of a SUDS treatment train at the runoff source.

SUDS are designed to achieve a number of goals within the WSUD framework (Fletcher *et al.*, 2014a), without compromising the primary performance criteria of the SUDS device (Armitage *et al.*, 2013).

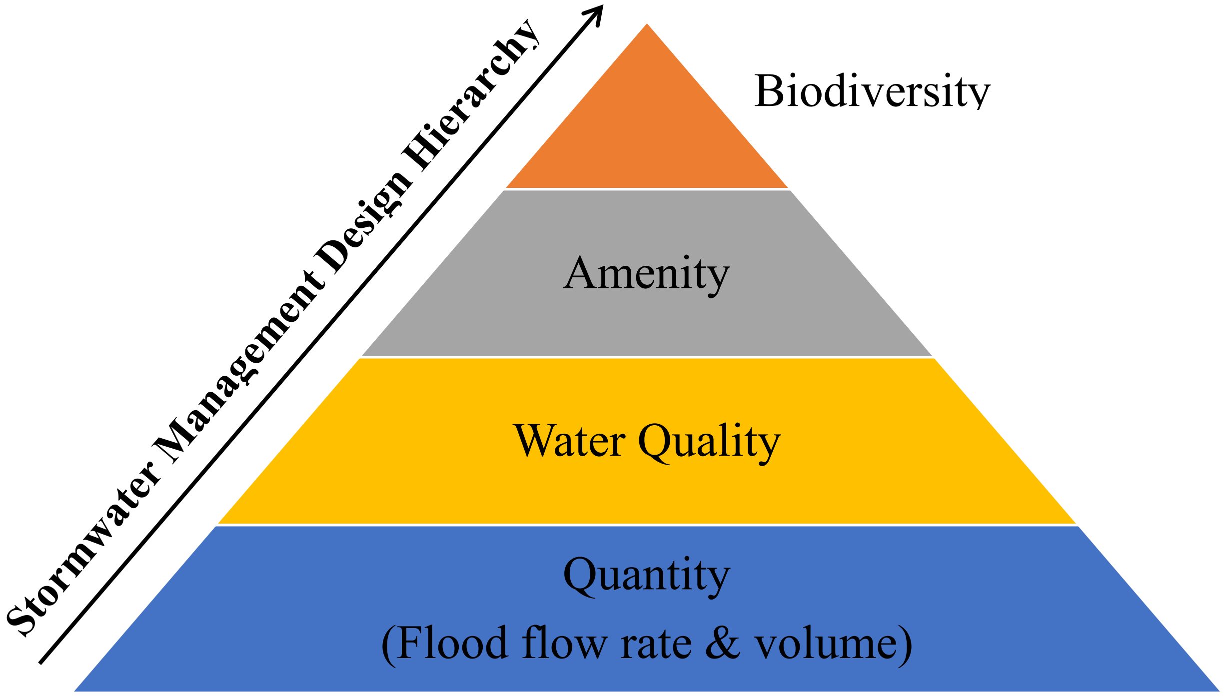


Figure 2-5: The Stormwater Design Hierarchy (Armitage et al., 2013)

The design hierarchy in Fig.2 above suggests that SUDS must, above all, be designed in order to meet flow criteria, and then water quality. The top two tiers can be considered ‘lateral benefits’, especially as Biodiversity refers to on-site biodiversity and not biodiversity benefits attained from any downstream restoration, rehabilitation or conservation of aquatic habitats due to SUDS-related stormwater management.

2.3.2 Source Control Strategies

Source control, also known as dispersed or decentralized stormwater measures, aims 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 decentralized form of SUDS implementation has numerous benefits for both water quality and flow management.

2.3.3 Source Control and Water Quality

Managing stormwater quality is inherently problematic, as most pollutant sources are diffuse in topography and temporally highly variable (Goonetilleke *et al.*, 2005; Barbosa *et al.*, 2012). Pollutant loadings and concentrations can vary considerably even within a single storm event, making management extremely difficult. Pollutant management via source control is a popular concept as they deal with pollutants at the source. As pollutant generation is highly site specific, this allows for the site specific design to target particular pollutants and pollutant loads as opposed to a generic system which has to deal with a wide and uncertain range of inputs.

2.3.4 Source Control and Flow

Like all SuDS, source controls try to mimic natural hydrology patterns. Infiltration-oriented systems do so by simulating natural soil infiltration and, in some cases, permitting infiltration 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). Source control measures with an aim to stormwater harvesting can also 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 has shown that source control techniques, when flow timing is not considered, can actually increase runoff peaks at a catchment scale due the superposition of peak flows (Petrucci *et al.*, 2013). Furthermore, they can significantly disturb downstream low-flows if source controls are not designed in a catchment-integrated manner.

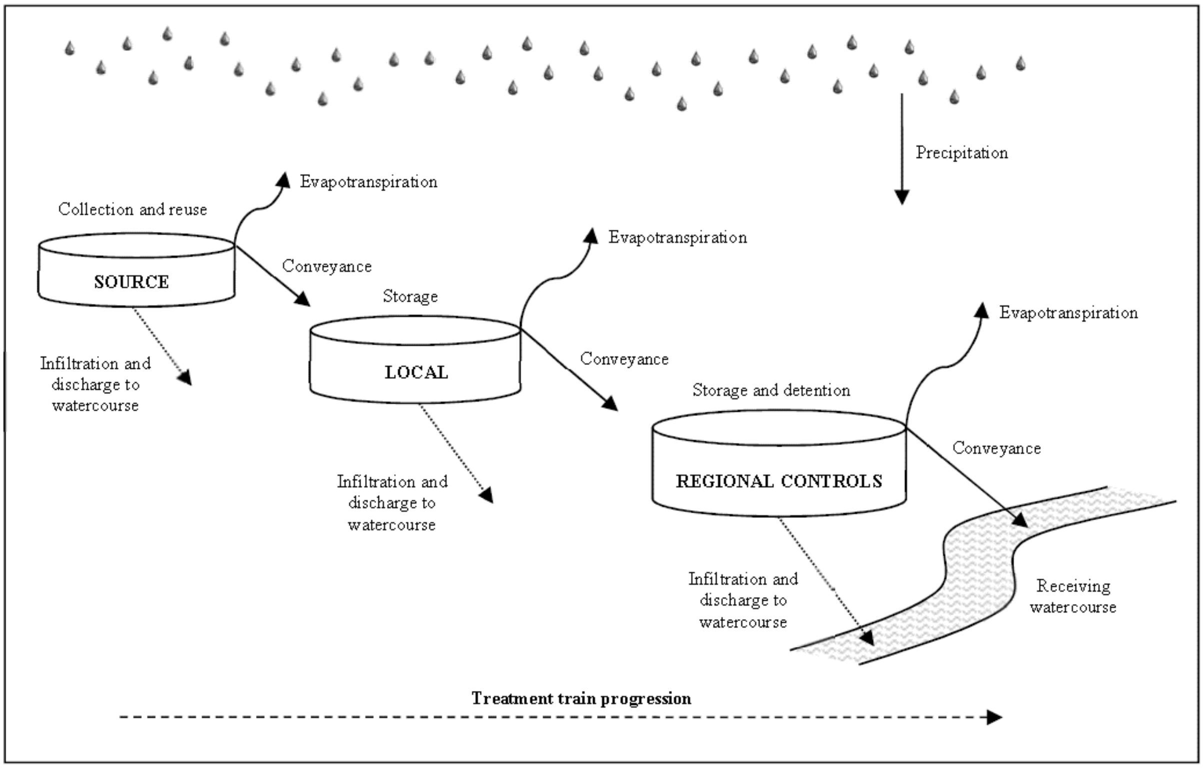


Figure 2-9: The SuDS treatment-train (Woods-Ballard *et al.*, 2007)

2.3.5 SuDS in Cape Town

The City of Cape Town has several examples of SuDS implementations which are better addressed by Armitage *et al.* (2013). However, below is a summary of policies and guidelines released by the City of Cape Town and related researchers which promote and guide the use of SuDS:

- **Stormwater Management Planning and Design Guidelines for New Developments & Catchment, Stormwater & River Management Strategy, 2002:** The former represented an approach to integrated strategy and decision making, while the latter was a set of concrete guidelines to stormwater management which incorporated SuDS principles of mimicking natural flow patterns for the protection of receiving river ecologies (Haskins, 2012).

- **Green Building Guidelines, 2005/6** (Inca Concrete Products, n.d.)**:** The green building guidelines suggest on-site stormwater treatment methods such as permeable pavements or swales, both for attenuation and treatment and stormwater reuse.
- **Stormwater By-Law, 2005:** This by-law mainly served to protect stormwater management systems, and specifically prohibited the discharge of anything other than stormwater into the system. It regulates against tampering and interference with stormwater systems, even where these are on private property. While it does specifically regulate against pollution incidents on private property, it does not set any quality standards for stormwater discharge.
- **Management of Stormwater Impacts Policy, 2009:** This policy recognised that the Stormwater Management Planning and Design Guidelines were generally adhered to with regards to peak flow reduction, but failed to mitigate other impacts to receiving rivers (City of Cape Town, 2009). This policy specifically called for the implementation of SuDS in new developments as well as retrofitting existing sites, and gave some rudimentary guidelines to the percentage reduction of phosphate and total suspended solids that should be achieved by the implementation of the SuDS.
- **South African SuDS Guidelines, 2013:** This is a set of guidelines compiled by Armitage *et al*, (2013) and represents an expansive literature study. The guidelines are aimed at practitioners seeking to implement SuDS, and do not focus extensively on efficacy.

2.4 Permeable pavement systems (PPS)

Pervious surfaces are often used as a form of a SUDS treatment train for pollution and flow control. As they generally achieve on-site stormwater management objectives, they fall into the source control category of SuDS (Beecham *et al.*, 2012). There are two broad categories of pervious surfaces, pervious concrete and permeable pavement surfaces (PPS). Pervious concrete is a carefully created concrete mixture with little or no sand that creates substantial void spaces, typically between 15-20%. This mixture is poured over a pervious subgrade consisting of grit or gravel, which allows water to infiltrate (Tennis *et al.*, 2004). The focus of this study are Permeable Pavement Surfaces (PPS), which consist of a surface layer of interlocking pavement slabs laid over a bedding medium and an aggregate base course (Fassman & Blackbourn, 2010). Common applications of PPS are as a replacement for normal pavement, where vehicular load is expected to be fairly low (i.e. parking lots, driveways, road shoulders, bicycle & pedestrian paths etc.) (Scholz & Grabowiecki, 2007). PPS attenuate runoff and treat stormwater pollutants, and additional benefits 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, PPS are now widely considered as sustainable substitutes for conventional impervious surfaces (Beecham *et al.,* 2012). Most PPS implementations can be found in car parks (Scholz & Grabowiecki, 2007; Beecham *et al.*, 2012; Scholz, 2013; Revitt *et al.*, 2014).

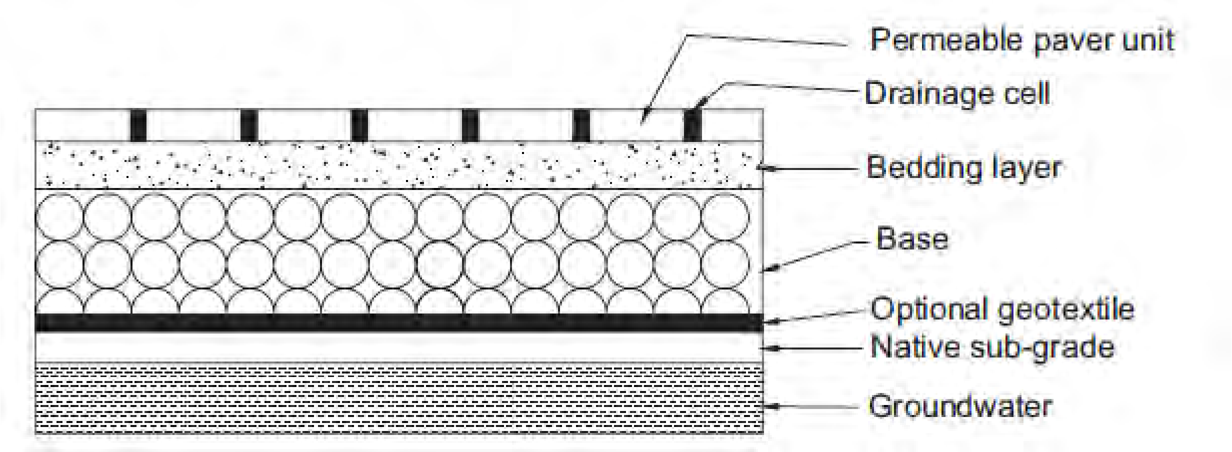


Figure 2-10: Schematic of a typical Permeable Pavement (Scholz & Grabowiecki, 2007)

2.4.1 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 or grit with a high voids ratio (James & Von Langsdorff, 2003). Joints between the pavers act as voids to allow water to seep through the surface, or the 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). Drake *et al* list 10 different types of PPS surface materials, each with different environmental, aesthetic and cost requirements. Paver choice will also be significantly influenced by traffic characteristics (Shackel, 2006). The most commonly found form in South Africa are permeable concrete block pavers with open joints (Armitage *et al.*, 2013).

2.4.1.1 Bedding Layer

The bedding layer is typically 200-250 mm thick, and consists of 2-5mm aggregate which has been found to be the best compromise between high water infiltration and structural performance (Shackel, 2006; Imran *et al.*, 2013; Nichols *et al.*, 2014). This aggregate can also be used for jointing pavers, therefore simplifying construction.

2.4.1.2 Base Layer

The base of a PPS consists of one or multiple layers of coarser aggregate. The lower base layers generally comprise larger (10-70mm) and the upper layer smaller (5-20mm) stone sizes (Shackel, 2006; Woods-Ballard *et al.*, 2007). Base and sub-base materials must possess: adequate water storage capacity; the ability to effectively drain water without migration of fine materials; adequate stiffness to carry the full spectrum of traffic loads and sufficient pollutant removal capacity. Additionally, where geotextile fabrics are undesirable, the materials must have characteristics that prevent movement of fines between the bedding and base layers (Shackel, 2006). Various materials can be incorporated into aggregate, from traditional coarse stone to mixtures of recycled concrete and organic matter (Bentarzi *et al.*, 2013).

The thickness and structure of the base layer depends on design characteristics such as cost, height of the water table, frequency of rainfall, volume of stormwater to be detained, permeability of sub-grade and downstream drainage considerations (James & Von Langsdorff, 2003).

2.4.1.3 Subgrade

While exfiltration of water to the subgrade yields significant performance and lateral benefits due to stormwater volume reduction, increased peak flow reduction, groundwater recharge and improved nutrient reduction (Scholz & Grabowiecki, 2007), there are scenarios where exfiltration to the subgrade is either undesirable or impractical. These are generally where water tables are high, soils are impermeable or groundwater contamination is a concern. In these cases, an optional impermeable liner serves to seal off the subgrade and prevent infiltration into soils (Scholz & Grabowiecki, 2007; Drake *et al.*, 2013). Another reason to seal off the subgrade is if the treated stormwater from PPS is to be harvested and re-used.

2.4.1.4 Optional Underdrain

In cases where the subgrade is impermeable, or insufficiently permeable, an underdrain may be installed to discharge treated stormwater into the downstream drainage system (Scholz, 2013). The invert elevation of the underdrain, as well as it's sizing will affect the amount of storage in the PPS and the discharge rate; changing these parameters will have an impact on how closely the hydrological characteristics of the resulting PPS resemble pre-development flow conditions (Fassman & Blackbourn, 2010; Walsh *et al.*, 2012; Drake *et al.*, 2013). However the presence of an underdrain will negatively impact the nitrogen removal capacity (Scholz & Grabowiecki, 2007).

2.4.1.5 Geotextile

The geotextile membrane prevents, *inter alia,* the migration of fines between base and sub-grade layers (Yong & Deletic, 2008) and has been shown to improve the pollutant removal efficacy of the system in some studies (Tota-Maharaj *et al.*, 2012; Nnadi *et al.*, 2014). It has been particularly associated with the removal of hydrocarbons, as it facilitates the formation of a bioslime layer (Newman *et al.*, 2006).

2.4.1.6 Slope

PPS are usually designed with a maximum slope of 5% (Lucke & Beecham, 2011). The reasons for this however, are rarely explained in research results. 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 maybe 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.*, 1996) and even 20% (Lucke & Beecham, 2011) suggesting a design slope guideline of 5% may be overly conservative.

2.4.2 Hydraulic and hydrological features

Outflow attenuation to the drainage system occurs through PPS by wetting, pore space storage in the base course and a hydraulically inefficient flow path through the layers, while exfiltration into the subgrade provides flow volume reduction (Fassman & Blackbourn, 2010). While Fassman & Blackbourn (2010) suggest that most PPS systems receive and treat only flow that is received by that particular installation, Beecham *et al. (*2010) argue that due to their significant capacity, only a fraction of an installation should be PPS, with the remainder being impermeable surfaces designed to drain water into the PPS.

Like with many other SUDS/LID source control implementations, a big concern for permeable pavement is clogging of the surface layer (Fassman & Blackbourn, 2010); as such, they are considered to be better suited in areas with low sediment generation (Beecham *et al.*, 2012; Armitage *et al.*, 2013; Drake *et al.*, 2013). The general impact of clogging is highly dependent on permeable pavement design (filter media size, presence/absence of geotextile, paver), cumulative runoff, flow rate, maintenance history, sediment load and particle size distribution (Beecham *et al.*, 2009; Yong *et al.*, 2013; Nichols *et al.*, 2014). While there is a dearth of studies investigating PPS older than 12 years, research on infiltration rates of mature PPS (up to 12 years) suggest that these remain mostly acceptable despite age and that even clogged PPS permit a significant amount of infiltration (González-Angullo *et al.*, 2008; Boogaard *et al.*, 2014). Furthermore, laboratory simulations have suggested that PPS may continue operating effectively after more than 15 or 20 years with minimal maintenance (Yong & Deletic, 2008; Aryal & Beecham, 2014) and studies show that a PPS can perform sufficiently until 90% of the surface is clogged (Scholz & Grabowiecki, 2007).

There is variability in terms of the extent of clogging to the point that many PPS display differential infiltration rates within one installation. Authors generally agree that ensuring good long-term infiltration performance requires good construction techniques, careful design and paver selection as well as regular maintenance (Scholz & Grabowiecki, 2007; Beecham *et al.*, 2009; Yong *et al.*, 2013; Nichols *et al.*, 2014). For PPS treating run-on from impermeable surfaces, clogging tends to occur from the outer edge inward (Beecham *et al.*, 2009; Al-Rubaei *et al.*, 2014) as suspended solids are washed onto the PPS.

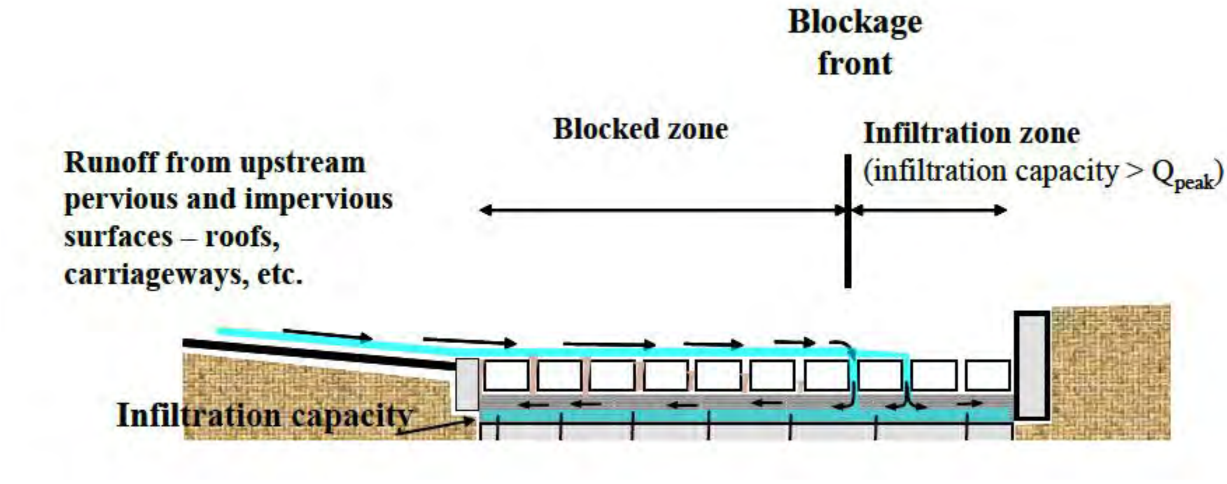


Figure 2-6: Concept of a Clogging Front (Beecham et al., 2010)

2.4.2.1 Performance

Permeable pavements have inherently high potential for hydrological benefits, and hydrological performance is a prominent theme in the literature (Drake *et al.*, 2013). Hydrological performance implicitly refers to the systems' potential for reducing surface runoff and peak stormwater flows (Andersen *et al.*, 1999; Abbot & Comino-Mateos, 2003; Dietz, 2007; Drake *et al.*, 2013). Runoff infiltrating into the pavement is retained within the voids of the subgrade. In fact, for small rainfall events, PPS may have sufficient storage to retain the entire event (Andersen *et al.*, 1999). The technology has proven to be extremely effective in reducing surface runoff; an investigation undertaken on a PPS in Sydney shows a steep decline in the runoff coefficient post construction of the permeable pavement, effectively reducing the catchment imperviousness from 45% to 5% (Ball & Rankin, 2010). The same study suggested that rainfall intensities greater than 20mm/hr were required to generate surface runoff.

Overall runoff reduction refers to the reduction of flows from a drainage area to the drainage system affected by the implementation of SuDS in this area. Permeable pavements have been shown to reduce total flow volumes from between 24% and 93%, while consistently achieving peak flow reductions of more than 30%; sometimes as high as 80% (Rushton, 2001; Abbot & Comino-Mateos, 2003; Drake *et al.*, 2013). These measurements range widely due to variable designs, environmental conditions and the lack of a unified measuring metric, and should be seen qualitatively rather than as an absolute performance metric.

Attenuation of flows is achieved by the temporary storage of stormwater within the permeable pavement structure. These flows are released slowly when the storage is at capacity, resulting in a timing lag of peak flows. Time lags are highly variable and depend on the storm and design characteristics. The longest reported peak flow lag was 57.5 hours, although lags in the order of one hour seem to be more common(Drake *et al.*, 2013). Concomitantly, PPS will also increase the duration of flows; Abbot & Comino-Mateos (2003) reported that a two hour event may require two days to drain out of the system.

The hydrological performance of PPS varies widely with different environmental and design considerations. Typically, PPS tend to be more efficient at flow attenuation and peak flow reduction for smaller storm events, losing some efficiency in storms with high rainfall intensities and saturated soil conditions (Andersen *et al.*, 1999; Rushton, 2001)..

2.4.2.2 Maintenance

Frequent inspection and maintenance are recommended for ensuring the long-term effectiveness of PPS (Legret *et al.*, 1996; Yong & Deletic, 2008).. A number of studies have investigated possible methods of periodically removing the crust material from the pore space of permeable pavement installations e.g. Balades *et al.* (1995) and Pratt *et al.* (1995). One possible method is washing with water at high pressure, using a man-operated portable or vehicle-mounted pressure-washing unit. Other typical maintenance includes vacuum sweeping of the surface every three months (Woods-Ballard *et al.*, 2007; Armitage *et al.*, 2013) and sweeping with ordinary brooms. In the event of pavement failure across a PPS, Woods-Ballard *et al.* (2007) suggest removing surface layering, bedding layer and geotextiles as well as removing and washing the sub-base, if required.

User concerns around clogging and maintenance are cited as one the limiting factors of more widespread SuDS uptake (Heal *et al.*, 2009). However, SuDS have been cited as having lower maintenance costs than traditional drainage systems (Heal *et al.*, 2009; Houle *et al.*, 2013). This may not relate directly to PPS, however.

2.4.3 Drivers of Pollutant Removal

The main form of pollution reduction in PPS is by physical removal of material via filtration and sedimentation (Balades *et al.*, 1995). This affects reduction of Total Suspended Solids (TSS) and heavy metals, which are often adsorbed to TSS particles; most of these pollutants are stored in the top layers and at the geotextile layer (Legret *et al.*, 1996; Mullaney *et al.*, 2011).

Sedimentation occurs throughout the pavement, at various rates depending on the hydraulic characteristics of the medium. As sedimentation progresses, smaller particles may adsorb to the deposited sediment (Minton, 2002). This postulate would suggest that pollutant removal capacity increases with time.

Apart from filtration, which only treats TSS and adsorbed pollutants, PPS also promulgate a microbial diversity which is capable of significant hydrocarbon removal (Coupe *et al.*, 2003; Newman *et al.*, 2006). Biofilm generation is improved by the presence of a geotextile layer, which traps oils and provides a substrate for microbial community development, whereby natural occurring microbial diversity outlasts targeted inoculation attempts (Coupe *et al.*, 2003). Studies have shown that hydrocarbons trapped on geotextiles provide a food source for aerobic bacteria and fungi, converting the hydrocarbons into sugars for growth and carbon dioxide (Newman *et al.*, 2006).

2.4.4 Pollutant removal capacity in literature

PPS have often been credited with significant pollutant removal capacity. A significant focus in research has been the removal of heavy metals and oils, both of which is typically very high (Balades *et al.*, 1995; Pagotto *et al.*, 2000; Brattebo & Booth, 2003; Fach & Geiger, 2005). Most heavy metals are retained in the top layers of the PPS, where they remained adsorbed to particulates. Studies have shown reductions of heavy metals up to >90%, although ~80% is more typical (Rushton, 2001; Scholz & Grabowiecki, 2007; Scholz, 2013). While some hydrocarbons such as petrol and diesel fuel have been found to have removed completely, motor oil removal has also been consistently high at >90% (Brattebo & Booth, 2003; Scholz & Grabowiecki, 2007). TSS removal varies from 37% to 94% (Beecham *et al.*, 2012; Drake *et al.*, 2013).

Nutrient removal rates are varied, and difficult to summarize due to different reporting forms for different nitrogen species. However, studies suggest pollutant removal rates of >80% for ammonia, >50% for total nitrogen and >70% for orthophosphate (Tota-Maharaj & Scholz, 2010; Beecham *et al.*, 2012). Furthermore, Tota-Maharaj & Scholz (2010) found that removal of key microbial indicators was >99%.

It should be noted that all the figures above refer to 'removal' as a 'reduction in concentration'. Therefore, if pollutant removal is considered from a Total Maximum Daily Load (TMDL) perspective, the reduction of outflow in combination with the reduction of pollutant concentrations would lead to a significant reduction in pollutant loading (Tennis *et al.*, 2004).

2.4.5 Stormwater Harvesting

Stormwater harvesting is an increasingly popular water source alternative. While stormwater harvesting systems have been designed before, the concept has only recently developed into an integrated approach with stormwater management (Goonrey *et al.*, 2009). Use of stormwater for irrigation is not a new concept, and an investigation of stormwater quality in the Maltese Islands showed promising results for stormwater reuse (Gatt & Farrugia, 2012). Stormwater harvesting by the use of rainfall tanks is a long-standing practice which can reduce water demand, but can also exhibit catchment-wide volume reduction and flow attenuation (Mitchell *et al.*, 2006).

In the past years, the possibility of using permeable pavements as integrated treatment and harvesting systems has received widespread attention by researchers and engineers. Studies aimed specifically at utilising harvested water from PPS have determined that harvesting and re-use is possible, and that PPS are capable of providing water of adequate quality for a variety of purposes (Nnadi *et al.*, 2008; Beecham *et al.*, 2010). Many modern water uses such as flushing toilets make use of high-quality potable water, effectively wasting a valuable resource. Many of these use-cases could benefit from utilising harvested stormwater, thereby reducing overall water demand.

A team of researchers in Britain found that irrigating with stormwater from PPS was feasible (Nnadi *et al.*, 2008). Similarly, a number of studies have evaluated the concept of integrating geothermal heat pumps or ground source heat pumps into the PPS substructure (Coupe *et al.*, 2009a, 2009b; Scholz & Grabowiecki, 2009; Tota-Maharaj, 2010; Nnadi *et al.*, 2014). The collaborative effort between multiple authors found that PPS could effectively be used as a thermal exchange system without significantly affecting the effluent water quality. While this is not a result directly impacting the primary focus of this study, the potential to simultaneously reduce water consumption and energy consumption may have significant environmental benefits. Water and energy are closely coupled resources.

As mentioned above, PPS are not particularly effective at nutrient removal (although some studies show high removal rates of nitrogen and phosphate). This makes irrigation with harvested stormwater from PPS feasible, as it serves the dual benefit of providing bio-available nutrients to plants and reducing the nutrient concentration within the stormwater as it percolates through the natural substrate.

In a PPS with an impermeable liner, water is stored within the substrate up to the level of the underdrain pipe. This storage causes an overall volume reduction of runoff, but this effect is neutralised in successive events if the water is not remove. Furthermore, if the water is used for irrigation purposes this promotes groundwater recharge and stabilises low-flow regimes (Hamel & Fletcher, 2014).

2.5 Assessing PPS Performance

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 its goals for stormwater that flows through, or is processed by the system, whereas ‘efficiency’ is a measure of pollutant removal, and ‘effectiveness’ refers to performance for all stormwater flows, including flow by-passes (Strecker *et al.*, 2001). When evaluating a SUDS/BMP/LID implementation, it is thus important to carefully qualify performance, effectiveness and efficiency with regards to specific objectives.

The concept of ‘performance’ of drainage systems is an evolving one. Under the ‘drainage efficiency’ approach performance refers to the ability to rapidly drain stormwater away from urban areas to prevent flooding(Burns *et al.*, 2005, 2012; Shuster *et al.*, 2005). With the appearance of LIDS in the 1970s, performance criteria began to change (Fletcher *et al.*, 2014a). As the name suggests, LID was concerned mostly around impact-reduction.

With increasing awareness around the effects of stormwater pollution, the concept of ‘efficiency’ began to emerge as a concern in stormwater management infrastructure (Walsh, 2000). Performance criteria for SUDS began to increasingly include pollutant reduction (efficiency), largely popularizing SUDS with good pollution reduction characteristics such as PPS and constructed wetlands (Goonetilleke *et al.*, 2005).

With increasing implementation of SUDS, performance and efficiency moved from a single-development scale to a sub-catchment and catchment scale as cumulative impacts of SUDS began to emerge (Petrucci *et al.*, 2013). Many Australian authors began to look at catchment-wide stormwater management, and while the concept of 'pre-development' flows had existed in LID considerations, there is a lack of understanding as to how these systems scale to catchment-wide impacts (Burns *et al.*, 2013). In addition to this, maintenance of low-flow and base-flow has also become a recent concern in SUDS literature (Hamel *et al.*, 2013; Hamel & Fletcher, 2014).

While the concept of 'natural flow regime' or 'pre-development flow' are often quoted as objectives, a move towards an ecohydrological approach calls for the consideration of the flow and quality requirements of urban streams in order to meet ecological objectives (Fletcher *et al.*, 2014b). While the proponents of said approach still argue largely for 'natural' stream flow, ecological objectives need not include a return to pre-development status, as ecological restoration or rehabilitation is a highly normative concept in environmental management. There is also a distinct difference between the concepts of restoration and rehabilitation, as restoration implies that the ecosystem will be restored to pre-development conditions. However, the feasibility, possibility and desirability of complete restoration are questionable. Rather than unilaterally declaring pre-development conditions as being a rehabilitation goal, managers should aim for water management objectives which provide appropriate ecosystem function and human amenity within the given context.

In summary then, objectives of stormwater management have become increasingly diversified, have experienced a shift from site-specific to multi-scale, and are increasingly cognizant of ecosystem resilience type management rather than technocratic flow and pollutant reduction.

2.5.1.1 Problems with the percentage reduction performance metric

While percentage reduction (ratio of pollutant concentration in the effluent *vs*. the influent) is a widely used performance metric for SuDS, there are a number of systemic and methodological concerns around its validity, as it can result in misrepresentations of system performance (Wright Water Engineers and Geosyntec Consultants, 2007).

A system may have a significant percentage reduction of a pollutant, but may still discharge unacceptable concentrations of the pollutant resulting in adverse downstream effects for both aquatic ecosystems and potential users of harvested stormwater. Furthermore, the nature of using relative metrics as performance criteria is inherently flawed as a high percentage reduction is more commonly driven by a high influent concentration. SuDS also tend to display complex relationships between influent and effluent concentrations; they also tend towards ‘irreducible concentrations’ of pollutants (USEPA, n.d.; Wright Water Engineers and Geosyntec Consultants, 2007). For PPS, which treat water from their own surface area additionally to any runoff from other sources, accurately determining the influent quality is extremely challenging. Thus, percentage removal ratios would have to rely on either tests under laboratory conditions or direct comparisons to impermeable surface areas. The latter method is problematic as runoff quality is highly site-specific, while the former may not give a true representation of field conditions. Furthermore, filter-type SuDS such as PPS have been shown to exhibit a mostly constant effluent concentration of TSS regardless of the influent quality, which makes the percentage removal metric solely reliant on the influent quality (Wright Water Engineers and Geosyntec Consultants, 2007).

Methodological problems arise from inconsistent statistical handling of measured parameters. Outliers and single readings may skew performance reporting, and different methods of estimating percentage reduction may give varying results for the same dataset.

2.5.2 Pollutant Performance Metrics in the literature

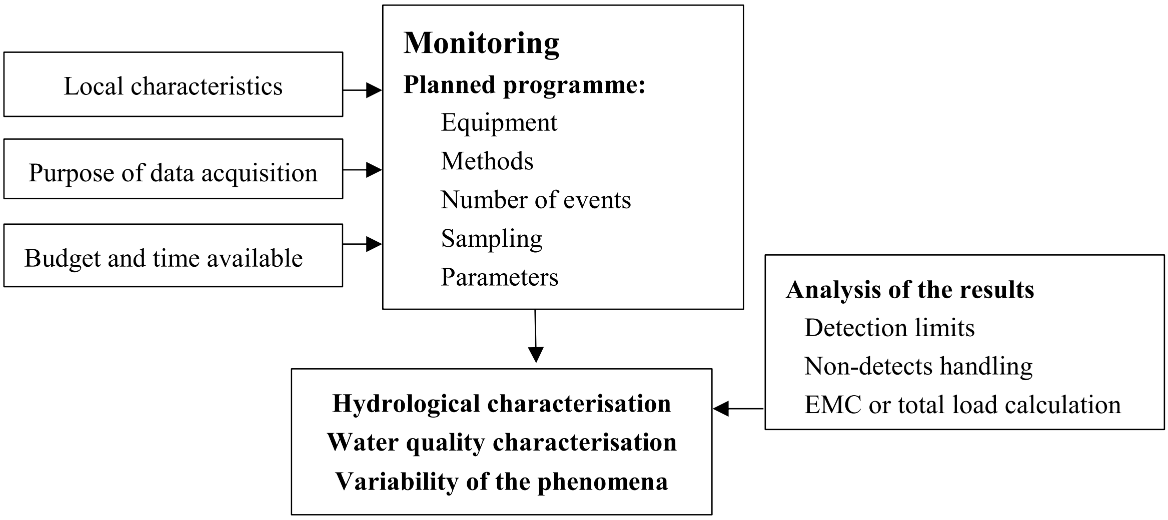
Three main methods of reporting pollutant treatment performance of PPS were identified in the literature. They are as follows:

- Removal Efficiency: This metric is mostly used to report on laboratory and simulated studies on permeable pavements. This is the only scenario where influent pollutant concentration can be accurately determined, and thus is the only type of study where true removal can be determined. (e.g. Fach & Geiger, 2005; Mullaney *et al.*, 2011; Tota-Maharaj & Scholz, 2010)
- Reduction with regards to an impervious ‘reference’: This is commonly found in field studies of PPS. This is an attempt at quantifying the ‘improvement’ in quality performance of PPS over impermeable areas. (e.g. Legret *et al.*, 1996; Legret & Colandini, 1999; Beecham *et al.*, 2012)
- Reporting absolute values: These are studies which do not attempt to make comparisons, or to compare the influent and effluent. Commonly, results are reported along with common stormwater pollutant values from the literature. The previous two methods often incorporate this, as effluent concentrations are usually listed in results, but do not us absolute values as a performance metric (e.g. Shackel *et al.*, 2003; Newman *et al.*, 2013).

2.5.3 Monitoring

Figure 2-15 illustrates the general parameters that need to be considered when undertaking monitoring of any stormwater processes. It is important to understand that monitoring is goal-driven, but also constrained to local characteristics and budget. These two limiting factors will impact the planned programme.

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 – capturing variability becomes crucial to a comprehensive understanding of the behaviour of the permeable pavement system.



1 - Figure 2-7: Monitoring stormwater processes (Barbosa et al., 2012)

2.5.3.1 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). 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 hand samples

3 - METHODOLOGY

This section will describe the general approach towards field monitoring of PPS, as well as details about sampling and analysis. The methodology emphasises the monitoring of a newly constructed and specifically designed test pavement. Since ordinary flow monitoring was not available, the main focus was on quality monitoring, and obtaining sufficiently representative data to account for potential event-specific variability, as recommended in Barbosa *et al.* *(*2012). The main limiting factors of the study the number of events sampled and a relatively low number of qualifying storm events.

3.1 Field Sampling

It is difficult to analyse influent quality of PPS as the pavement acts as its own source of pollutants. Furthermore, the site for analysis did not receive any run-on flows from other catchments which could be intercepted and analysed pre-treatment. As such, simple treatment efficiency (in terms of overall pollutant removal) is problematic in a field analysis. This study instead took the approach of evaluating the absolute effluent quality of PPS, and comparing it to the South African Water Quality Guidelines. Where possible, some impermeable reference sites were analysed in order to contextualise the water quality results.

Due to a limited budget, only one site could be monitored using a sequential automatic sampler capable of taking distinct samples throughout the event. The effluent from this site correspondingly received the most intensive analysis. However, this monitoring could only commence in June 2015 and in the meantime an existing PPS and nearby impermeable site were monitored using grab sampling. This monitoring continued during the winter season, where possible.

Two impermeable reference sites at the University of Cape Town (UCT) where monitored using a sequential bottle sampler setup. This consisted of self-sealing 500ml PET bottles joined with agricultural piping. The assumption was that as each bottle filled and sealed, it would preserve a different segment of the storm event, thereby increasing the understanding of the ‘first flush’ effect. In practice, this consisted of two self-sealing bottles, followed by a one litre bottle which was kept open. The last bottle was intended to mix throughout the event, and give an indication of the quality towards the tail end of the storm.

Figure 3-1: Sequential bottle sampler in the background, with first bottle containing sample shown in the foreground

3.2 Site Descriptions

3.2.1 NEB PPS

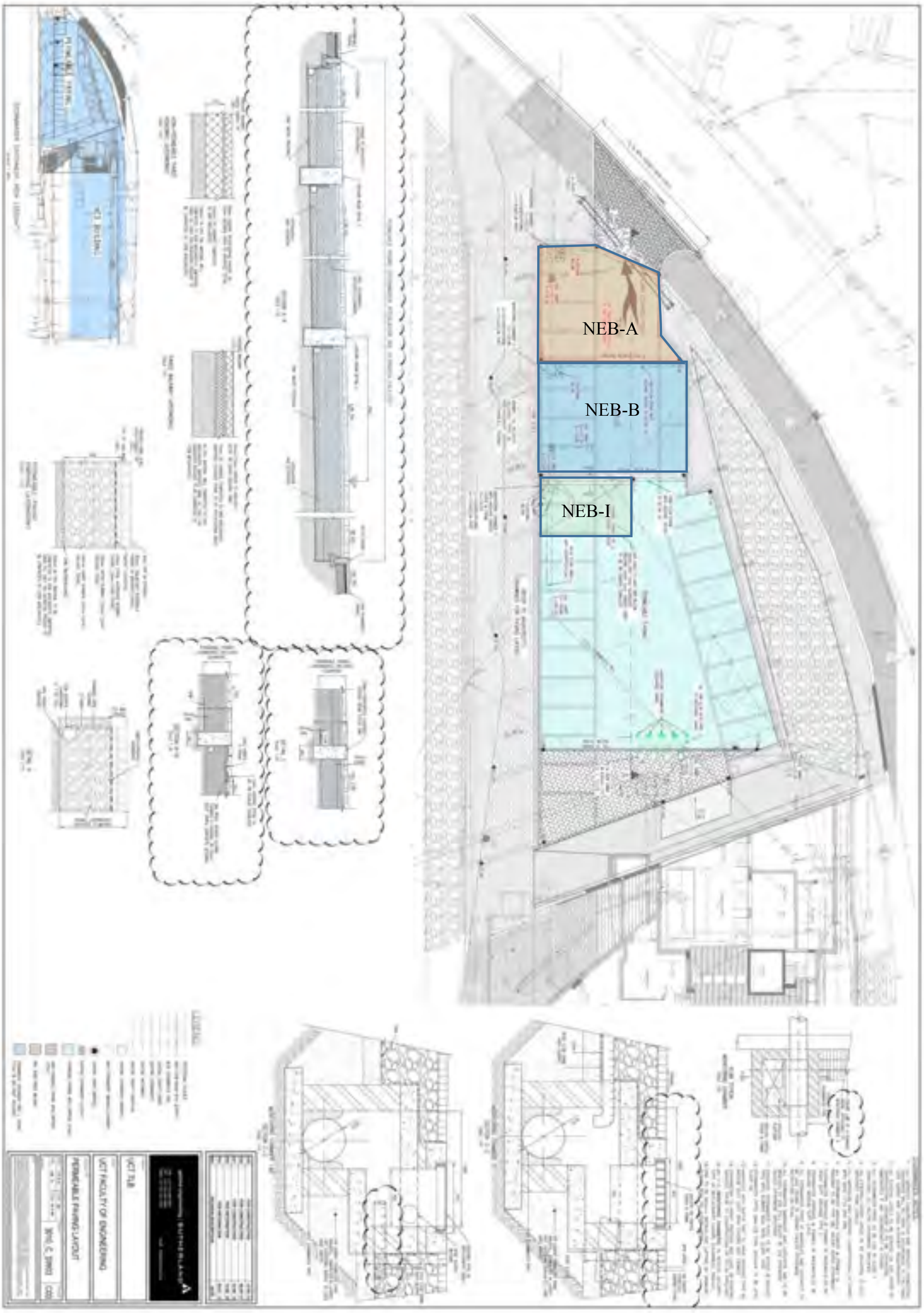


Figure 3-2: Original consultants drawing for design of NEB PPS parking lot

Constructed end 2014, the site was initially intended to attenuate rainfall falling onto the parking lot for the New Engineering Building (NEB) at the University of Cape Town (UCT). The original design plans are available in0. This parking lot was initially designed to provide parking for 26 cars. As UCT was built on a steep slope, the pavement is bordered by two steep embankments, with a rain garden located on the uphill embankment. This garden is raised above the PPS and held back with curb stones.

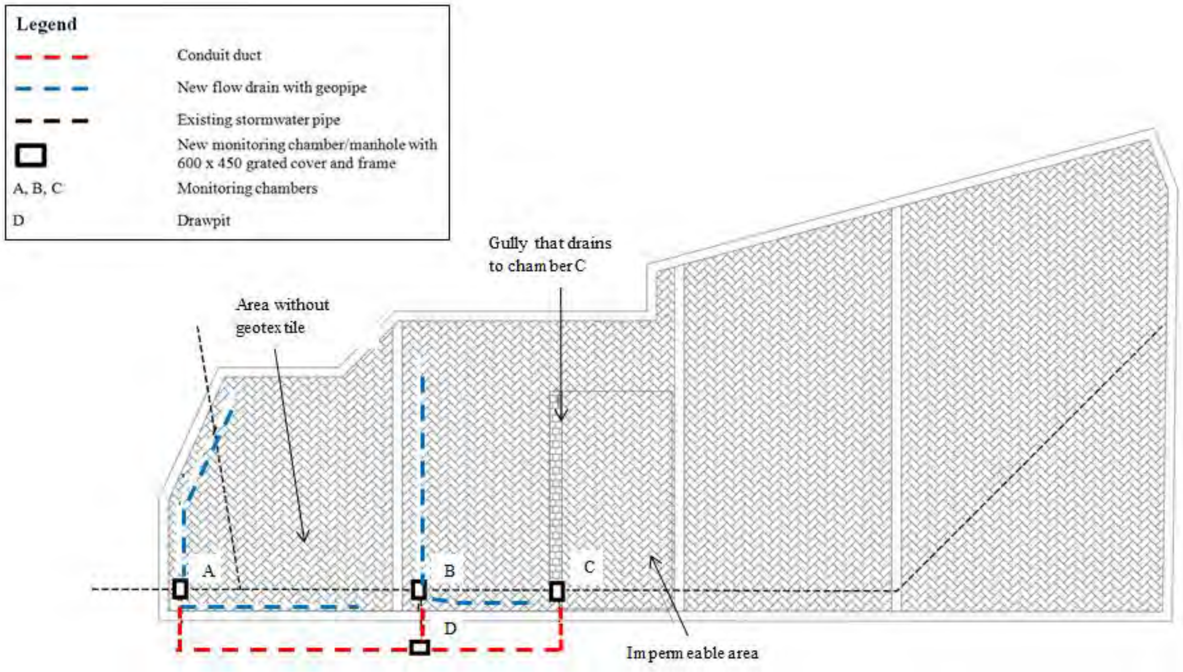


Figure 3-3: Schematic of the NEB PPS surface layout, including monitoring chambers.

During the design phase, the PPS it was modified to facilitate ongoing monitoring. The site was split into three different segments separated by ground beams. This modification was a requirement due to the slope of the site, and it provided an opportunity for modifying the pavement as an experimental site. One of these sections was intended to receive roof runoff, and was excluded from the monitoring plan, with the exception of NEB-I (Figure 3-3); this section was intended to have its surface sealed in order to provide an impermeable 'reference' site. Figure 3-4 illustrates the sub-surface layers of the PPS, which in this case includes an impermeable layer above the sub-grade. NEB-A was constructed without a geotextile, in order to later monitor the long term effects of the presence of a geotextile.

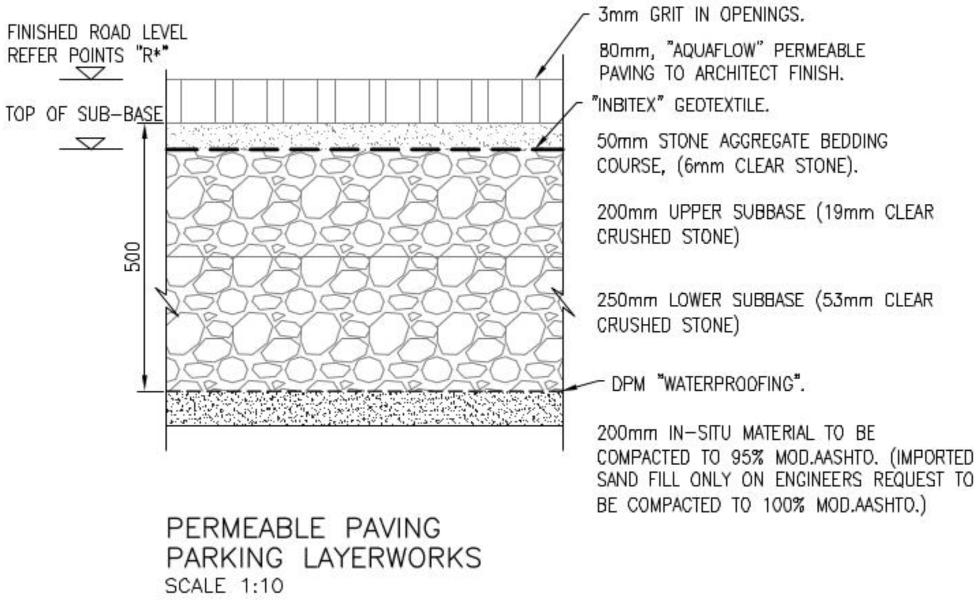


Figure 3-4: Layer works design diagram for the NEB PPS. Note that the top layer of geotextile was omitted for NEB-A

As the PPS was constructed with an impermeable bottom layer due to unfavourable subgrade conditions, an underdrain was placed in each section in order to discharge stored water into an existing stormwater pipe. An accessible monitoring chamber was placed at junction of the stormwater pipe and the underdrain, elevated in order to allow PPS effluent to be sampled. An instrumentation chamber was constructed near the PPS, and conduits where laid to each monitoring chamber.

Figure 3-3 shows how the pavement has been divided into three test areas, NEB-A, NEB-B and NEB-I. NEB-I was sealed off, and surface runoff was directed via a surface channel into a stormwater grate, where a sequential bottle sampler was placed to receive surface runoff. A funnel was fastened to the underside of the grate, as close to the channel as possible. The funnel was attached to the sampler via a piece of silicon hose. This sampler was placed no longer than 24 hours before a storm event (where possible) and retrieved within ten hours of cessation of rainfall.

Figure 3-5: Picture of the NEB PPS. Note the ground beam separating PPS sections in the middle of the picture

In both monitoring chambers of NEB-A and NEB-B, a 90^{o} V-notch weir box was placed, which was intended to serve the dual purpose of acting as a container for the sampling hose and for future flow monitoring purposes.

The monitoring chamber at NEB-B was linked to an Isco^{TM} 6712 autosampler housed in the instrumentation chamber via a 25ft sampling hose laid through the provided conduit.

Figure 3-6: ISCO 6712 Sampler with 24 bottle arrangement

The sampler had a sequential setup consisting of 24 500ml HDPE bottles and 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 programme was level-actuated by a float switch placed in the weir. The 6712 breaks out three pins for Input/output (I/O) programming on the Rain Gauge panel mount connector. In this case, I/O pin 1 was programmed to receive an active low signal. The simple circuit shown in Figure 3-7 below was soldered onto stripboard and connected to the float switch via a wire through the conduit. The float switch was normally closed, pulling the I/O Pin to +12V (a high signal). When the water rose, causing the switch to open, Pin 1 was pulled low through the 100kΩ pulldown resistor, thereby enabling the programme. The resistor selected had a high resistance value to reduce quiescent current draw.

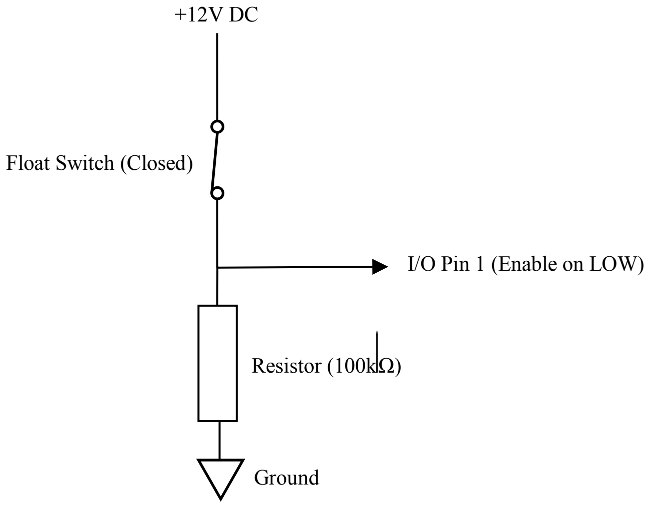


Figure 3-7: Active low switching circuit used with float switch to enable the sampling program at a suitable water level

The sampler was programmed to “take sample at enable” and the programme allowed for repeatable enables in case rainfall and consequent flow was intermittent.

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 the monitoring, 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, in order to prevent contamination of dormant water for subsequent events.

NEB-A was monitored with an ISCO GLS composite sampler, programmed to take a composite sample consisting of 49 samples of 150ml each, at 30 minute intervals. Unfortunately, the instrumentation chamber proved too small to house both samplers. Therefore, the sampler had to be placed in the NEB-A monitoring chamber instead. Since direct access to the chamber was required to set up and retrieve the sampler, several events were missed when this was not possible.

3.2.2 Rondebosch Permeable Pavement (RPPS)

While NEB-B was being constructed, another permeable pavement was selected for monitoring via grab samples. This PPS is located in an upmarket residential area called The Rondebosch, within a 1km radius of the NEB site. Unfortunately, the initial design schematics were not available, so the depth and layering of the PPS are unknown, though it also contained an impermeable substrate layer.

The PPS provides parking for The Rondebosch residents, and received runoff from roof surfaces as well as impermeable pavement.

Figure 3-8: Image of RPPS. The PPS covers the parking bays only, while the remainder of the pavement is impervious

Flow from the PPS was discharged into a chamber covered by a stormwater grate, before flowing into a suspended slab. Unattended sampling without an automated sampler was impossible for this site, and a sampler could not have been accommodated. Consequently this site was monitored by grab samples alone. Notably, this site was the only site without any vegetative cover.

3.2.3 Rondebosch Train Station (RTS)

This was an impermeable parking lot for the Rondebosch train station, directly adjacent to The Rondebosch. It was selected for grab sampling in order to obtain comparative samples for RPPS. The site had two stormwater inlets which could be sampled. While initially only one (RTS 2) was sampled, during the winter sampling period it was noted that the other inlet was blocked. This allowed for sampling even after flow had subsided. However, the two inlets also showed significant quality differences, and thus both were later monitored.

Figure 3-9: Picture of RTS, a public parking lot for a train station

3.2.4 P8

P8 was an asphalt parking lot at the University of Cape Town, providing parking for the Department of Chemistry. It was added during the winter period as it became obvious that too many events were being missed from NEB-I, where the grate was commonly inaccessible. The site was downhill of a steep, vegetated embankment.

Like NEB-I, it was monitored with a sequential bottle sampler. A small baffle was created in the channel, and a silicon hose was used to siphon off gathered water into the sequential sampler.

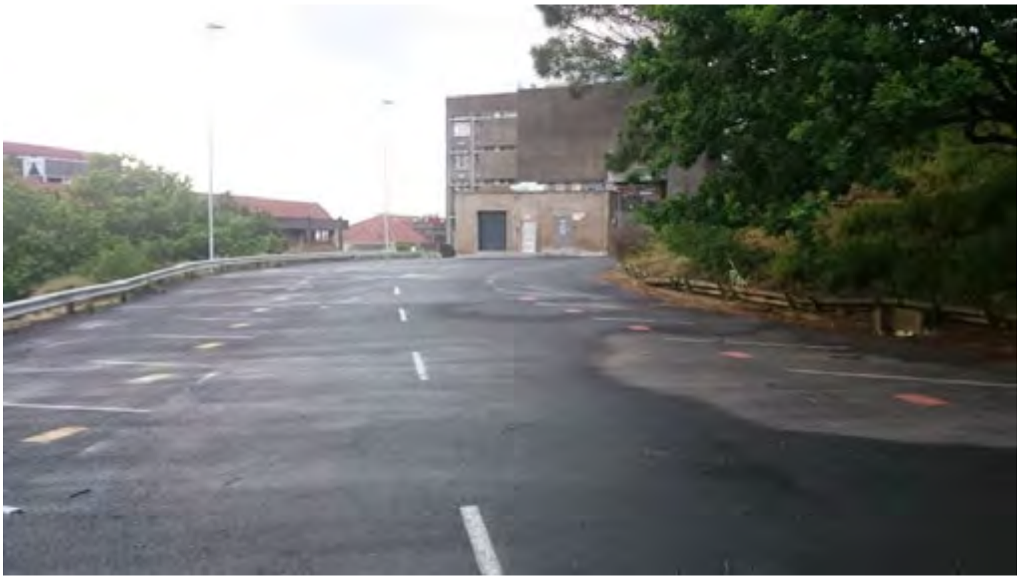


Figure 3-10: Picture of P8 shortly after rainfall. Runoff discharges into an open culvert on the left of this picture

3.3 Pilot Study Sampling

Only three rainfall events were sampled during the pilot study, on the 4th, 13th and 26th of November. Water samples were taken at regular intervals, initially as close to 15 minutes as possible. pH and Electrical Conductivity (EC) was tested *in-situ* using hand held probes. Samples were taken in 100ml PET sample bottles, which were returned to the laboratory and stored at less than 4°C. Samples were analysed for ammonia-nitrogen and orthophosphate as soon after collection as feasible. Samples were analysed using a Hach DR2700 Spectrophotometer and Hach Methods 8155 and 8048 for Ammonia Nitrogen and Reactive Orthophosphate respectively. Lack of available equipment at the time, and an insufficient sample volume resulted in samples not being preserved for TSS analysis.

3.4 Parameter Selection

The parameters tested during the study were Electrical Conductivity (EC), pH, Ammonia-Nitrogen (Total Ammonia), Orthophosphate, Total Suspended Solids (TSS) and Heavy Metals. Electrical conductivity and pH were selected as readily measurable parameters using hand-held and laboratory probes. TSS is one of the most widely recorded parameters in water quality assessments, as other pollutants such as heavy metals and micro pollutants often adsorb to the surface area. Furthermore, elevated TSS can have inherent adverse effects on downstream ecosystems and pose a potential risk for stormwater reuse.

Orthophosphate and Ammonia readings were selected as convenient proxies for nutrient levels, as used by Winter & Mgese (2011). Heavy metal analysis was conducted by the

University of Cape Town Chemistry Department via Microwave Plasma Atomic Emission Spectroscopy (MP-AES).However, the only results received for analysis to this date were for Copper and Lead.

Table 3-1: Analysis methods followed, along with their EPA equivalent methodologies and concentration ranges

Parameter	Method	EPA Equivalent	Range/ detection limit
Nitrogen, Ammonia	Hach Method 8155	N/A	0.01-0.5 mg/l
Orthophosphate	Hach Method 8048	4500-P-E	0.02-2.5 mg/l
Total Suspended Solids	EPA Method 160.2 (Modified)	EPA Method 160.2	2 mg/l detection limit for 50ml samples

It should be noted that this study uses the terms ‘Orthophosphate’ or ‘O-phosphate’ and ‘Ammonia’ instead of referring to the ion formula for abbreviation. This is because PO_4^+ may refer to other forms of phosphate (meta-, poly- and pyrophosphates), while NH_4^+ or NH_3 may be ambiguous. Ammonia here is defined as Total Ammonia unless otherwise specified Total Ammonia is the sum concentration of the ionised and unionised forms of ammonia.

3.5 Full scale 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% H_2SO_4 and distilled water. Samplers were programmed and tested. The ISCO GLS sampler had to be programmed to take a sample at the estimated time of start of flow, as automated activation was not possible. 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 while stored at less than 4ºC. Retrieval was, in some cases, impaired by parked cars, but generally retrieval occurred within 4-10 hours of cessation of rainfall. Where possible, grab samples were also taken from RPPS and RTS for comparison. These were analysed immediately for pH, EC, ammonia-nitrate and orthophosphate.

After nutrient analysis, samples were preserved by addition of HNO_3 to reduce the pH to less than 2, and stored at below 4ºC in PET bottle. TSS samples were performed more than 28 days after collection, due to equipment and laboratory availability; while this may have compromised samples for EPA reporting, little impact is expected on actual TSS values. For TSS testing, 47mm diameter, 1.5 micron glass fibre filter paper was used, and filters were washed out with three aliquots of deionised water. Filters were then dried in an oven at 105ºC for one hour, before being weighed with an electron scale with 0.1mg accuracy. Filters were placed in a Millipore™ sterile filter holder, and where possible, 150ml of sample was filtered through the paper. The sample volume varied depending on available sample amount and suspended solid concentration, but no less than 50ml was used. Samples were removed carefully with forceps, placed on tinfoil and returned to the oven to dry for another hour at 105ºC. Samples were then weighed again using the same scale; the difference in mass of the filters was recorded and converted to a concentration of TSS. One in every 20 samples was a blank, where deionised water was used instead of sample. The blank ensured test accuracy.

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.

3.6 Data Analysis

3.6.1 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 the 01/11/2014 to the 01/11/2015. The pilot study was conducted from the 01/11/2014 to the 01/12/2014, while monitoring the NEB site began after the arrival of the automatic samplers on the 02/06/2015.

For events from the 16 June onwards (5-11) the amount of rainfall required to emit significant flow was determined by summing the rainfall values from that event up to the sampler start time. Rainfall data was only available in hourly intervals, so where the sampler start timing included a significant portion (20 minutes or more) of the next interval, that interval was included in the estimate (i.e. if rainfall began at 13:00 and the sampler began at 16:40, rainfall was summed from 13:00 to 17:00). This provided a crude measure of the amount of rainfall required to generate flow from the PPS.

3.6.2 Inter event analysis

For NEB-B, the results for each event were averaged. Due to the lack of flow data, these averages were not flow-weighted, and thus do not represent a true EMC. The Standard Error of the Mean (SEM) was calculated for each event and reported. RPPS and RTS sites were analysed similarly.

The sites monitored with bottle samplers were treated differently. Samples were averaged across the study period. Total averages were computed along with the averages for each of the three bottles.

3.6.3 Intra Event Analysis

NEB-B was the only site with sufficiently high temporal resolution and representativeness to warrant intra-event analysis. The values were standardised to the event mean, then categorised depending on which time segment they occurred in, and all values for a particular time segment were averaged and reported with SEM. This was done to determine if there were any temporal dynamics exhibited at the intra-event level.

3.6.4 Correlation

Each of the parameters was rank and linearly correlated with selected rainfall-based drivers, as well as with each other. Drivers included the following:

- Total Event Rainfall: The total precipitation during the event.
- Event Number: The number of the measurable event in the study (1-11).
- Cumulative rainfall: Cumulative rainfall from measurable events only on NEB-B from the 02/06/2015
- Antecedent Dry Weather Period (ADWP): Number of days since the last rainfall event, regardless of event size (i.e. including non-measurable events).
- Time Since Last Measurable Event (TSLME): Number of days transpired since the last event which generated outflow. Effectively, days between measurable events.

4 - RESULTS

Results are presented in below. Results from NEB-B are preceded by a brief description of sampled events and rainfall patterns throughout the study. NEB-B results are first described by inter-event averages, explaining the progression of pollutant concentrations in effluent from event to event. Intra-event analyses investigate whether or not NEB-B displayed any variability in pollutant concentration throughout the event. Summary results from the other pavements precede a summary table showing all study averages. Results from the pilot study can be viewed in Appendix A, along with correlation matrixes for parameters and rainfall characteristics.

4.1 Rainfall Characteristics

Results were gathered over a period from the 01/11/2014 to 01/11/2015. During this period, 48 unique rainfall events were identified, of which 11 were sampled. Three of these constituted the pilot study, and were all sampled during November 2014. The remaining eight occurred between June and November 2015. These rainfall events totalled 409.2mm cumulatively, which is more than 50% of the 784.6mm that were recorded over this period. This does not consider potential lost records due to equipment malfunction or rainfall below detection limits, but suggests that data gathered may be considered strongly representative of a rainy season. Table 4-1 displays the sampling dates as well as which sites were sampled and the corresponding event identifier.

Table 4-1: Sampled Rainfall Event dates, with sites sampled and event duration

Event #:	Sampling Event:	Rainfall (mm):	Date:	Number of Days:	Study:	Sites Sampled:
1	**1**	11.43	03/11/2014	2	Pilot	RPPS, RTS
2	**2**	19.05	12/11/2014	4	Pilot	RPPS, RTS
3	**3**	15.24	26/11/2014	2	Pilot	RPPS, RTS
25	**4**	38.354	02/06/2015	2	Full	NEB-B, NEB-I
26	**5**	64.77	15/06/2015	2	Full	NEB-B, NEB-I, RPPS, RTS
27	**6**	32.004	23/06/2015	3	Full	NEB-B, RPPS, RTS
31	**7**	42.418	16/07/2015	3	Full	NEB-B, RPPS, RTS, P8
32	**8**	50.8	22/07/2015	3	Full	NEB-B, P8
33	**9**	52.832	29/07/2015	2	Full	NEB-B, P8
36	**10**	37.592	15/08/2015	2	Full	NEB-B, P8
48	**11**	45.466	01/11/2015	2	Full	NEB-B, P8

Monitoring in NEB-B began from the second of June 2015, and eight events were sampled by November 2015. Each event exhibited rainfall levels of 25mm or more, while events below this threshold did not appear to generate flow. Two events meeting this criteria were not sampled throughout the study. The first was on the fifth of January before the monitoring set up was complete, and the second on the 15 of September which was confirmed as a missed event. Confirmation was possible, as evidence of outflow was present in the monitoring chamber.

The eight events sampled during the period of June to November 2015 were coincidentally the largest rainfall events during the study period, and seven of these events occurred within a two month window.

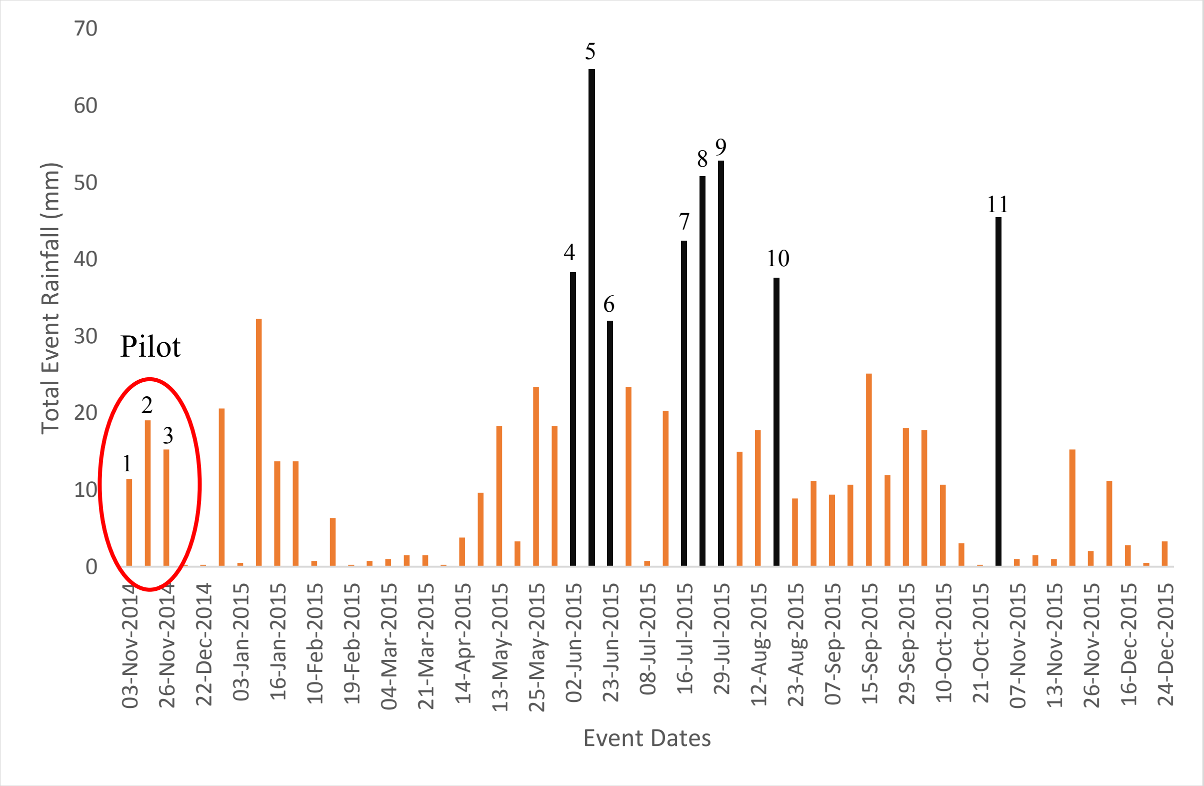


Figure 4-1: Rainfall event dates during study period. Black bars indicate the sampled events during the main study; sampled event numbers are shown above the bars.

According to the EPA Industrial Stormwater Monitoring Guide of 2009, a storm event qualifies for monitoring if:

- It generates discharge from the monitoring site (i.e. it constitutes a “measurable storm event”)
- The measurable event occurs at least 72 hours after the preceding measurable event, unless a less than 72-hour period is representative of distinct local storm events (USEPA, 2009)

All recorded events met the requirements of being measurable (generating discharge) at NEB-B, and of being more than 72 hours after a preceding measurable event. However, event 4 and event 10 were both preceded by non-measurable events within four days. Stored water from these preceding events may have magnified the outflow from the measurable events.

4.2 NEB-B

NEB-B has been studied more thoroughly than any other site, with 94 separate readings across eight rainfall events, and taken at regular time intervals. This allows for analysis of not only the event averages but also of intra-event behaviour. These trends can be interesting in their own right, but become extremely useful in elucidating any underlying mechanistic biases inherent in the event averages (such as the presence of a ‘first flush’ effect).

Table 4-2: Cumulative rainfall per event before sampler was triggered shown with antecedent dry weather days for that event. Note missing event 4, as it was only automated by event 5

Event:	Antecedent Dry Weather Days:	Cumulative Rainfall before sampler trigger (mm):
5	12	20.06
6	7	19.3
7	3	8.13
8	4	20.83
9	5	16.77
10	2	8.39
11	11	19.05

Table 4-2 is an indication of how much rainfall was required to generate meaningful outflow. There is a clear indication that NEB-B requires around 20mm of rainfall if there have been no events (measurable or non-measurable) more than three days prior. Where rainfall had occurred beforehand, the amount required seemed to sink to 8mm. Event 9 is a slight outlier, as the sampler triggered after just less than 17mm of rainfall.

4.2.1 Inter-Event Variability

4.2.1.1 Total Suspended Solids

A surprising result from NEB-B emerged, as effluent was elevated in TSS and suspended solids were visible to the naked eye. The suspended particles consisted mainly of fines that were light brown in colour, and could be clearly seen after the TSS test. It was concluded that the contractors had constructed the sub-base of NEB-B with unwashed aggregate, and that this construction sediment was being washed out of the pavement.

Figure 4-2: Image of filters after TSS test. From left to right are RTS, NEB-B and RPPS. Note the fine brown layer of sediment on the filter from NEB-B, whereas RPPS is almost indistinguishable from the deionised water blank

Event-averaged TSS concentrations are shown in Figure 4-3 below. Averages ranged from 15.5mg/l to 54.9mg/l. While displaying an initially linear increase in average concentration, the TSS then decreased sharply during event 8, and increased to peak levels during event 10. Event 11 showed an unusually high Standard Error, which was mostly due to an abnormally high initial TSS during the event (184.6 mg/l, more than twice as high as any other single reading) which dropped off sharply to levels below 10mg/l after the fourth sample. Standard error was quite high in general, indicating that there is considerable intra-event variability of TSS.

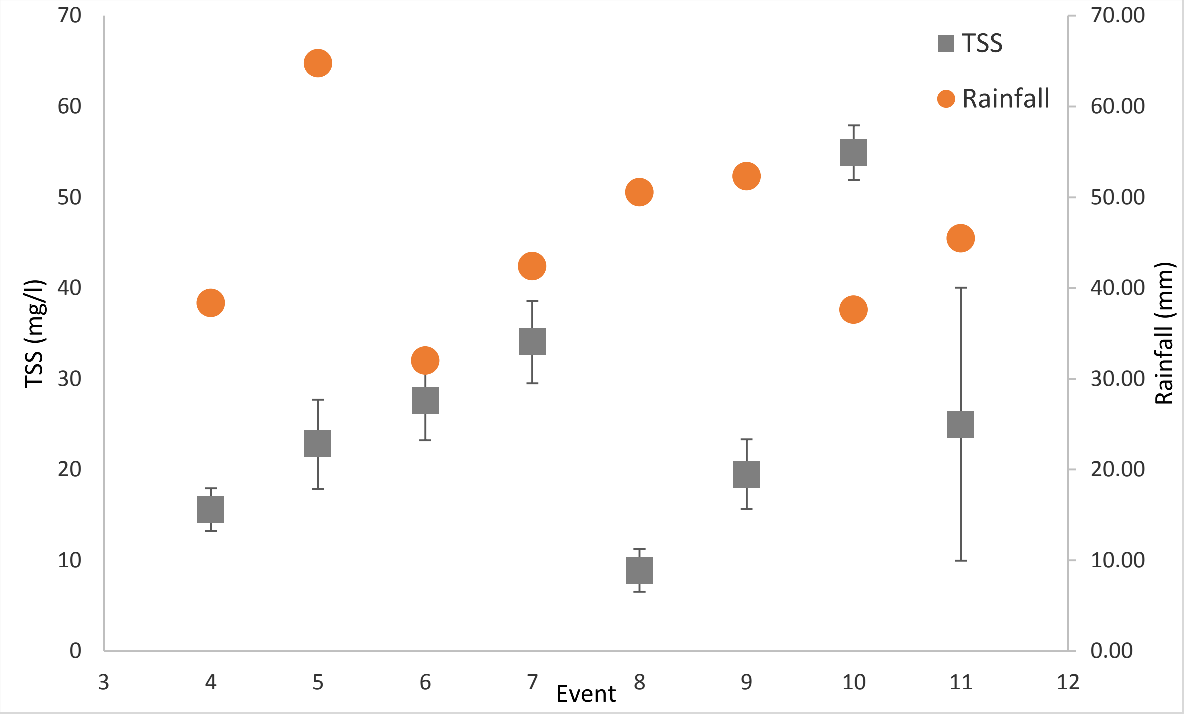


Figure 4-3: Average TSS concentrations for each event, along with total event rainfall. Initially, TSS appears to increase linearly from event to event.

While it would be expected that the sediment contained in the PPS structure would be washed out incrementally, this was clearly not the case. Given that TSS concentrations correlate significantly with TSMLE, the most feasible explanation of the trend would be that TSS was being migrated through the pavement by sequential, smaller rainfall events and then transported out during measurable events. However, this would require further study on comparable sites.

4.2.1.2 Orthophosphate

Orthophosphate concentration increased with consecutive rainfall events, from a level of about 0.05 mg/l to a level between 0.25 and 0.3mg/l. Like TSS, the pattern of increasing event averages was interrupted by events 8 and 9. Unlike TSS, orthophosphate in event 11 did not drop off sharply, but remained at fairly constant levels throughout the event.

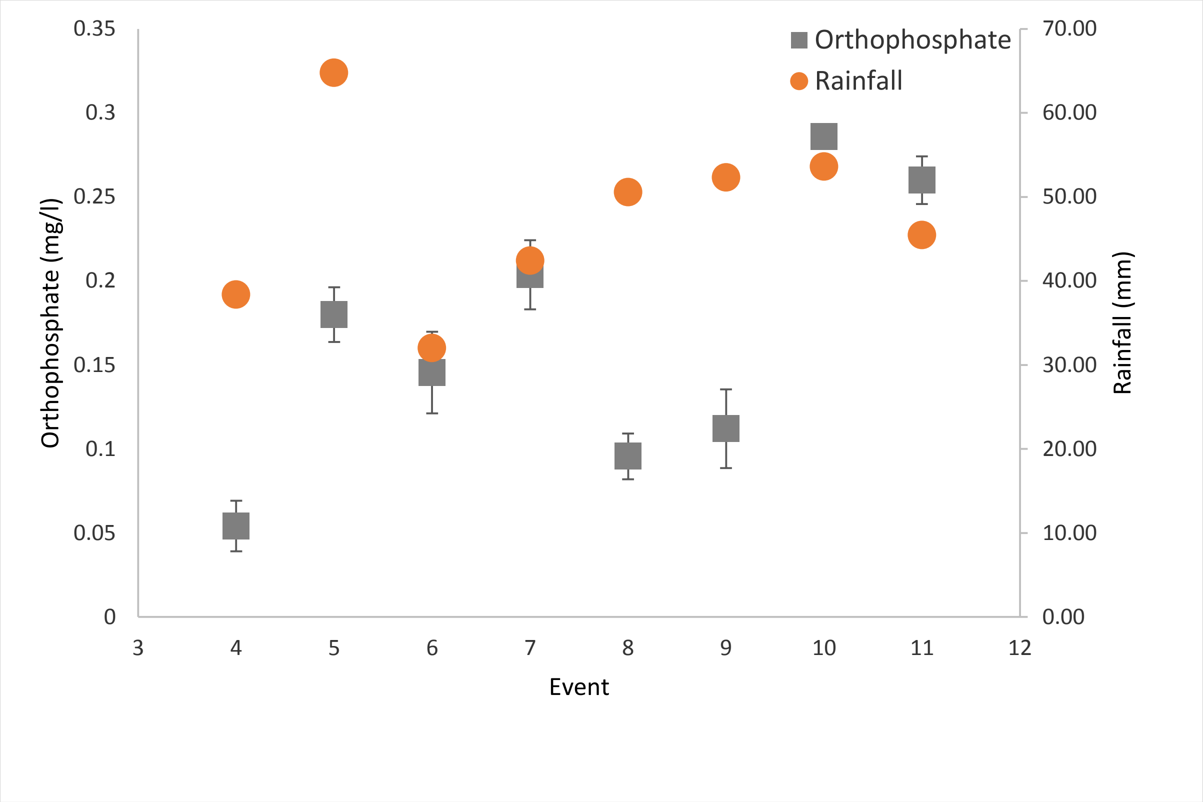


Figure 4-4: Average Orthophosphate concentrations for each event, along with total event rainfall. Similarities in progression with TSS are evident.

Like TSS concentrations, Orthophosphate concentrations rank-correlated strongly with TSLME. Since they did not correlate with antecedent dry weather period, this suggests that smaller events may be a driving factor in the event averages of measurable events. The parameter also correlated well, both linearly and by rank, with TSS. While this may support the assumption that higher orthophosphate levels are caused by phosphates adhering to suspended sediment, the correlation became far weaker when the two were correlated by each reading rather than by the event averages. I.e. a sample with high TSS did not necessarily display high orthophosphate, but events which demonstrated high TSS averages also tended to have high orthophosphate averages. This would indicate that there is not a direct causal relationship between TSS and orthophosphate but rather a common cause affecting both TSS and orthophosphate at the event-average scale.

4.2.1.3 Ammonia

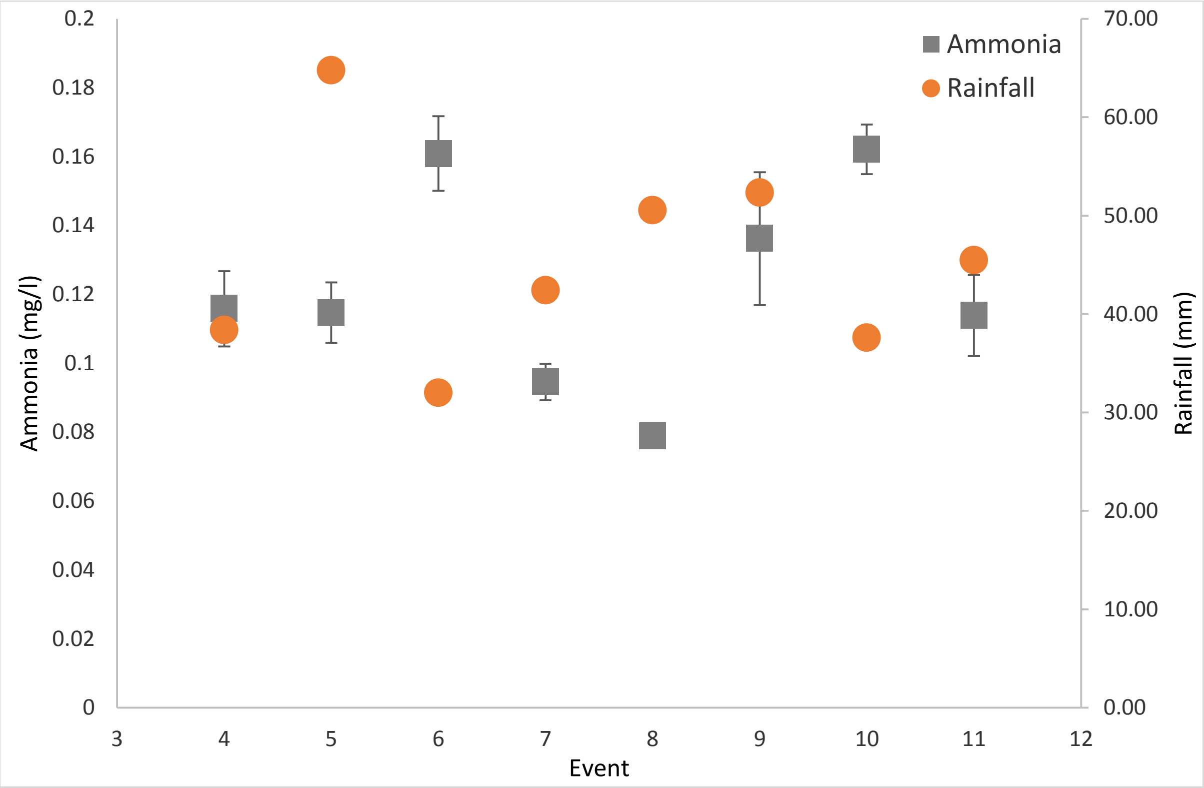


Figure 4-5: Average Ammonia concentrations for each event, along with total event rainfall

Average Ammonia concentrations were consistently below 0.2 mg/l with remarkably low variation. While Ammonia concentrations show a far less discernible pattern than TSS or Orthophosphate, the peak at event 10 is evident. Similarly, event 8 is identifiable as having the lowest overall average concentration. While the Ammonia concentrations correlate somewhat with TSS, the correlation coefficient is not significant.

4.2.1.4 Electrical Conductivity

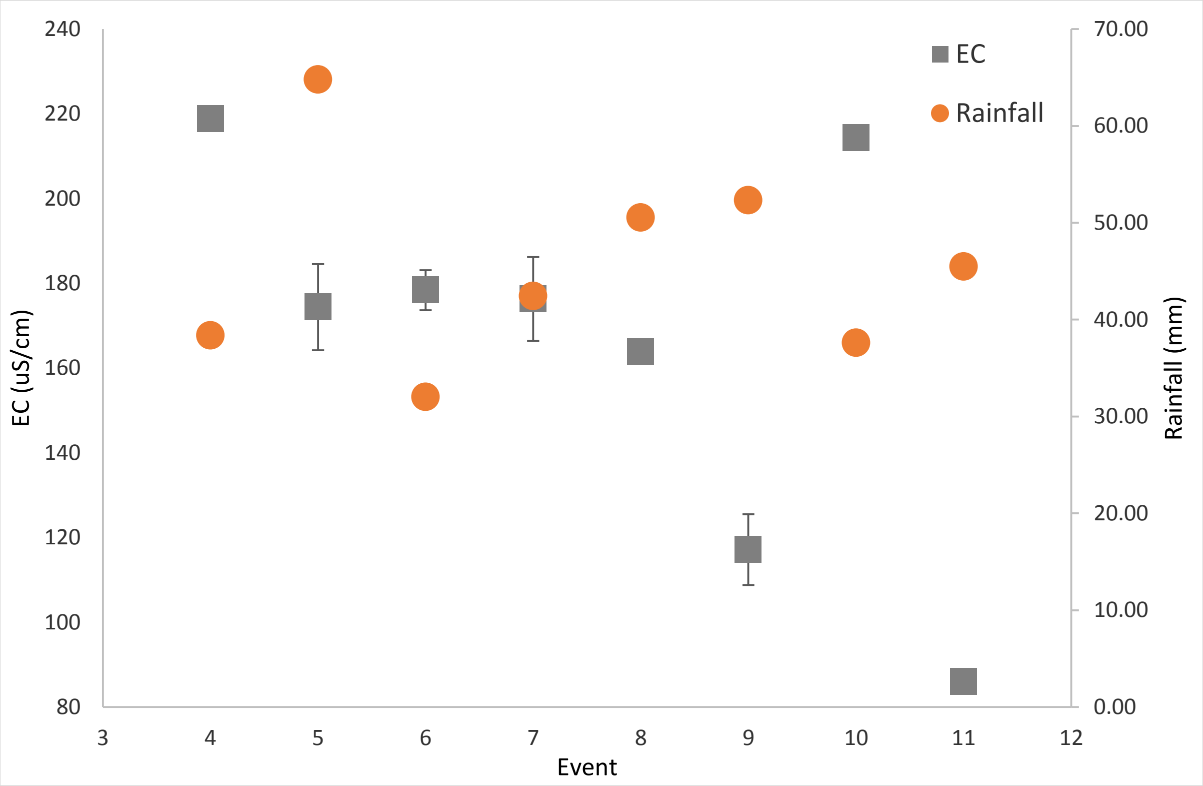


Figure 4-6: Average EC for each event, along with total event rainfall.

Apart from the single outlier of Event 10, EC showed a continuous linear decrease from event to event. This is given statistical significance by the linear correlation coefficient, and while the significance level was rather low (0.1), the fact that removing the outlier increased the correlation coefficient drastically strongly supports the theory that EC decreases linearly with each successive event.

Results from RPPS show a similar pattern of decrease, where initial readings from the pilot study showed an EC of 235µS/cm, which dropped down to 97µS/cm during the winter rainfall. This was similar to the decrease from 220µS/cm to 86µS/cm from events 4 to 11. Since RPPS is an older site this could be a seasonal pattern.

Linear correlation coefficients further suggest negative relationships between EC, ADWP and time between measurable events. Rank correlation coefficients for EC were similar to linear correlations, except for a weaker correlation with TSLME and stronger correlation with event rainfall.

4.2.1.5 pH

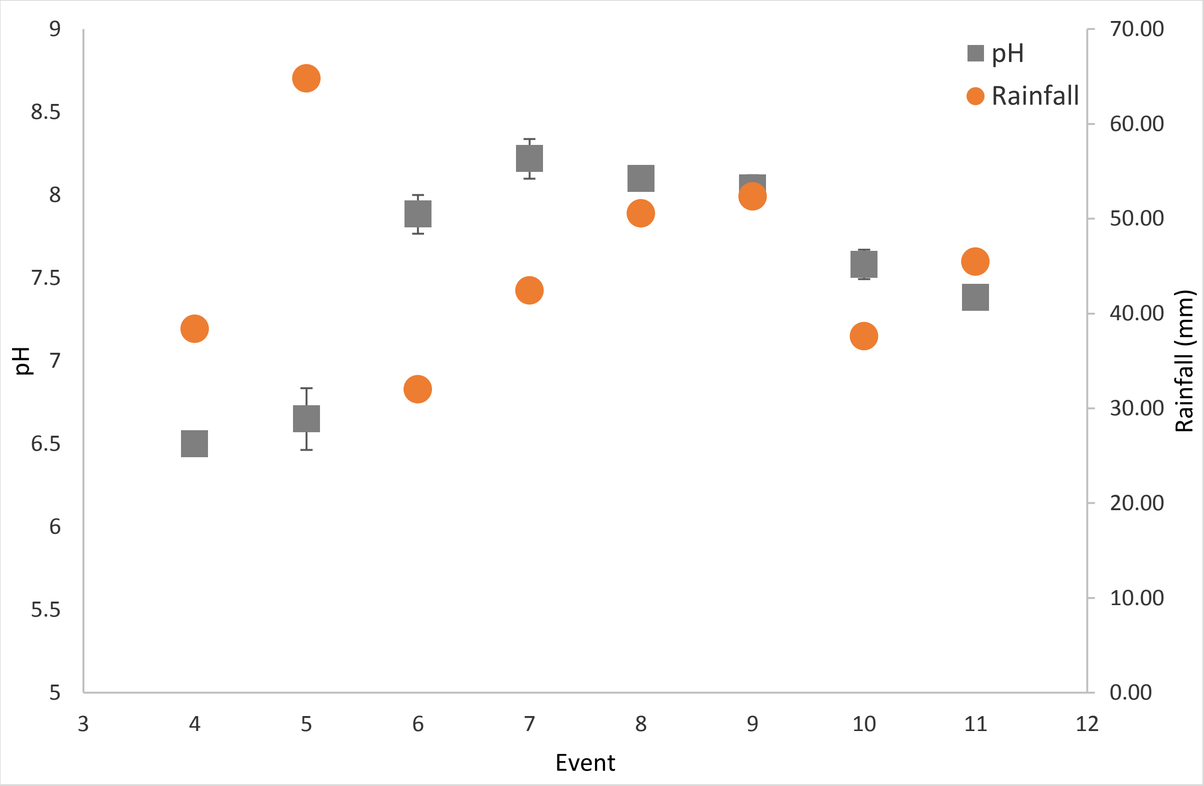


Figure 4-7: Average pH for each event, along with total event rainfall.

Average pH ranged from 6.5 to 8.2 across events. Of all the parameters, pH appeared to show the smoothest pattern of initial increase and slow decrease towards the beginning of summer. Concurrently, a decrease of intra-event variability with time is apparent, with event 5 having the widest variability. Event 4 has no error bars as only pH testing strips with low precision were available and therefore any high resolution variability was lost.

4.2.2 Intra-Event Variability

4.2.2.1 Total Suspended Solids

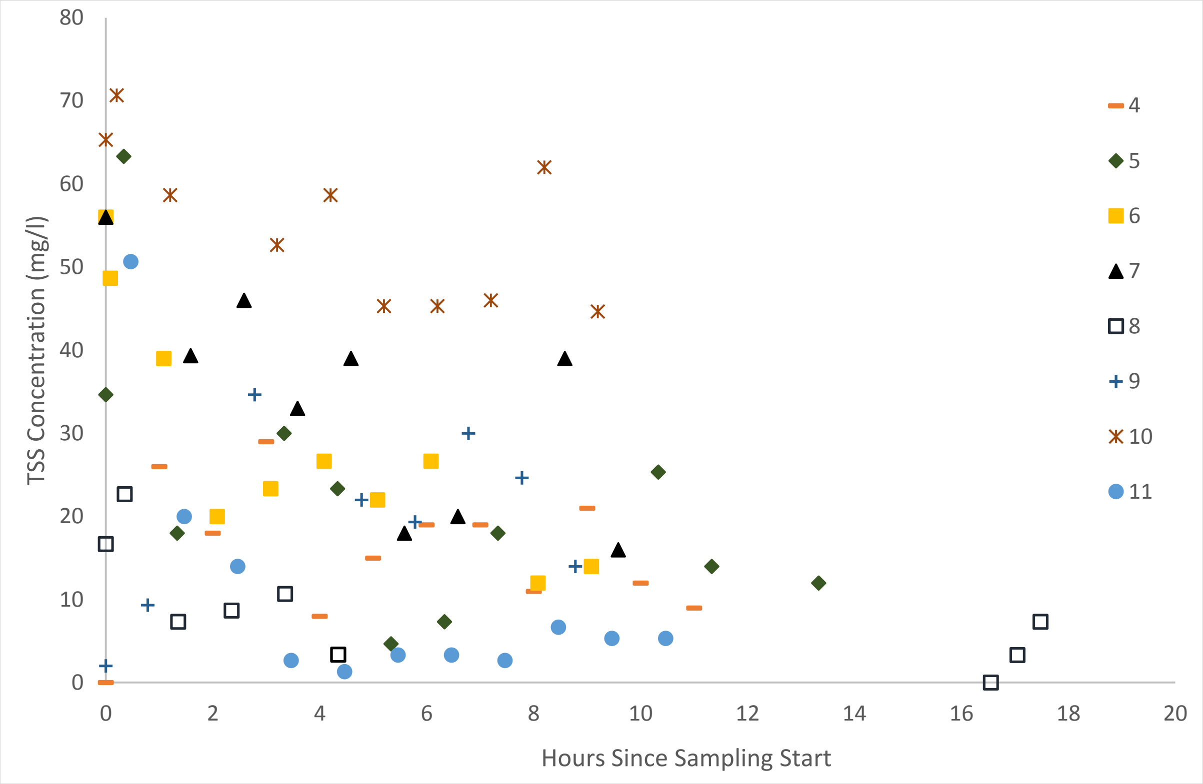


Figure 4-8: TSS concentrations shown at relative sampling time per event.

Figure 4-8 above is a scatterplot of all TSS concentrations according to the time they were taken from the start of the specific sampling event. The first sample is always irregular (in that it does not fall into the one hour time step), due to the programming of the sampler as described in more detail in the analysis section below. Irregular intervals are also seen in event 8, where the water level in the sampling chamber would have dropped below the cut-off limit and the programme would have been suspended before consequent rainfall reactivated it. The shorter time steps are due to a ‘bounce’ effect caused by the trigger system and the sampler pump backwash function, which will be described later.

It is readily apparent that the highest data density is at less than 12 hours after sampling start. Only four samples were taken later than that. Three of those are from event 8, where rainfall ceased early in the event and started again later.

Each event in Figure 4-8 is represented as a separate data series showing intra-event progression. Each progression displays a trend of decreasing TSS throughout the rainfall event. For event 11, the first data point has been removed to prevent scaling issues (TSS concentration of 184.6 mg/l). The low TSS values evident towards the end of event 11 could indicate that most of the sediment had been washed out by this stage. Since there have been no measurable events since, this cannot be confirmed.

Figure 4-9 shows the trend more clearly. Here, data points across all events have been grouped according to which segment of the sampling event they fall in, and standardised to event averages. A strong negative linear correlation between TSS concentration and sample time was present, suggesting that TSS decreases linearly throughout the event.

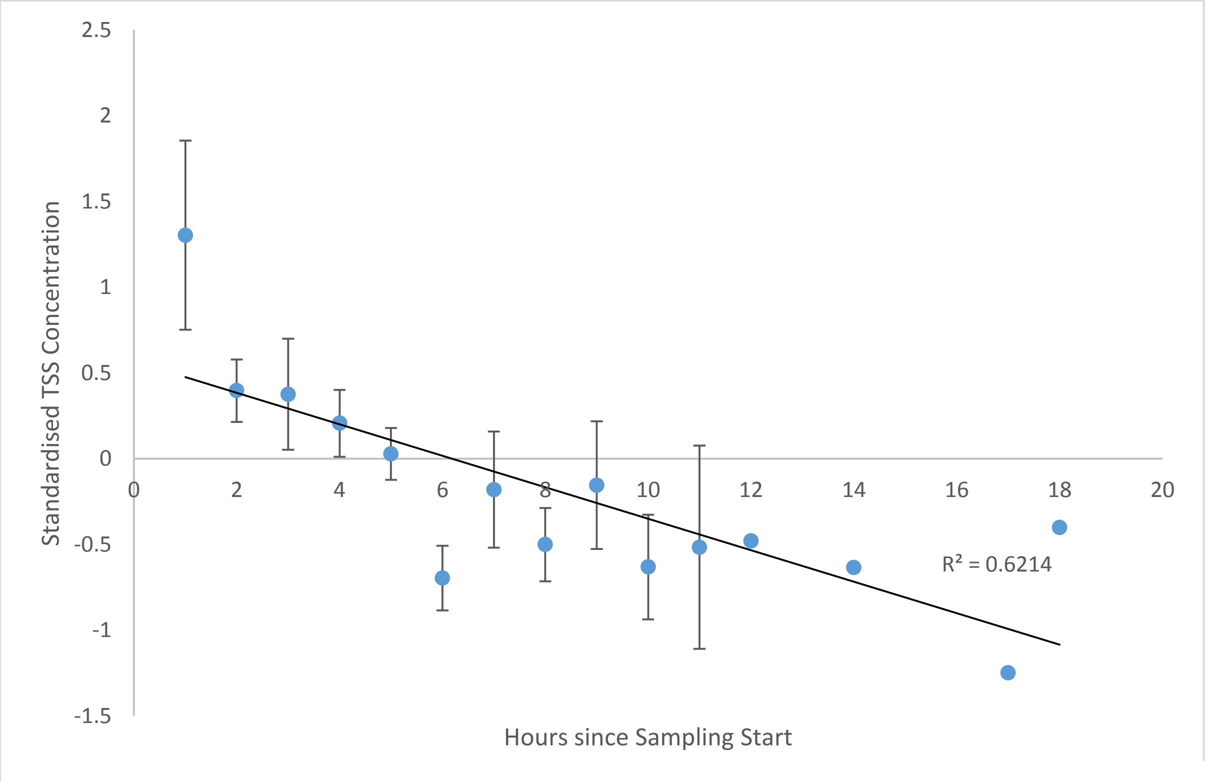


Figure 4-9: Event-standardised TSS concentrations aggregated according to sampling time. R^2 value shown on graph suggests negative linear correlation between TSS concentration and event progression. The data point at hour one is an average of the sample at enable and the 'first' program sample.

4.2.2.2 Electrical Conductivity

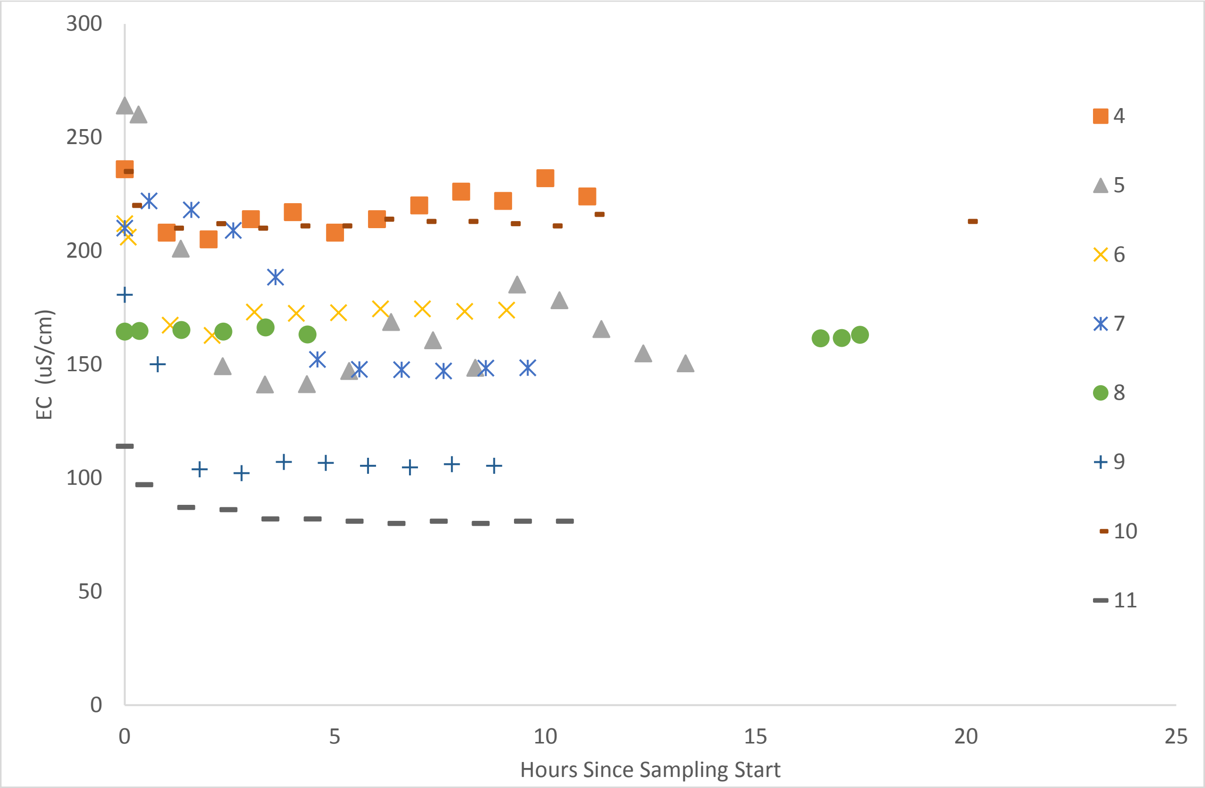


Figure 4-10: EC shown at relative sampling time per event. Event numbers displayed on the right border.

Figure 4-10 shows relatively smooth intra-event trends for EC. In general, these are patterns of decreasing EC with increasing event time. Some added variation is evident in events 4 and 5.

When these values are standardised and aggregated in Figure 4-11 below, a clear initial outlier is evident, suggesting that the first two readings of each event are significantly elevated above the rest. The remainder of the readings show no clear pattern, suggesting that they tend to merely vary stochastically around the mean.

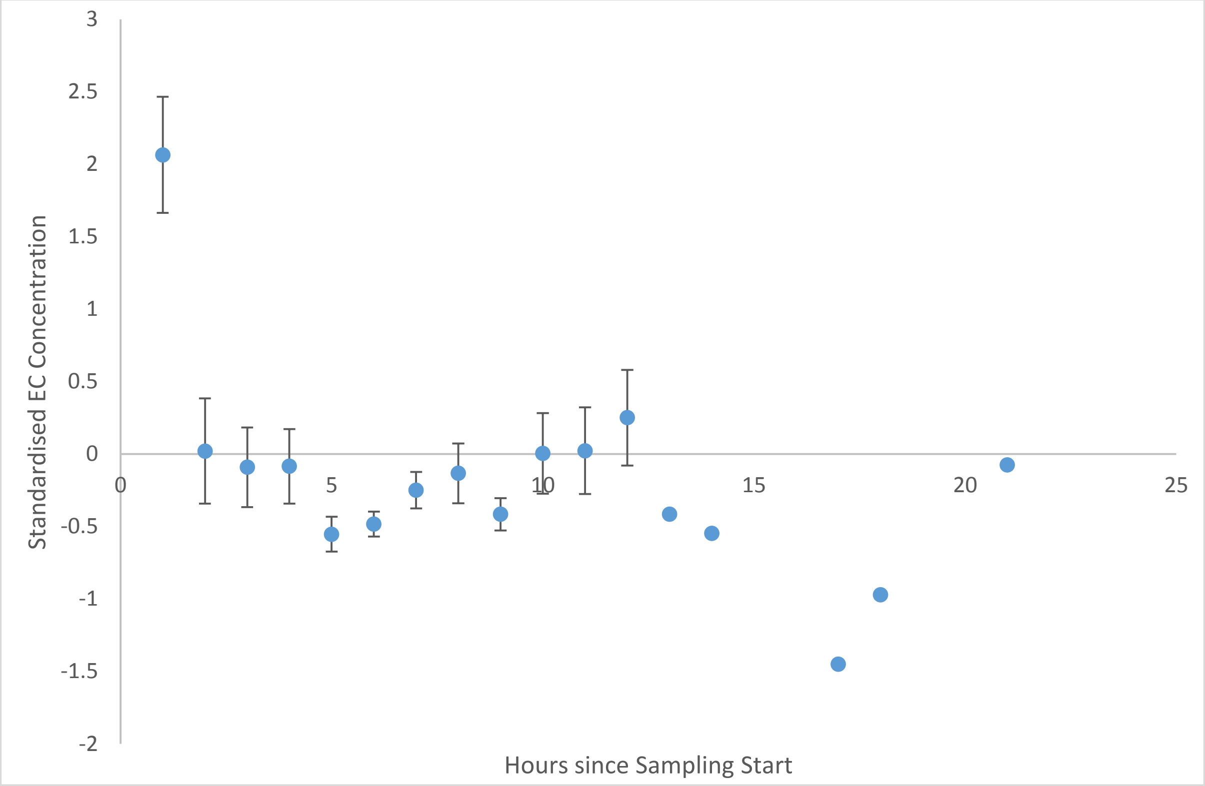


Figure 4-11: Event-standardised EC aggregated according to sampling time

4.2.2.3 Orthophosphate

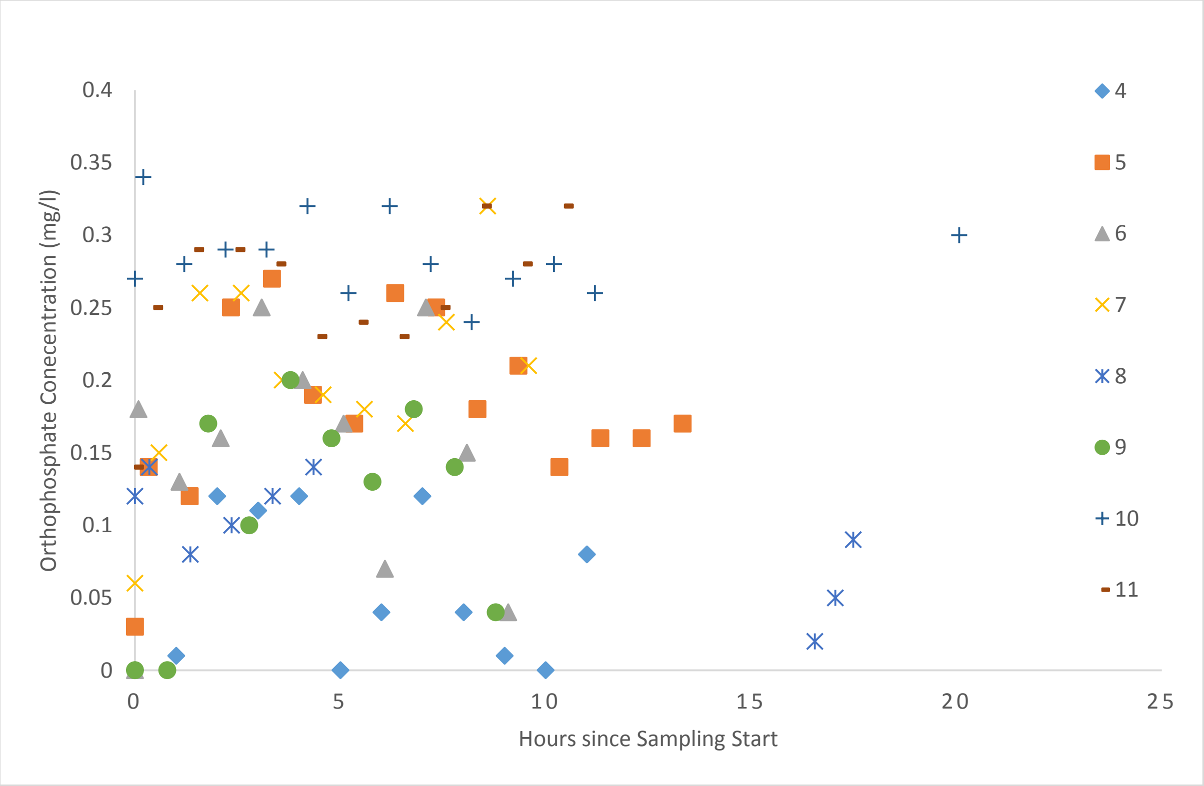


Figure 4-12: Orthophosphate concentration shown at relative sampling time per event. Event numbers displayed on the right border

Orthophosphate concentrations as shown in Figure 4-12 above show no clear consistent pattern throughout events, except for a tendency for initial samples to display a lower concentration, and samples in the middle of the event to show higher concentrations. Variability within events was quite high.

Figure 4-13 supports the theory that concentrations from initial samples are considerably lower than those of consecutive samples, and also indicates that samples taken from the middle of an event are more likely to show elevated concentrations of orthophosphate.

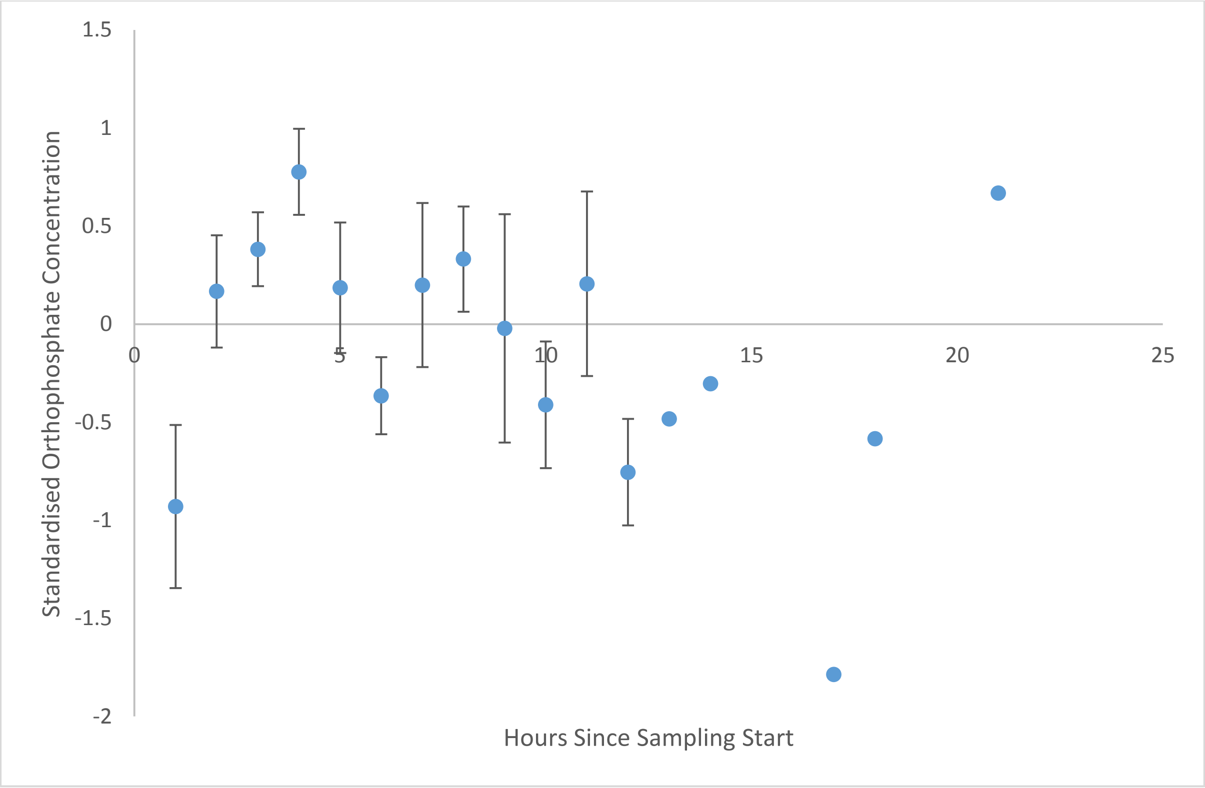


Figure 4-13: Event-standardised Orthophosphate concentrations aggregated according to sampling time

4.2.2.4 Ammonia

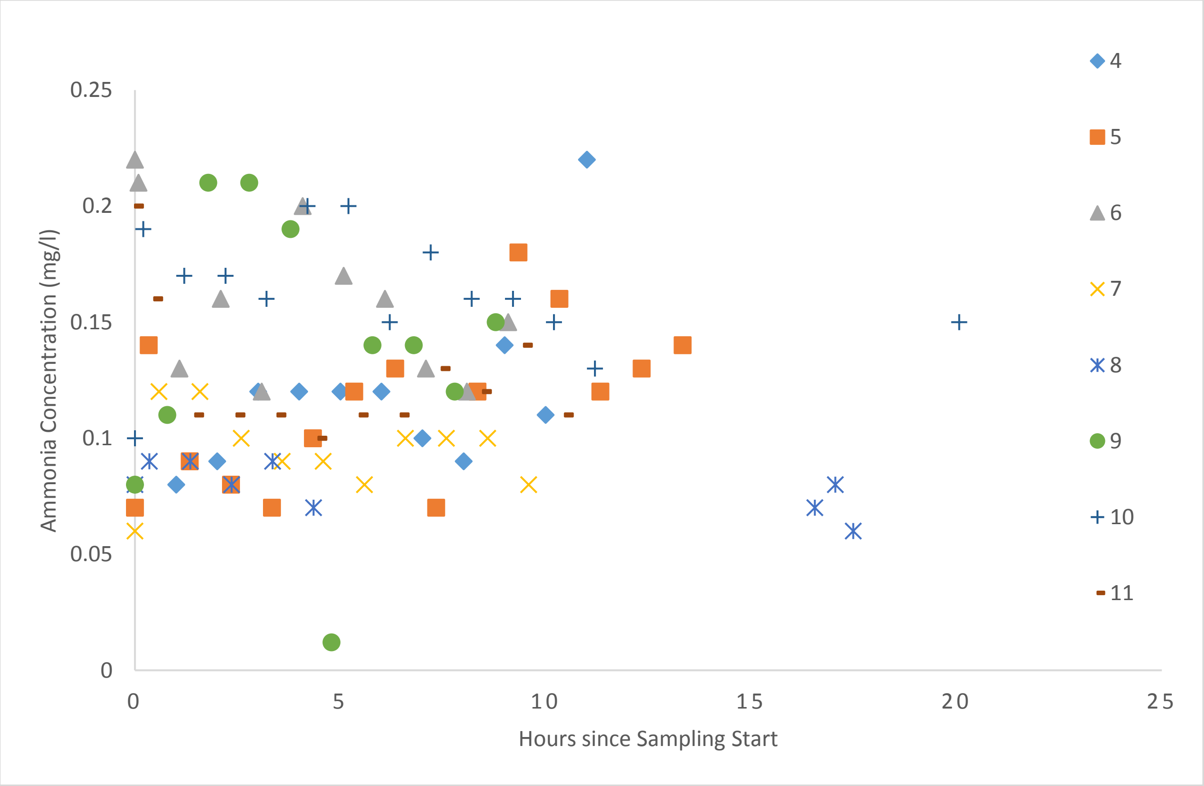


Figure 4-14: Ammonia concentration shown at relative sampling time per event. Event numbers displayed on the right border.

Unlike the other parameters, Ammonia concentrations do not show a tendency for increasing or decreasing concentrations. No clear pattern can be discerned here, and Figure 4-15 indicates that values appear to be varying only slightly from the mean. Furthermore, overlapping error bars indicate that no significant difference can be inferred between readings.

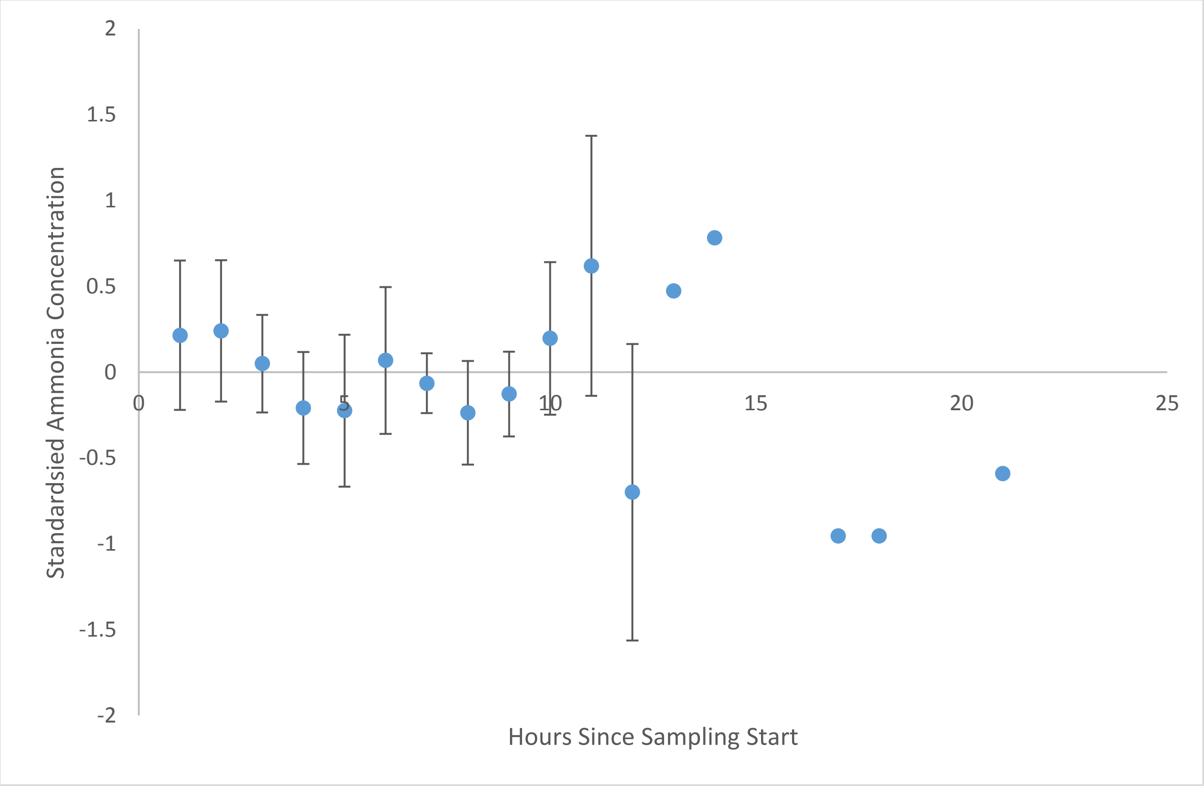


Figure 4-15: Event-standardised Ammonia concentrations aggregated according to sampling time

4.2.2.5 pH

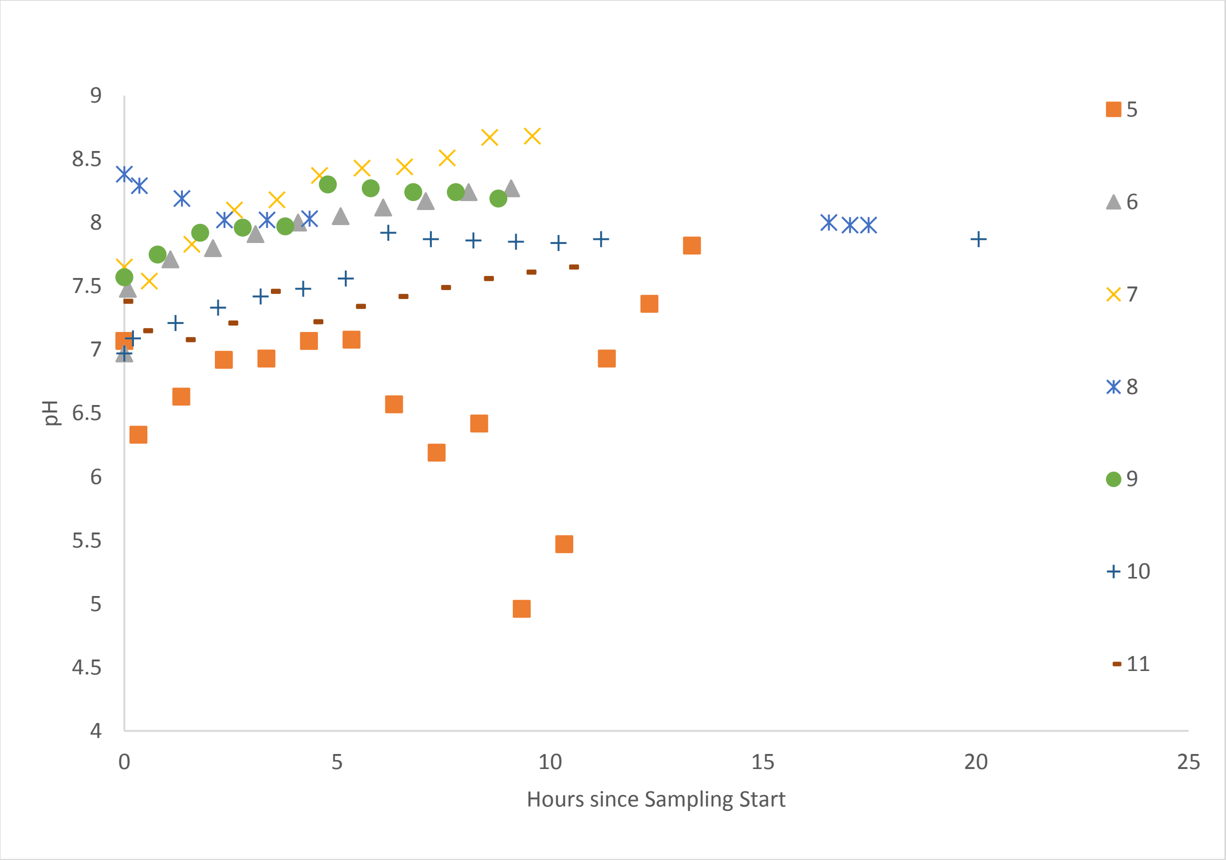


Figure 4-16: pH shown at relative sampling time per event

pH progresses very consistently to a level between 7.5 and 9, with only event 7 climbing above a pH of 8.5. Event 8 is an exception in that it is the only event where pH decreases during the event, whereas all other event show an increase. Event 5 also shows a sharp drop in pH which is not evident in any other storm event. Figure 4-17 shows the trend of smooth progression during events. While most of the error bars overlap, there is still a strong correlation evident in this data. The trend is one of increasing pH, which saturates out.

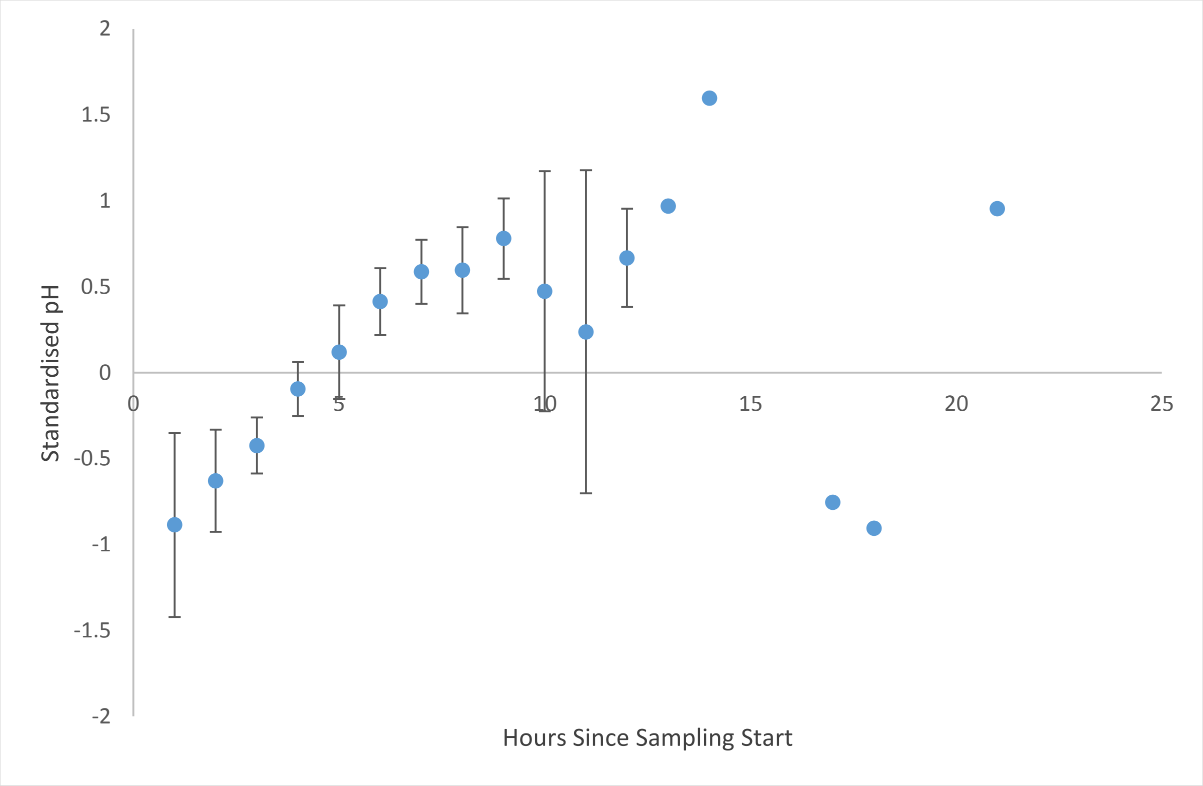


Figure 4-17: Event-standardised pH aggregated according to sampling time. A smooth 'saturation curve' pattern is evident.

4.2.3 Correlations

4.2.3.1 Linear Correlation

Table 4-3: Correlation coefficients for each water quality parameter and selected rainfall characteristics. Bold numbers indicate a level of significance of above 0.1, underlined bold number indicate a significance level above 0.05

Drivers	**TSS**	**EC**	**o-Phosphate**	**Ammonia**	**pH**
Event	0.371	-0.599	**0.636**	0.132	0.494
Event Rainfall (mm)	-0.390	-0.348	-0.076	-0.457	-0.221
Cum. Meas. Rainfall (mm)	0.362	-0.615	**0.637**	0.135	0.486
ADWP (Days)	-0.209	-0.581	0.265	-0.034	-0.301
TSLME (Days)	0.173	**-0.669**	**0.659**	-0.097	-0.013

TSS	-	0.309	**0.802**	0.606	0.128
EC	-	-	-0.181	0.194	-0.299
o-Phosphate	-	-	-	0.304	0.123
Ammonia	-	-	-	-	-0.046
pH	-	-	-	-	-

Error! Reference source not found. above shows the correlation coefficients between each parameter and Total Event Rainfall, Cumulative Rainfall and Event Number. Cumulative Rainfall was computed by cumulating only qualifying rainfall events (i.e. cumulative rainfall at event 5 would be Total Event Rainfall of event 4 and 5 added). As such, there is an obvious forced correlation between Cumulative Rainfall and Event Number.

If a parameter correlates strongly with rainfall, this would suggest that said parameter is highly event-specific. Alternately, if it correlates strongly with Event Number, this would suggest that the parameter is more dependent on the inter-event progression of the system. Cumulative rainfall is essentially a combination of the two, representing the effect of the total amount of water that has run through the pavement on the parameters.

Table 4-4: Levels of Significance for correlation coefficients at six degrees of freedom (Siegle, 2015)

Level of Significance:	**0.1**	**0.05**	**0.02**	**0.01**
Correlation Coefficient:	0.622	0.707	0.789	0.834

Error! Reference source not found. shows the different significance levels for correlation coefficients at six degrees of freedom (df). The only parameter which shows statistical significance at any level for any of the selected rainfall characteristics is Orthophosphate. It shows significant correlation at a 0.1 significance level for both Cumulative Rainfall and Event Number.

TSS shows a slight negative correlation with rainfall, and equally weak correlations with event number and cumulative rainfall. All parameters show a slight negative correlation with rainfall, which can be attributed to dilution effects of higher rainfall.

Error! Reference source not found. also shows cross-correlations between parameters. Correlations between parameters may be due to causality (parameter A causes parameter B), shared causality (another factor causes A and B) or coincidental. A strong correlation is evident between Orthophosphate and TSS. While not as strong, a correlation between Ammonia and TSS is also evident. Apart from these two relationships, the remaining parameters show weak correlation.

4.2.3.2 Rank Correlation

A rank correlation measures the strength of interactions between parameters by correlating the relative rank of each reading with the rank of the paired parameter. This helps in reducing the dependence of the correlation on a linear relationship between two parameters. In an attempt to identify the driving parameter between the curious progression displayed by both TSS and Orthophosphate, both parameters were rank-correlated with Event number, Event Rainfall, Cumulative Rainfall, TSLME and ADWP.

The following is a table of the results of rank correlation between the parameters themselves as well as all possible rainfall drivers:

Table 4-5: Rank correlation matrix between parameters. Note significant correlation between TSS, O-Phosphate and TSLME

Drivers	**TSS**	**EC**	**o-Phosphate**	**Ammonia**	**pH**
Event	0.310	-0.571	0.595	0.024	0.310
Event Rainfall (mm)	-0.524	**-0.690**	-0.167	-0.500	0.024
Cum. Meas. Rainfall (mm)	0.310	-0.571	0.595	0.024	0.310
ADWP (days)	-0.096	**-0.659**	0.132	-0.180	-0.132
TSLME (Days)	**0.762**	-0.310	**0.929**	-0.071	0.119
TSS	-	0.262	**0.857**	0.429	0.143
EC	-	-	-0.119	0.476	0.286
o-Phosphate	**-**	-	-	0.190	0.048
Ammonia	-	-	-	-	-0.333
pH	-	-	-	-	-

Using rank correlation, Orthophosphate and TSS still correlate strongly with each other, sufficiently to satisfy a 0.05 significance level. But now, both Orthophosphate and TSS also correlate with the time between measurable events. Both correlations are strong enough to satisfy statistical significance. EC now shows a stronger correlation with event rainfall, but weaker correlation with event number. All other parameters show some positive correlation with TSS, but to no particular statistical significance. Again, most parameters show a negative correlation to Event Rainfall, with pH being the only one to show virtually no correlation to this driver. Ammonia levels display a slight positive correlation to both EC and TSS.

4.3 RPPS & RTS

Samples from RPPS and RTS 1 and 2 are summarised in Table 4-6 below. Values were averaged across the three winter events sampled. RPPS was characterised by low TSS values, a pH close to 8 as well as low orthophosphate and ammonia values. The average EC value of 97.896 µS/cm was lower than those taken during the pilot study, and was within the standard error margin of the EC of RTS 2.

RTS 1 & 2 both show significantly higher TSS values than RPPS, as well as significantly higher ammonia values. ammonia values of RTS 1 and 2 are have overlapping error bars, but RTS 2 shows significantly higher orthophosphate levels. RTS 2 shows lower ammonia values when compared to the pilot study, but orthophosphate levels are approximately equal. EC values dropped to about half the levels seen in the pilot study.

Table 4-6: Average values and standard error for samples collected from RPPS and RTS 1 and 2

Site	TSS (mg/l)		pH		Orthophosphate (mg/l)		Ammonia (mg/l)		EC (µS/cm)	
	Average:	SE:	Average:	SE:	Average:	SE:	Average:	SE:	Average:	SE:
RPPS	4.156	2.287	7.979	0.253	0.071	0.013	0.078	0.015	97.896	13.780
RTS 1	27.215	21.042	8.228	0.195	0.096	0.015	0.231	0.056	39.017	10.152
RTS 2	31.736	15.760	7.686	0.102	0.844	0.165	0.174	0.020	84.433	3.840

4.4 NEB-I & P8

Both the impermeable reference site and the parking lot P8 were monitored with sequential bottle samplers, a methodology which differs significantly from those used to monitor RPPS, NEB-B and RTS. Results are listed in Table 4-7 and Table 4-8 below. Due to the discretized values caused by the consequential bottle system, it makes more sense to compare ranges of values, and averages for each bottle than to attempt a high-resolution analysis. Sparse data from NEB-I due to inaccessibility limits the representativeness of this dataset.

Table 4-7: Water quality values from P8

	pH	EC	Orthophosphate(mg/l)	Ammonia (mg/l)	TSS (mg/l)
Max	8.1	291	4.93	3.5	668
Min	6.12	21.4	0	0.12	4
Bottle 1	7.178	132.42	0.625	1.736	79.29
Bottle 2	7.314	80.84	0.17	1.176	95.40
Bottle 3	7.436	47.8	1.7425	0.234	350.59

Results from P8 showed the highest values of orthophosphate, ammonia and TSS across the entire study. In fact, 7 of a total of 15 readings exceeded the threshold of accurate Ammonia readings. Of those 7, 3 exceeded the detection limit of 3.5 mg/l. Where this occurred, readings were listed as 3.5 mg/l. One sample also exceeded the accuracy threshold for orthophosphate readings of 2.5mg/l.

High ammonia levels are generally associated with the first two bottles, which are representative of only a small fraction of the storm event. High orthophosphate levels are evident in both the first and last bottles. TSS levels exhibit a wide range, but may be artificially elevated in the last bottle due to materials settling out throughout the storm event. Suspended solids appeared to be quite large, and mostly organic in composition and samples from this site showed visible discolouration.

NEB-I showed the lowest average orthophosphate values in the study, with averages mostly beneath 0.1mg/l. Ammonia was also lower here than at P8, as were TSS levels. Interestingly, the highest TSS, orthophosphate and ammonia averages at this site were found in the second bottle. It should be noted that, while there was insufficient data to verify this, orthophosphate appeared to become elevated later in the study period.

Table 4-8: Water quality values from NEB-I

NEB-I	pH	EC	Orthophosphate(mg/l)	Ammonia(mg/l)	TSS(mg/l)
Max	9.46	152.9	0.35	1.52	100
Min	7.69	56.4	0	0.1	6
Bottle 1	8.63	98.33	0.08	0.21	28.33
Bottle 2	8.85	73.93	0.18	0.59	56.33
Bottle 3	8.92	91.27	0.05	0.22	6

4.5 Summary Statistics

Table 4-9 below displays the summary averages across all events. The sites monitored with sequential samplers show very high variability due to the nature of the methodology (for instance, P8 has an SEM of more than 50%). Since the methodologies differ amongst sites, cross correlation between these sites is unfeasible, but the results do give context for the analysis of results from NEB-B. It is evident, for instance, that NEB-B shows the highest EC values, and that TSS values are comparable to most impervious sites, although TSS variability is far lower. Orthophosphate levels are higher in NEB-B than in most sites excluding P8 and RTS 2, and ammonia levels are slightly higher than in RPPS, but consistent.

Table 4-9: Summary averages across all sampling sites (excluding pilot). Results reported with Standard Error of the Mean (SEM).

	pH	EC (µS/cm)	o-Phosphate (mg/l)	Ammonia (mg/l)	TSS (mg/l)
NEB-B	7.477 ± 0.075	168.323 ± 4.951	0.173 ± 0.010	0.125 ± 0.004	26.008 ± 2.789
RPPS	7.947 ± 0.157	93.700 ± 10.415	0.080 ± 0.020	0.093 ± 0.024	4.233 ± 1.351
NEB-I	8.801 ± 0.250	87.844 ± 10.271	0.094 ± 0.042	0.340 ± 0.150	35.067 ± 14.481
UCT P8	7.309 ± 0.177	87.020 ± 18.971	0.846 ± 0.457	1.049 ± 0.378	165.512 ± 52.214
RTS 1	8.175 ± 0.195	35.807 ± 7.868	0.093 ± 0.023	0.215 ± 0.050	23.014 ± 15.223
RTS 2	7.609 ± 0.099	77.333 ± 7.252	0.808 ± 0.137	0.179 ± 0.015	31.771 ± 10.267

4.6 Heavy Metal Results

The only results available for heavy metal analysis were for Copper (Cu) and Lead (Pb), and are summarised in the table below. Very little analysis for the samples were possible in this study, but Cu concentrations PPS are around 25µg/l, and 3.5-4.8µg/l for Pb. Lowest heavy metal concentrations overall were evident in RTS, with the highest in NEB-I.

Table 4-10: Heavy metal concentrations for Pb and Cu. Note the highest concentrations evident in NEB-I, which generally showed low results for other parameters. Average and standard error for each are shown.

Sites:	Pb (µg/l):		Cu (µg/l):		
	Average:	SE:	Average:	SE:	Number of Samples
NEB-B	4.865	0.741	25.932	3.921	91
RPPS	3.505	1.443	24.270	15.375	11
RTS 1	4.951	2.578	5.933	1.840	12
RTS 2	4.084	2.470	9.390	3.080	9
NEB-I	10.372	6.359	59.913	13.876	9
P8	6.339	5.273	48.557	22.495	16

4.7 Results Summary

While the results showed significant variability which makes discerning clear trends challenging, some key results can be summarised for analysis:

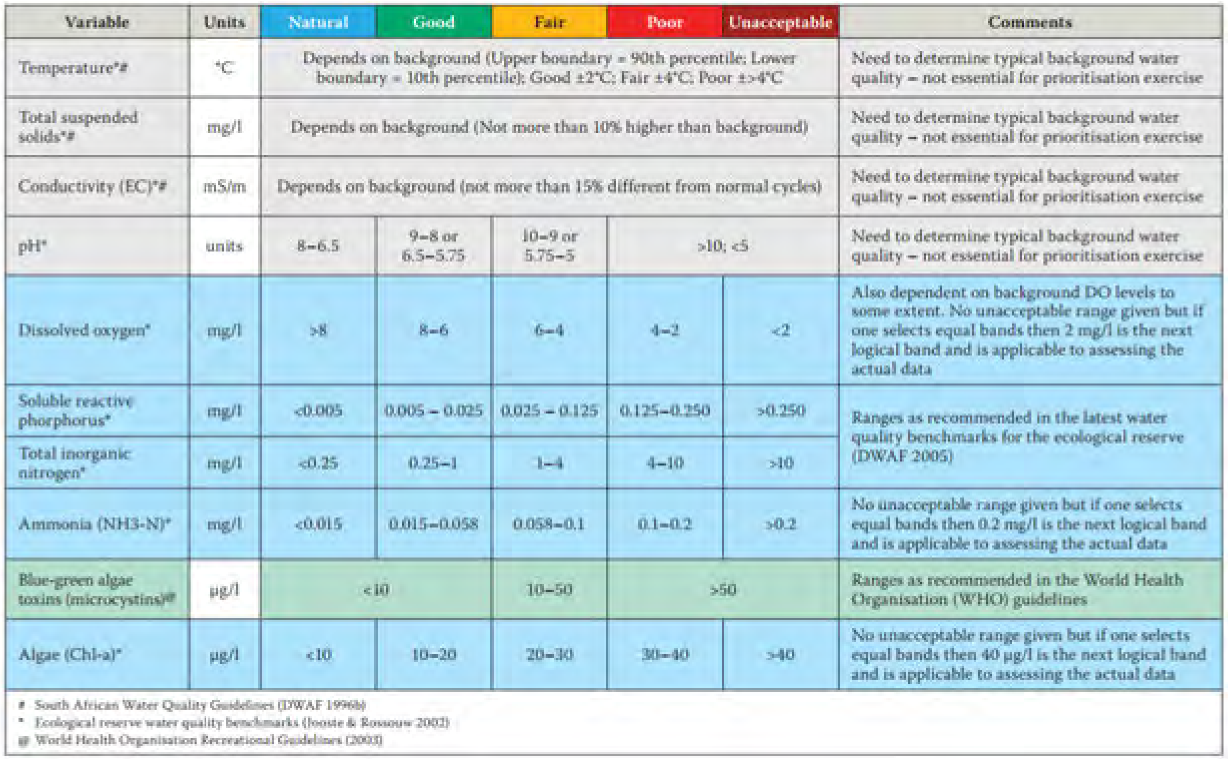
- NEB-B concentrations for TSS and orthophosphate were higher than expected; as this site treated only its own runoff, it was expected to have lower effluent concentrations than RPPS. The TSS was caused by the use of unwashed aggregate, which may have had an impact on orthophosphate levels as well
- Impermeable sites showed considerable variability in runoff concentrations, both temporally and between sites.
- Inter-event progressions from NEB-B were observed for EC, TSS and orthophosphate. Trends for orthophosphate and TSS were not easily explained, but may be related to the parameter TSLME.
- Intra-event progressions were observed for all parameters except for ammonia. In all cases, the average of the first two samples differed considerably from the event mean

5 - ANALYSIS

Elevated TSS and orthophosphate levels shown in the results may be a concern for the potential reuse of stormwater and could have impacts on downstream ecosystems. This section will analyse the effluent water quality from PPS against target water quality criteria.

5.1 Water quality from NEB-B: 'fit for use'?

To analyse the performance of NEB-B, the water quality must be evaluated against target water quality for its intended use. The South African Water Quality Guidelines are used to evaluate whether PPS effluent meets target water quality for harvesting and reuse. The SAWQG will be used in conjunction with a scoring system proposed by Nel *et al.*,(2013) for aquatic ecosystem assessments in the City of Cape Town. This used research on the background water quality status and the impacts of concentrations of certain parameters to create a set of water quality categories for rivers in the Cape Town region. These categories range from 'natural' to 'unacceptable' depending on the significance of the impact (Figure 5-1). As categories overlapping with this study include only ammonia and orthophosphate, water quality impacts from PPS can only be evaluated with respect to eutrophication risk.



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 phorphorus*	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 (NH3-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)

Figure 5-1: Ecosystem health criteria categories and thresholds from Nel *et al. (* 2013)

5.1.1 Total Suspended Solids

TSS levels are particularly relevant when the outflow is intended for reuse. Excessive TSS levels may cause clogging or fouling of machinery and irrigation equipment, create a surface crust which impedes plant growth and sprouting and affect the performance of industrial processes (Department Of Water Affairs And Forestry, 1996). In aquatic ecosystems, increases in TSS will reduce clarity, thereby reducing water temperatures, photosynthetic activity and hampering predatory fish. High levels of TSS may also damage fish gills.

While the South African Water Quality (SAWQ) guidelines clearly stipulate TSS levels for industrial process categories and irrigation, as well as potential hazards of exceeding those guidelines, aquatic ecosystems are more complex in that many ecosystems have a pre-existing background levels of TSS, and impacts of TSS are thus evaluated against the ecosystem-specific background levels.

5.1.1.1 Irrigation

Most of the norms of TSS concentration are qualitative, and have no numerical data associated to them. However, guidelines do exist for the impact of TSS on the clogging of drip irrigation systems. These are categorised into virtually no impact (0-50mg/l), slight to moderate impact (50-100mg/l) and increasingly severe impact (>100mg/l). On average, TSS from NEB-B falls into the virtually no impact category, and effluent can thus be recommended for use. Only 11 readings from NEB-B exceeded the 50mg/l threshold, and only one exceeded the 100mg/l threshold. This accounts for about 13% of the total readings. Since the TSS levels are expected to drop as solids migrate out of the pavement, future use should be secure. Furthermore, TSS from the PPS exhibits a strong first flush signature, and a first flush separator may be sufficient to remove sufficient TSS to mitigate damage to irrigation systems and other negative impacts.

5.1.1.2 Industrial Use

Most industrial processes (category 1-3 according to SAWQ guidelines) require water with very low TSS concentrations, and stormwater from PPS would be unsuitable for these. Category 4 industrial processes are less sensitive, and include uses such as irrigation, rough washing, firefighting and dust control. While levels below 25mg/l are recommended, 25-100mg/l will cause only minor impacts. If NEB-B develops as expected, and begins to show TSS levels similar to RPPS, water from this site could be used for Category 4 processes.

However, effluent from PPS constructed with unwashed stone should not be used for industrial processes within the first year, possibly longer. While water may be post-treated, it may be more efficient to wait until solids flush out of the pavement.

5.1.1.3 Aquatic Ecosystems

The SAWQ for Aquatic Ecosystems suggests that TSS changes in aquatic ecosystems may not be more than 10% of background levels. This makes evaluating water from a SuDS more complicated, as it requires knowledge of the background TSS levels in the receiving aquatic ecosystem (which are inherently dynamic), knowledge of TSS levels in SUDS effluent and knowledge of the mixing ratio of effluent versus receiving waters. Additional complexities may be introduced by the settling rate of the TSS and the transport capacity of the ecosystem in question.

Without knowing any of the factors above, it is difficult to adequately analyse the impact of PPS. The fact that NEB-B is actively exporting TSS is a concern, but levels of TSS are not above those from impervious sites, while peak flow rates and total outflow from PPS are reduced. This means that even though NEB-B is a net TSS exporter, it probably still reduces the TSS load to receiving systems when compared to impervious surfaces. Also, it reduces the number of outflow events and therefore the number of polluting events significantly, as roughly 80% of all events and thereby just less than 50% of all rainfall is retained within the pavement structure[1].

Simply permitting water to pass through a settling structure is likely to remove appreciable amounts of TSS. The catchment chambers were frequently filled with significant TSS deposits after rainfall, suggesting TSS removal by settling.

5.1.2 Ammonia

Total Ammonia (TAN) is a combination of unionised ammonia (NH_3) and ammonium (NH_4^+), where the former exhibits toxic effects and the latter may contribute to eutrophication as an ionised form of nitrogen. The relationship between unionised ammonia and total ammonia is dependent on pH and water temperature. For the pH and temperature ranges present in this study, the coefficient for the conversion of total ammonia to unionised ammonia ranges from 0.59 (pH 6.5, T 10ºC) to 5.3 (pH 8, T 25ºC). Since temperatures were not measured the range from 10º to 25º was used as an upper and lower bound. Under the pH

---

[1] According to rainfall data gathered 01/11/2014-01/11/2015.

conditions prevalent in NEB-B, the highest NH_3 reading was recorded at 0.015 mg/l, well below the target water quality range of 7 mg/l.

While this means that none of the ammonia emitted would have displayed toxic effects, virtually all of the ammonia was released as bioavailable ammonium ions. According to the ecosystem criteria categories, the ammonia levels from NEB-B vary between ‘poor’ and ‘fair’.

5.1.3 Orthophosphate

The recommended level of orthophosphate in rivers and streams is listed in the guidelines for aquaculture rather than in aquatic ecosystems. The threshold is given as 0.1mg/l in order to protect the trophic status of rivers and streams. Only RPPS, NEB-I and RTS 1 averaged orthophosphate below this level, suggesting that phosphate effluent may be a concern for PPS effluent. According to the ecosystem health criteria, effluent from NEB-B would be classified in a range from ‘poor’ to ‘unacceptable’

However, the effect of these concentrations in receiving rivers and streams is again difficult to quantify, as the mixing dynamics are unknown. Furthermore, if the stormwater system (including streams) discharges into the ocean, potential negative impacts due to Orthophosphate may be avoided as eutrophication in marine environments is usually caused by nitrogen loadings. Regardless, if effluent is discharged into receiving waters or the stormwater system, it should receive further treatment to reduce the phosphate levels.

Phosphate is not a constituent in any of the other water quality requirements, and the slightly elevated levels of phosphate from NEB-B are likely to have some benefits for plant growth if used for irrigation. Intercepting, and using effluent for irrigation should have an added benefit for downstream aquatic systems, as the phosphate levels are likely to be reduced due to filtration and adsorption in the soil.

5.1.4 Electrical Conductivity

EC is often used as an approximating parameter for Total Dissolved Solids (TDS) as it captures all the inorganic ions dissolved in water. It is thus an estimate of salts dissolved in the water, which can affect industrial processes by scaling, corrosion and precipitation. In irrigation, salt sensitive crops may show reduced yields from 900 µS/cm EC. In industrial processes, negative impacts start to show with EC levels of 400 µS /cm. Since the highest recorded EC showed at about 220 µS/cm for NEB-B and 280 µS /cm for RPPS, both values are safely below the 400 µS /cm requirement for the most sensitive industrial processes. Furthermore, soil salinization will not be a concern if the water should be used for irrigation.

5.1.5 pH

The pH range from 6.5-8.0 of PPS effluent meets the target water quality requirements for industrial processes of category 2 or higher, and for irrigation. Whether or not it meets the aquatic ecosystem requirements will depend on local conditions. At those levels, pH is not likely to elicit any other side effects such as increased solubility of heavy metals or increased levels of toxic unionised ammonia. pH levels are important for many aquatic processes, and varying pH can be detrimental to aquatic ecosystems. But the pH levels in the pavement vary, on average, between 6.5 and 8 over sufficiently long periods that aquatic ecosystems would adapt readily

5.1.6 Heavy Metals

The SAWQG does not set limits for Lead or Copper concentrations for industrial use, but they do set criteria for aquatic ecosystems and irrigation. For irrigation, the thresholds for bothlead and copper are 0.2 mg/l (200 µg/l). Below this level, no significant impacts on plant growth are expected. The effluent from NEB-B is well below that threshold; for aquatic ecosystems, however, the Chronic Effect Values are 0.53µg/l and 0.5 µg/l for copper and lead respectively, with target water quality ranges of 0.3µg/l and 0.2 µg/l respectively. All sites consistently show levels above this, and thus none of them should discharge into the aquatic ecosystem.

5.1.7 Is NEB-B Effluent ‘fit-for-use’?

While there are several water quality constituents which affect the suitability of water for a particular use or process which have not been assessed, the effluent from NEB-B appears to be suited for reuse, given certain restrictions. The high TSS due to unwashed stone may be a nuisance, and the high orthophosphate levels would likely impact downstream ecosystems if PPS were more widely implemented.

While it is unlikely that NEB-B effluent could have been contaminated with pathogens or faecal coliforms, it would still be prudent to sterilise harvested water before using it for indoor purposes and for growing produce. However, for outdoor use and irrigation of gardens, effluent from NEB-B could be used immediately.

5.1.8 Target Water Quality Ranges for Aquatic Ecosystems

The SAWAQ for Aquatic Ecosystems and the ecosystem categories derived by Nel *et al.* *(*2013) guided the water quality thresholds derived for the classification of effluent from PPS. Figure 5-2 and Figure 5-3 illustrate the number of samples which fall into each of the ecosystem health categories. For NEB-B, ammonia readings fall into the 'poor' and 'fair' categories, while a significant number of samples also fall into the 'unacceptable' category. For RPPS, most orthophosphate readings fall into the 'fair' category, while ammonia is spread fairly evenly amongst the categories, though with a tendency towards 'poor'.

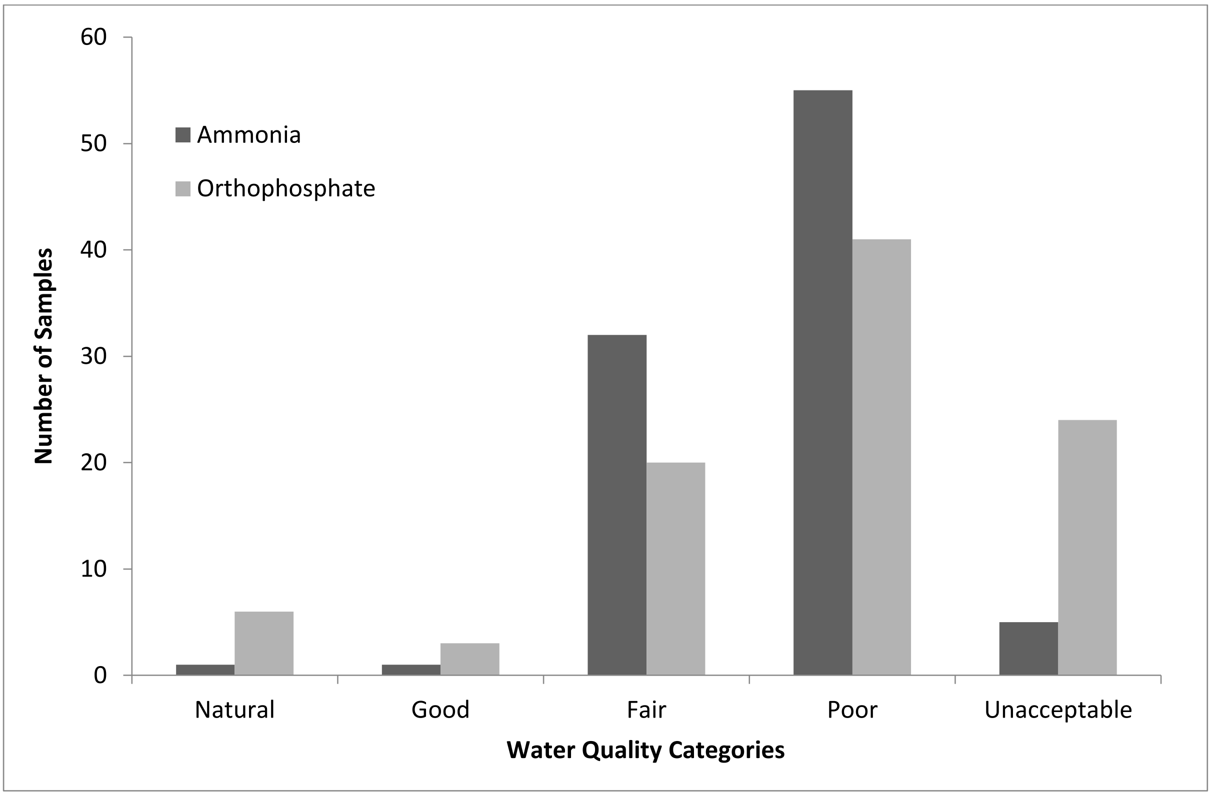


Figure 5-2: Bar graph depicting the distribution of NEB-B sample concentrations as categorised against criteria outlined by Nel *et al*, (2013).

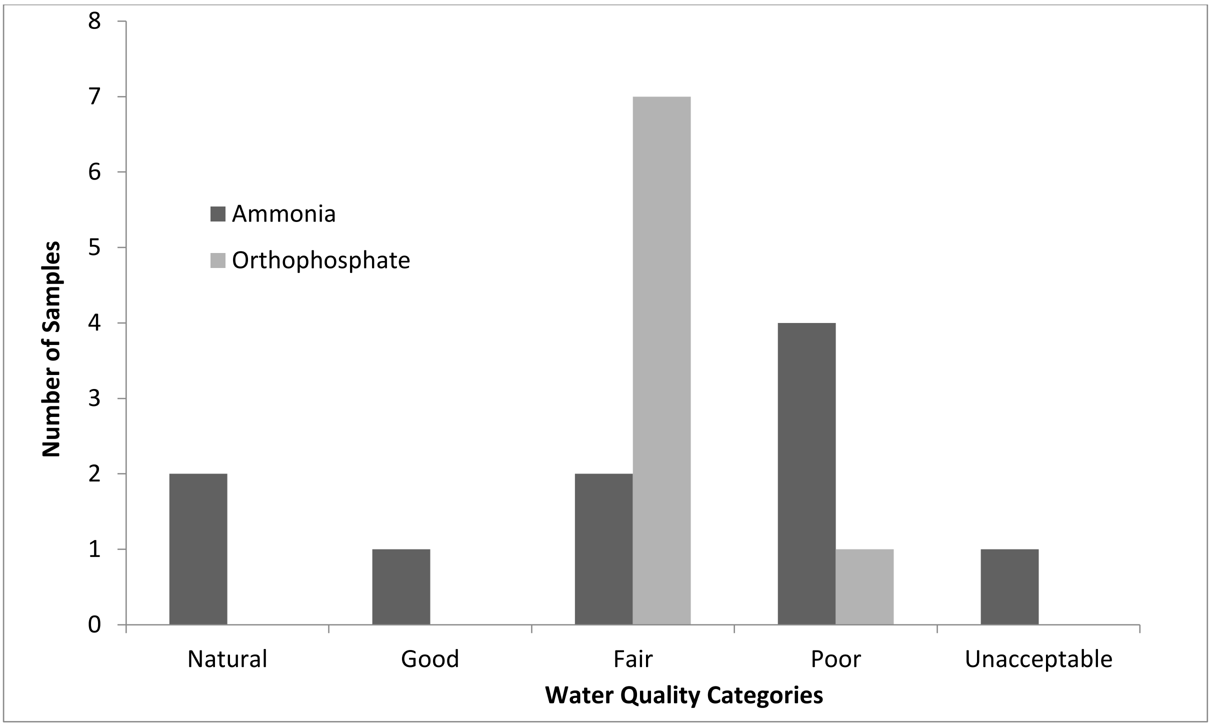


Figure 5-3: As Figure 5-2 above, for RPPS

According to Nel *et al*, 2013, this means that most ammonia levels from NEB-B, if they were to translate into the same concentrations in the downstream aquatic ecosystem, would elicit eutrophic to hypertrophic conditions. This model assumes that NEB-B is the only source of water and nutrients to downstream systems.

The categories for orthophosphate differ from those prescribed in the SAWQ Guidelines. These recommend that O-phosphate is to be kept below 0.1mg/l in streams to prevent trophic changes. This threshold would score ‘fair’ in the ecosystem criteria, and be predicted to cause eutrophic conditions in downstream lakes.

The results indicate that PPS will likely be unsuitable as a stand-alone implementation to achieve ecological targets. They exhibit nutrient levels which may pose a risk for the trophic status in downstream ecosystems in the City of Cape Town.

5.2 Performance of NEB-B against other sites and Literature values

The table below compares the pollution performance per site for nutrient and TSS parameters. Values from Newman *et al. (*2013) for stormwater concentrations and PPS concentrations were included in the table. Two permeable pavements reported on were described as the NATS car park (Macdonald & Jefferies, 2001 cited in Newman *et al*, (2013) and the Royal Bank of Scotland car park (Schlüter & Jefferies 2001 cited in Newman *et al,* 2013).

Table 5-1: Comparison of results from this study with results summarised by Newman *et al.*, 2013

Parameters	Concentration levels in stormwater (Mitchell *et al*., 2012)		Concentration levels in stormwater (Heal *et al*,. 2009)	Concentration levels in RBS PPS Car park effluents (Schlüter and Jefferies, 2001)		Concentration levels in NATS PPS Car park effluents (Macdonald and Jefferies, 2001)		Averages from this study						
	Global Mean conc.	UK Mean conc.	Mean conc.	Min	Max	Min	Max	*RPPS*	*NEB-I*	*UCT P8*	*RTS 1*	*RTS 2*	***NEB-B***
TSS (mg/l)	138.9	55.2	16.8	1	68	9.8	24	4.233	35.067	165.512	23.014	31.771	**26.008**
NH4–N (mg/l)	0.45	0.55	0.08	0.02	0.57	0.03	1.13	0.08	0.094	0.846	0.093	0.808	**0.173**
o-Phosphate (mg/l)	–	–	–	0.05	0.53	0.01	0.23	0.08	0.034	1.049	0.215	0.179	**0.125**

Average TSS levels from NEB-B are within the range of the RBS PPS Car Park, though they exceed the range of the NATS PPS Car Park. The full range of TSS recorded in NEB-B was 0-186.4 mg/l, which is higher than the ranges reported for NATS and RBS. Evaluating comparative performances with ranges is challenging; especially as 92 out of 94 readings fall within the RBS PPS range. RPPS shows the best performance for TSS, with a TSS range of 0 to 10 mg/l. Comparatively, a global study aggregating TSS data for 67 rivers showed the lowest TSS concentration as 5mg/l (Meybeck *et al.*, 2003).

NEB-B orthophosphate average values also fall within the ranges of NATS and RBS, though the maximum value for orthophosphate from exceeds the NATS maximum recorded value. Other field testing literature results showed orthophosphate levels of 0.013-0.23mg/l (Brown & Borst, 2015) and 0.08-0.30mg/l (Bean *et al.*, n.d.). The ranges from all four studies overlap with each other and the ranges from RPPS and NEB-B.

Ammonia values were higher at NEB-B than at several impermeable sites and RPPS, but still present an improvement over the UK and global ammonia averages, as well as an improvement over P8 and RTS 2. The ammonia ranges seen in RBS and NATS show significantly higher concentrations than recorded in either PPS.

5.3 Summary of Analysis

Analysis of the results from PPS study has yielded several key findings:

- Effluent from PPS is acceptable for most of the use cases which it is likely to be selected for, despite contamination by sediment from unwashed aggregate.
- Both NEB-B and RPPS frequently exceed the prescribed nutrient thresholds specified by Nel *et al.* *(*2013). As such, they cannot safely be recommended as stand-alone treatment devices for the Cape Town area.
- Effluent concentrations from NEB-B and RPPS are comparable to several international PPS installations. Particularly interesting is that there appears to be a common orthophosphate range of 0~0.3 mg/l across several studies.

6 - DISCUSSION

This study aimed to assess the use of permeable pavements for stormwater management in Cape Town, South Africa. Permeable pavements are widely covered in the literature, and have commonly been praised for their significant pollutant removal and hydrological capacity while providing additional lateral and direct benefits. As they can contribute to stormwater management while still retaining all the benefits of traditional impermeable surfaces they do not compromise space for urban development. Since the City of Cape Town is moving towards runoff mitigation as a requirement, interest in SuDS is rising and several new developments have begun to include permeable pavements as a mitigation measure. This study has investigated the literature reported performance of PPS and conducted a thorough analysis of selected pollutant parameters from a newly constructed PPS. The discussion centres on the assessment of PPS performance, before analysing the methodology used and illustrating potential sources of error.

6.1 PPS in Literature

The findings in the literature review show a common theme: that PPS are an effective SuDS tool with significant removal capabilities for hydrocarbons, heavy metals and total suspended solids, and variable reports for removal of nutrients. The hydrological performance of PPS has mostly been analysed site-specifically, rather than assessing the catchment wide benefits and performance criteria tend to be peak flow attenuation and volume reduction. Only one study assessed the reduction on Effective Imperviousness, and found a significant reduction in EI.

6.1.1 Performance Assessment of PPS

While stormwater management is increasingly moving towards the ecohydrological approach suggested by Walsh and other Australian authors, where ‘performance’ is catchment-specific and criteria are improved ecological function of downstream aquatic ecosystems, the performance assessment of PPS remains largely limited to impact mitigation by percentage reduction criteria. The City of Cape Town uses percentage reduction as a requirement, whereby Brownfield developments are required to reduce TSS and Phosphate by 85 and 45% respectively (City of Cape Town, 2009).This despite the recommendation of the United States Environmental Protection agency that BMP (SuDS) performance should not be evaluated using percentage reduction, as the metric does not accurately represent impacts to aquatic ecosystem health (USEPA, n.d.).

Furthermore, the requirement of on-site treatment and flow reduction is insufficient by itself. SuDS have been shown to have complex interactions at the catchment level which may lead to cumulative impacts that are ignored in current requirements (Petrucci *et al.*, 2013). Addressing these concerns will require absolute quality standards on discharge to streams, reducing catchment effective imperviousness to below a threshold level and prescribing site appropriate flow management targets to prevent peak flow superposition and promote adequate groundwater recharge.

6.2 Assessing NEB-B

The study found that water quality of NEB-B was suitable for irrigation and category 4 industrial processes. It is also likely suited for some domestic processes such as flushing toilets, though the water may require further sterilisation and filtration.

It becomes more difficult to assess the water quality for aquatic ecosystems. The concentrations of orthophosphate and ammonia regularly exceed the recommended standards for streams in Cape Town. However, since the change in concentration in the receiving stream will depend on the streams prior concentrations, its flow rate and the flow rate from NEB-B. It is likely that NEB-B effluent may actually decrease downstream concentrations, as Cape Town's urban rivers commonly carry significant nutrient loads (Haskins, 2012; Nel *et al.*, 2013)

While the concentrations exhibited in NEB-B were quite variable, they are not outside the range of other O-Phosphate levels reported in the literature (Tota-Maharaj *et al.*, 2010; Newman *et al.*, 2013). Single sites from the UK also showed considerable O-Phosphate variation within a single pavement (Table 5-1). This suggests NEB-B concentrations are not unusual, which means that PPS in Cape Town will require further treatment to reduce nutrient concentrations before they become sufficiently effective at mitigating downstream impacts.

Heavy concentrations have been shown to be consistently above target water quality ranges for Copper and Lead. Curiously, PPS has been attributed with significant heavy metal removal, and indeed it appears that NEB-B has achieved about 50% reduction over NEB-I. However, still remains insufficient to meet water quality targets for aquatic ecosystems.

Again, the true impacts to the stream will only be determined if the load contribution of heavy metals is considered. It is also interesting to note that 40 out of 91 samples analysed for lead yielded non-detects, suggesting that lead deposition is highly variable.

6.2.1 Pollution Reduction

The issues around using percentage reduction to quantify the performance of SuDS have been discussed in depth in this study. However, City of Cape Town Regulations stipulate percentage reduction of phosphate and TSS as a management objective. While other studies have achieved this in the past by comparing PPS to specific impermeable reference sites, the inherent spatial and temporal variability of stormwater pollution is likely to give highly skewed data at the site scale. For instance, RPPS orthophosphate reduction would vary from 55% to 63% depending on whether it is compared to RTS 1 or RTS 2. If compared to NEB-I, which is most similar in land use, its orthophosphate reduction would be -135%. Similarly, it would show a removal rate of TSS of 97% if compared to P8, as opposed to 81% if compared to RTS 1.

With these limitations in mind, NEB-B displays TSS reduction rates of 26%, 84%, -13% and 18% for NEB-I, P8, RTS 1 and RTS 2 respectively. Similarly, orthophosphate reduction rates are -267%, 88%, 42% and 30% respectively. Clearly, there is no coherence in these performance rates, and they are likely to be more reliant on local pollution characteristics. Regardless, it appears that NEB-B does not meet the City of Cape Town's requirement of 85% TSS reduction, and it does not provide 45% orthophosphate reduction – although this parameter cannot be used as a simple proxy for total phosphorous levels which include particulate bound phosphorous.

6.2.2 Pollutant Progression

NEB-B was a new PPS, and the inter-event progression of the outflow quality showed definite patterns. First, it is interesting to note that none of the pollutant parameters showed a statistically significant correlation with total rainfall, which has been identified as one of the main factors driving EMCs (Brezonik & Stadelmann, 2002; Kim *et al.*, 2007; Maniquiz *et al.*, 2010)). None of the studies investigating this have focused on effluent from SuDS; however the drivers of EMCs from PPS effluent are far less understood, with most studies focussing on PPS removal efficiency.

The weak correlation of event mean concentrations with rainfall could be attributed to the capacity of NEB-B relative to the catchment size rather than a common characteristic of PPS. RPPS, which has a much lower capacity relative to its catchment size, was observed to be more influenced by total rainfall. The increasing orthophosphate levels throughout the study could be due to bacterial activity; as the pavement ages, it is expected to develop its own microbial diversity, which could degrade elemental phosphorous in the subgrade to orthophosphate. Interestingly, Tota-Maharaj & Scholz (2010) found significant orthophosphate removal in their PPS test rigs and attributed that reduction to bacterial activity, presumably with the assumption that bacteria were acting as phosphate sinks. More research on the microbial action within permeable pavements is required to understand how microbial activity may influence orthophosphate and phosphorous levels.

The strong correlation between TSS and Orthophosphate was also an interesting finding, determined to be due to a common cause. It is possible that bacterial action on particulate-bound phosphorous resulted in biodegradation to the more soluble form of phosphate, to be dissolved and washed out of the pavement during rainfall. This could explain the observed correlation at event level.

6.2.3 Unwashed Stone

From a management perspective, the artificially elevated TSS levels are of particular interest, as it raises questions about construction methods, and what impacts unwashed stone may have on the performance of PPS. This is a topic which is not well explored in the literature, though the use of "washed aggregate" or "clean stone/gravel" is often reported when PPS are being described (Abbot & Comino-Mateos, 2003; Tennis *et al.*, 2004; Grabowiecki *et al.*, 2008; Yong & Deletic, 2008; Scholz & Grabowiecki, 2009; Tota-Maharaj & Scholz, 2010; Yong *et al.*, 2013; Mullaney & Lucke, 2014), suggesting that the use of cleaned aggregate is commonplace. Grabowiecki *et al.* (2008) specifically mentioned the use of "commercially available washed aggregate" in several experimental setups. Since the NEB PPS has clearly not been constructed with washed aggregate, sediment from the aggregate was washed out of the pavement and detected as elevated TSS, where no suspended solids were expected on a new pavement. While this was an initial concern as it was believed that this may present a risk to downstream ecosystems, the levels of TSS, while elevated significantly above what was expected, remained fairly low. The impact on downstream ecosystems, if any, is likely to be small.

As the season studied may not be typical of a normal rain season, and significantly larger events are still expected to wash through the pavement, it is not possible to gauge to what extent TSS has been removed from the pavement, however, and more may be flushed out yet. However, as urban streams are more significantly affected by pollutant concentrations than long-term pollutant loads (Fletcher *et al.*, 2014b), a slow release of TSS may not pose a significantly adverse effect to downstream ecosystems. And, as discussed above, the TSS levels evident in the study do not significantly compromise the value of the effluent for stormwater reuse.

What may be a concern is the potential for clogging that entrained sediment poses. While the appearance of the sediment in the effluent is indicative of suspended material washing out of the system relatively easily, underdrains are often wrapped in geotextile and larger sediment could accumulate at the interface and slowly block the drain. Similarly, in systems that infiltrate to the subgrade, smaller particles and dissolved solids may adhere to larger sediment at the geotextile interface between the PPS and the subgrade, forming a sealing layer which could negatively impact hydraulic efficiency.

6.3 Outliers: Events 8, 9 & 10

The average levels of events 8, 9 and 10 present unusual behaviour which makes finding a trend towards pollutant progression difficult. Event 10 is the most significant, as it is an outlier for all parameters except for pH. It shows peak levels of TSS and orthophosphate throughout the study, as well as near-peak levels of ammonia and EC. The declining trend of EC makes Event 10 a particularly jarring outlier for this parameter. Since EC does not correlate with any of the other parameters, it raises the question of what could have caused this outlier. For example, if the outlier had been an increase in TSS and orthophosphate only, this could have been explained by the correlation between these two parameters.

Event 10 was the second-smallest measured rainfall event during the full study, where Event 4 was the smallest. It was preceded by two non-measurable events within one week in August. The previous measurable event showed overall lower EC, TSS and Orthophosphate. This suggests that the two smaller events may have played a role in creating this outlier. While external factors such as contamination from the pavement surface might explain the increases in EC and Orthophosphate, the fact that most of the TSS from the surface would have been retained in the surface structure of the pavement suggests that pollutants were transported through the pavement surface by smaller events. Since event 10 also had relatively little rainfall, this would have resulted in a generally higher pollutant concentration throughout the event, rather than a sudden washout, which is what appears to have happened in event 11 (extremely high initial TSS, followed by significantly lower levels).

Events 8 and 9 are outliers in that their average concentrations for orthophosphate and TSS are much lower than expected. Events 8 and 9 showed the two highest rainfall amounts apart from event 5 and occurred after the pavement had received flow from several measurable events throughout the winter period. Furthermore, no smaller events occurred between these two, and they were less than five days apart. It is possible that the amount of water flowing through the pavement during this period served to dilute the concentrations.

6.4 Pilot Study: Findings, limitations and difficulties

The pilot study was characterised by several limitations, the most significant of these being the number of events sampled and the lack of total suspended solids analysis. The latter parameter was added to the study after it became apparent that the four initial parameters would not suffice for analysis. The pilot study was also conducted on three relatively small events, which was possible due to the structure of the Rondebosch Permeable Pavement. This PPS treats runoff from roof surfaces and driveways as well, which increases the amount of runoff available to the pavement per mm of rainfall.

While sampling by hand was effective for the purposes of the pilot, this method showed severe limitations in terms of representativeness, convenience and safety. Since most of the periods of significant rainfall occurred at night, safety was a major concern. Furthermore, achieving true representativeness is challenging unless rainfall events are easily predicted. Grab sampling, rainfall periods or even entire events can easily be missed due to a poor prediction or an unexpected event. Grab sampling was continued for this site, but the lessons learned here strongly reinforced the requirement of unattended sampling for the continuation of the project.

The higher EC values of effluent from RPPS were initially surprising, but could easily be explained by leaching of ions from the pavement. EC decreased with successive rainfall events, which may be due to dilution or removal of leachable materials, or a combination of the factors.

While Nutrient levels of RPPS were shown to be considerably lower than those of RTS, this result could be influenced by the presence of vegetated areas, specifically trees, on and around RTS. RPPS does not have any vegetation in the vicinity.

No TSS samples were taken, but visual observations during sampling showed clear water. This was expected due to the widely reported TSS removal capacity of PPS. While oily sheens were frequently visible on runoff from RTS, no evidences of oil contamination could be observed in RPPS runoff.

6.5 Analysis of Methodology

6.5.1 NEB-A

While the study initially intended on reporting on two separate PPS sites build adjacent on the NEB parking lot, only data from NEB-B has been shown. NEB-A has been excluded due to the sparsity of data from the site as well as external interferences which may have compromised readings.

NEB-A was monitored with an ISCO-GLS composite sampler, which adds a prescribed amount of volume to a bottle every time it samples. As this sampler had to be placed into the catch pit itself, accessibility was the greatest difficulty in gathering data from NEB-A. Of eight events sampled, the first was missed as only one battery was delivered with the sampler. Two were missed because the manhole had been parked over, and two were missed due to sampler failure.

During the course of the study, it was observed that runoff from a road culvert above the PPS site frequently spills over the culvert and runs directly onto the pavement. This water carried a significant sediment load from construction activity uphill from the PPS, and considerable amounts of this sediment was deposited onto NEB-A, clogging some fractions of the pavement.

These complications have led to the exclusion of NEB-A from this study.

6.5.2 Using sequential bottle samplers

The sequential bottler samplers proved to be useful in supplying some reference data points for impermeable surfaces NEB-I and P8. They are easy to use and make, as well as extremely cost effective. However, their use is associated with certain limitations and unique characteristics. Samples gathered frequently display differences in pollutant concentrations between the bottles, indicating that the self-sealing mechanism is functional. However, due to the extremely rapid rate of filling of the first two bottles, the concentrations in these bottles are likely to only be representative of the first few moments of a storm event. Consequently, the concentrations measured in these bottles should not be used to characterise a storm event, but may rather indicate if there is a potential first flush effect. The last bottle is mixed continuously and should be more indicative of pollutant EMC.

6.5.2.1 'Passive' samplers as a low-cost alternative

'Passive' samplers are here described as sampling devices requiring no pump or other form of added energy to take a sample. A similar device to the sequential bottle sampler was previously used by Pezzaniti *et al.* (2012), whereby a 20l bottle was placed in a catch pit and filled up with initial runoff. This solution is likely to be more effective than the sequential bottle design due to the increased capacity, but is still likely to be unrepresentative of the event average, as the results from the intra-event analysis show. Orthophosphate is likely to be underestimated, while TSS and EC are likely to be overestimated. Furthermore, pavements need to be designed to accommodate these sample bottles and to allow ease of access. For further monitoring, a 20l bottle with a flow reducing attachment may be a viable alternative to more expensive autosamplers.

6.5.3 Using Automatic Samplers

The ISCO 6712 sampler with a 24 bottle setup provided the most consistent results and performance. As it can be programmed to accept external inputs, it was also easy to attach a low-cost float switch as an activator. A drawback of using this sampler with a level actuator became evident after flow ceased. The pump would remove sufficient water for the float switch to drop, and the program to be deactivated. However, the sampler would then flush out the sampling hose by running the peristaltic pump in reverse, thereby returning water to the container and re-activating the program. As the program was set to take a sample at activation (in order to capture the initial flow), this caused it to sample again. This on-off sequence caused a 'bounce' effect, which meant that multiple samples were taken towards the end of the programme. Fortunately, this only caused the loss of some samples towards the end of event 8 as all other events were characterised by shorter duration rainfall. This 'bounce' could be prevented by not permitting the sampler to be enabled repeatedly, but this would mean that any successive flow after the first disable would not be sampled.

6.5.4 Monitoring Permeable Pavements

This study has shown that there is a degree of intra-event variability within PPS. As such, future studies and future monitoring plans for PPS should take into account the potential for variability, and structure their monitoring plans to ensure representativeness of their samples.

It is more effective to consider PPS performance in terms of the absolute water quality of effluent under various conditions, rather than calculate a relative performance metric which evaluates pollutant removal. To achieve this, widespread monitoring of PPS post-construction is required, with uniform methodologies and reporting standards. Acceptance and implementation of these will depend on their cost and accessibility. This study has several findings on what sampling methodologies will have to consider:

- **Representativeness**: While it is intuitive that PPS would 'smooth' temporal variability, results of this study show that there is an element of intra-event variability evident in pollutant concentrations. A flow-weighted sample would best represent this, but the costs of samplers and flow measuring equipment is likely to be prohibitive.
- **Duration:** The results from NEB-B have been heavily influenced by construction practices, and may change significantly in the future. Studies of performance need to take this into account, and either continue over an appropriate period of time, or several more intense surveys should take place in a seasonal fashion, as appropriate.
- **Cost:** This factor will influence the previous two factors. A more representative study over a longer period of time will be more costly.

This study attempted to find some alternatives to monitoring SuDS and stormwater that are cost-effective and location appropriate.

6.5.5 pH measurement difficulties

While the pH error bars are low, standard error does not account for sampling error. In the case of pH, there may be considerable sampling error as all samples were only collected after the rainfall event – usually 8-15 hours after the first sample had been taken. This meant that the first sample would, at best, have been eight hours old at measurement time. pH is known to be a volatile parameter, and it is generally recommended that a sample be tested within eight hours. This may also have affected the remarkably smooth intra-event progression shown by pH, as samples later on in the rainfall event would have been 'fresher'. Unfortunately, it remains impossible to quantify the effect that this may have had. RPPS showed similar pH levels, and these were tested immediately after sampling. Furthermore, the low intra-event variability in pH levels is another indicator that this factor may not have had a significant impact on pH readings.P8

While P8 was used as a convenient additional site which could readily be monitored with no interference, it yielded the highest readings for Ammonia, Orthophosphate and TSS as well as consistently high error margins. The ammonia readings from this site can be ignored, as samples consistently exceeded the detection limits of the test. Ideally, these tests would have been retaken, but due to limited reagent availability, they were recorded as exceeding test limits.

Results from P8 are a good example of how highly variable stormwater pollution can be, and the high levels of pollutants observed provide motivation for an increased uptake in permeable pavements as SuDS in parking lots.

6.6 Study Observations

6.6.1 Pavement Clogging

RPPS shows clogging in its lower section, evident as a thin sheen of water during rainfall. This pavement likely requires maintenance soon, as the water build up is likely to provide a nuisance to residents.

Figure 6-1: RPPS during rainfall. Note the ponding in the centre of the pavement

NEB-B and NEB-A are developing a clogging front due to sediment spilled over from a rain garden placed above the pavement curb. While this is localised and probably has not great effect on the infiltration rate, it demonstrates a design flaw which could have easily been avoided. NEB-A is also clogged along a linear stretch where road runoff deposited sediment.

Figure 6-2: NEB Pavers nearer the centre remain clear after one rainfall season (left). However, pavers near the rain garden are filled with sediment (right)

This was further accelerated by construction sediment being washed into the road inlet upstream from the site, illustrating how off-site practices can impact on PPS. It is well documented in the literature that PPS are ineffective in areas where sediment generation is high, but sediment sources may often be dynamic. Due consideration should be given to preventative measures which could reduce clogging, and while these measures may be physical changes in the design, stakeholder education is also likely to yield benefits

7 - CONCLUSION

The aim of this study was to investigate the water quality performance of permeable pavements in the South African context, as well as the suitability of PPS effluent for potential stormwater harvesting and reuse. Performance was identified as a variable concept, with different objectives and metrics for assessment. This study chose to compare absolute concentrations to the South African Water Quality Guidelines and relevant literature results rather than percentage pollutant reduction (USEPA, n.d.; Wright Water Engineers and Geosyntec Consultants, 2007; Heal *et al.*, 2009). Further, it investigated the progression of pollutant concentrations of a newly constructed permeable pavement and the intra-event variability of pollutant concentrations. The literature review found that PPS were commonly associated with good pollutant removal and hydrological performance, but that percentage reduction was commonly used as a performance metric. It also showed that PPS are most likely to be impacted by poor construction practices, lack of maintenance as well as design characteristics.

Results showed that NEB-B had been constructed with unwashed aggregate which exported suspended solids. While this resulted in higher TSS levels than expected, these did not exceed some of the ranges reported in the literature, and are unlikely to cause difficulties for re-use or negative impacts in downstream ecosystems. The greater concern around the use of unwashed aggregate is the clogging potential in lower layers of the PPS. Premature clogging of lower layers would require labour intensive and costly maintenance processes which entail removing the lower layers.

Nutrient concentrations in the effluent, while lower than most impermeable sites and with less variability, were still sufficiently high to potentially elevate trophic levels in downstream systems. Orthophosphate in particular was a concern and results from other studies found similar effluent ranges. In order to reduce nutrients to acceptable levels, PPS should be used in conjunction with other SuDS treatment options more suitable for nutrient removal. As source controls, they would form the first section of a treatment train and other SuDS could readily be placed downstream. Heavy metals consistently did not meet target water quality ranges; while the literature quotes high reduction percentages of PPS, these are insufficient to reduce heavy metals to an adequate concentration for aquatic ecosystems. The true impacts of PPS contribution to downstream pollutant concentrations cannot be determined without knowledge of the existing pollutant concentrations and flow data for both PPS and the receiving stream, however.

NEB-B effluent was found to be of sufficient quality for re-use in irrigation, and could be used for Category 4 industrial processes where elevated TSS is not a concern. While hydrocarbon and heavy metal removal have not been tested, these have commonly been found to be low in PPS effluent. With NEB-B expected to exhibit lower TSS concentrations with successive rainfall, this PPS has the potential to deliver fit-for-purpose water for reuse.

Both inter-event progression and intra-event variability was observed. NEB-B was shown to exhibit initial concentrations deviating from the event mean for orthophosphate, TSS and EC which could skew monitoring plans sampling only a portion of the event. Inter-event progression, while observable, may require further study to explain. Correlations between orthophosphate, TSS and TSLME indicate that event averages may be partially driven by non-measurable rainfall events preceding outflow.

There are several aspects of PPS which can still benefit from further investigation. As the City of Cape Town increasingly leans towards the implementation of SuDS for stormwater management, it becomes essential to understand how SuDS scale from site-specific impacts to catchment-wide impacts. Petrucci *et al.* (2013) suggest that careless implementation of source-control strategies such as PPS may actually increase downstream flooding. Catchment-wide strategies are required to manage cumulative and unexpected scale-dependant impacts, but few studies are available to guide catchment-scale strategies.

Permeable pavements represent a class of SuDS which have the potential to provide substantial improvements for downstream ecosystems, while providing the possibility for significant other benefits to be derived from their use. They can act as decentralised pollutant treatment and flow reduction devices without limiting space for development, facilitate water harvesting, provide opportunity for renewable energy harvesting and reduce hydroplaning. The success of their future use depends largely on careful design and planning on the catchment and site scale and sufficient on-site maintenance.

The study met the objectives, and answered the research questions, but some findings from the study could benefits from the following further research:

- An investigation into the toxicity of effluent, and the relative impact that effluent may have on invertebrate community structures in downstream ecosystems, as these are commonly an important base of the aquatic trophic system.

- Investigating the impacts of scaling PPS implementation from site to catchment scale for hydrological impacts.
- An investigation into the potential impacts of the use of unwashed aggregate; this should include an analysis of the costs of using washed aggregate as well.

8 - REFERENCE LIST

Abbot, C. L., & Comino-Mateos, L. (2003). In-Situ Hydraulic Performance of a Permeable Pavement Sustainable Urban Drainage System. *The Journal*, *17*(3), 187–190.

Adewumi, J. R., Ilemobade, A. A., & Van Zyl, J. E. (2010). Treated wastewater reuse in South Africa: Overview, potential and challenges. *Resources, Conservation and Recycling*, *55*(2), 221–231. doi:10.1016/j.resconrec.2010.09.012. ISSN:09213449.

Al-Rubaei, A. M., Viklander, M., & Blecken, G.-T. (2014). Long-term hydraulic performance of stormwater infiltration systems. *Urban Water Journal*, (October 2014), 1–12. doi:10.1080/1573062X.2014.949796. ISSN:1573-062X. Retrieved October 23, 2014 from http://www.tandfonline.com/doi/abs/10.1080/1573062X.2014.949796

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).

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. Retrieved from http://www.psparchives.com/publications/our_work/stormwater/lid/paving_docs/Regulating Drainage with Permeable Paving-Andersen etal 1999.pdf

Armitage, N., Vice, M., Fisher-Jeffes, L., Winter, K., Spiegel, A., & Dunstan, J. (2013). *South African Guidelines for Sustainable Drainage Systems*. ISBN: ISBN 978-1-4312-0413-7.

Aryal, R., & Beecham, S. (2014). Assessment of Suspended Solids and Their Fraction on Permeable Pavement Clogging. In *13th International Conference on Urban Drainage, Sarawak, Malaysia* (pp. 1–8). Retrieved from http://www.13icud2014.com/fullpaper/Oral Presentations/Storm Water Source Control and Best Management Practices/ID-2600005 Assessment of Suspended Solids and Their Fraction on Permeable Pavement Clogging.pdf

Balades, J., Legret, M., & Madiec, H. (1995). Permeable pavements: pollution management tools. *Water Science and Technology*, *32*(1), 49–56. Retrieved from http://www.sciencedirect.com/science/article/pii/027312239500537W

Ball, J. E., & Rankin, K. (2010). The hydrological performance of a permeable pavement. *Urban Water Journal*, *7*(2), 79–90. doi:10.1080/15730620902969773. ISSN:1573-062X. Retrieved August 20, 2014 from http://www.tandfonline.com/doi/abs/10.1080/15730620902969773

Barbosa, A. E., Fernandes, J. N., & David, L. M. (2012). Key issues for sustainable urban stormwater management. *Water Research*, *46*(20), 6787–98. doi:10.1016/j.watres.2012.05.029. ISSN:1879-2448. Retrieved May 2, 2014 from http://www.ncbi.nlm.nih.gov/pubmed/22687523

Bean, E. Z., Hunt, W. F., & Bidelspach, D. A. (n.d.). A Monitoring Field Study of Permeable Pavement Sites in North Carolina. Retrieved January 24, 2016, from http://www.bae.ncsu.edu/info/permeable-pavement/SWFWMD.pdf

Beecham, S. C., Lucke, T., & Myers, B. (2010). Designing porous and permeable pavements for stormwater harvesting and reuse. Retrieved from http://web.sbe.hw.ac.uk/staffprofiles/bdgsa/IAHR_2010_European_Congress/Papers by session final/Urban Drainage II/UDIIa.pdf

Beecham, S., Kandasamy, J., & Pezzaniti, D. (2009). Influence of clogging on the effective life of permeable pavements. *Proceedings of the ICE - Water Management*, *162*(3), 211–220. doi:10.1680/wama.2009.00034. ISBN: 1741-7589. ISSN:1741-7589. Retrieved August 20, 2014 from http://www.icevirtuallibrary.com/content/article/10.1680/wama.2009.00034

Beecham, S., Pezzaniti, D., Kandasamy, J., Beecham, S., & Kandasamy, J. (2012). Stormwater treatment using permeable pavements. *Proceedings of the ICE - Water Management*, *165*(3), 161–170. doi:10.1680/wama.2012.165.3.161. ISBN: 1741-7589. ISSN:1741-7589. Retrieved November 10, 2014 from http://www.icevirtuallibrary.com/content/article/10.1680/wama.2012.165.3.161

Bentarzi, Y., Terfous, A., Ghenaim, A., Wanko, A., Hlawka, F., & Poulet, J. B. (2013). Hydrodynamic characteristics of a new permeable pavement material produced from recycled concrete and organic matter. *Urban Water Journal*, *10*(4), 260–267. doi:10.1080/1573062X.2012.727835. ISSN:1573-062X. Retrieved October 23, 2014 from http://www.tandfonline.com/doi/abs/10.1080/1573062X.2012.727835

Berndtsson, J. C. (2014, May 19). Storm water quality of first flush urban runoff in relation to different traffic characteristics. *Urban Water Journal*. Taylor & Francis. doi:10.1080/1573062X.2013.795236. ISSN:1573-062X. Retrieved April 3, 2014 from http://www.tandfonline.com/doi/abs/10.1080/1573062X.2013.795236

Bernhardt, E. S., Band, L. E., Walsh, C. J., & Berke, P. E. (2008). Understanding, managing, and minimizing urban impacts on surface water nitrogen loading. *Annals of the New York Academy of Sciences*, *1134*, 61–96. doi:10.1196/annals.1439.014. ISSN:0077-8923. Retrieved August 20, 2014 from http://www.ncbi.nlm.nih.gov/pubmed/18566090

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. doi:10.1080/14680629.2011.9690357. ISSN:1468-0629. Retrieved October 23, 2014 from http://www.tandfonline.com/doi/abs/10.1080/14680629.2011.9690357

Bertrand-Krajewski, J.-L., Chebbo, G., & Saget, A. (1998). Distribution of pollutant mass vs volume in stormwater discharges and the first flush phenomenon. *Water Research*, *32*(8), 2341–2356. doi:10.1016/S0043-1354(97)00420-X. ISSN:00431354. Retrieved from http://linkinghub.elsevier.com/retrieve/pii/S004313549700420X

Boogaard, F., Lucke, T., & Beecham, S. (2014). Effect of age of permeable pavements on their infiltration function. *Clean - Soil, Air, Water*, *42*(2), 146–152. doi:10.1002/clen.201300113. ISSN:18630650.

Brattebo, B. O., & Booth, D. B. (2003). Long-term stormwater quantity and quality performance of permeable pavement systems. *Water Research*, *37*(18), 4369–4376. doi:10.1016/S0043-1354(03)00410-X. ISBN: 2066853836. ISSN:00431354. Retrieved from http://linkinghub.elsevier.com/retrieve/pii/S004313540300410X

Brezonik, P. L., & Stadelmann, T. H. (2002). Analysis and predictive models of stormwater runoff volumes, loads, and pollutant concentrations from watersheds in the Twin Cities metropolitan area, Minnesota, USA. *Water Research*, *36*(7), 1743–57. ISSN:0043-1354. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12044074

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. doi:10.1016/j.scitotenv.2005.05.016. ISSN:0048-9697. Retrieved May 2, 2014 from http://www.ncbi.nlm.nih.gov/pubmed/16014309

Brown, R. A., & Borst, M. (2015). Nutrient infiltrate concentrations from three permeable pavement types. *Journal of Environmental Management*, *164*, 74–85. doi:10.1016/j.jenvman.2015.08.038. ISSN:1095-8630. Retrieved February 11, 2016 from http://www.sciencedirect.com/science/article/pii/S0301479715302425

Burns, D., Vitvar, T., McDonnell, J., Hassett, J., Duncan, J., & Kendall, C. (2005). Effects of suburban development on runoff generation in the Croton River basin, New York, USA. *Journal of Hydrology*, *311*(1-4), 266–281. doi:10.1016/j.jhydrol.2005.01.022. ISSN:00221694. Retrieved from http://linkinghub.elsevier.com/retrieve/pii/S0022169405000703

Burns, M. J., Fletcher, T. D., Walsh, C. J., Ladson, A. R., & Hatt, B. E. (2012). Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. *Landscape and Urban Planning*, *105*(3), 230–240. doi:10.1016/j.landurbplan.2011.12.012. ISBN: 0169-2046. ISSN:01692046. Retrieved October 19, 2015 from http://ac.els-cdn.com.ezproxy.uct.ac.za/S016920461100363X/1-s2.0-S016920461100363X-main.pdf?_tid=31548c4e-75f7-11e5-b92e-00000aacb362&acdnat=1445214205_ca16aaa85b5e42d26c38592f8d7a8e69

Burns, M. J., Fletcher, T. D., Walsh, C. J., Ladson, A. R., & Hatt, B. E. (2013). Setting objectives for hydrologic restoration : from site-scale to catchment-scale Objectifs de restauration hydrologique : de l ’ échelle de la parcelle à celle du bassin versant, 1–9.

Chocat, B., Ashley, R., Marsalek, J., Matos, M. R., Rauch, W., Schilling, W., & Urbonas, B. (2007). Toward the Sustainable Management of Urban Storm-Water. *Indoor and Built Environment*, *16*(3), 273–285. doi:10.1177/1420326X07078854. ISSN:1420-326X. Retrieved August 20, 2014 from http://ibe.sagepub.com/cgi/doi/10.1177/1420326X07078854

City of Cape Town. (2009). *Management of Urban Stormwater Impacts Policy*. City of Cape Town.

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. doi:10.1016/S1462-0758(02)00028-6. ISBN: 1462-0758. ISSN:14620758.

Coupe, S. J., Charlesworth, S., & Faraj, A. . (2009a). Combining permeable paving with renewable energy devices: installation, performance and future prospects. In *9th. International Conference on Concrete Block Paving.* (pp. 1–10).

Coupe, S. J., Smith, H. G., Newman, A. P., & Puehmeier, T. (2003). Biodegradation and microbial diversity within permeable pavements, *498*, 495–498.

Coupe, S., Tota-Maharaj, K., Scholz, M., & Grabiowiecki, P. (2009b). Water stored within permeable paving and the effect of ground source heat pump applications on water quality. Retrieved from http://www.cmaa.com.au/ICCBP2009.html

Deletic, A. (1998). The first flush load of urban surface runoff. *Water Research*, *32*(8), 2462–2470. doi:10.1016/S0043-1354(97)00470-3. ISSN:00431354. Retrieved from http://linkinghub.elsevier.com/retrieve/pii/S0043135497004703

Department Of Water Affairs And Forestry. (1996). *South African Water Quality Guidelines.* (Vol. 7). ISBN: 0798853387.

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. doi:10.1007/s11270-007-9484-z. ISSN:0049-6979. Retrieved July 17, 2014 from http://link.springer.com/10.1007/s11270-007-9484-z

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. doi:10.2166/wqrjc.2013.055. ISSN:1201-3080. Retrieved November 4, 2014 from http://www.iwaponline.com/wqrjc/048/wqrjc0480203.htm

Fach, S., & Geiger, W. F. (2005). Effective Pollutant Retention Capacity of Permeable Pavement for Infiltration Road Determined By Laboratory Tests. *Water Science and Technology*, *51*, 37 – 45.

Fassman, E. A., & Blackbourn, S. (2010). Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils. *Journal of Hydrologic Engineering*, *15*(June), 475–485. doi:10.1061/(ASCE)HE.1943-5584.0000238. ISSN:1084-0699.

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D., & Viklander, M. (2014a). SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, (August), 1–18. doi:10.1080/1573062X.2014.916314. ISSN:1573-062X. Retrieved July 24, 2014 from http://www.tandfonline.com/doi/abs/10.1080/1573062X.2014.916314

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*. doi:10.1177/0309133314537671. ISSN:0309-1333. Retrieved August 20, 2014 from http://ppg.sagepub.com/cgi/doi/10.1177/0309133314537671

Gaffield, S. J., Goo, R. L., Richards, L. A., & Jackson, R. J. (2003). Public health effects of inadequately managed stormwater runoff. *American Journal of Public Health*, *93*(9), 1527–33. ISSN:0090-0036. Retrieved from http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1448005&tool=pmcentrez&rendertype=abstract

Gatt, K., & Farrugia, E. S. (2012). Promoting the reuse of stormwater runoff in the Maltese islands. *Urban Water Journal*, *9*(4), 223–237. doi:10.1080/1573062X.2012.654802. ISSN:1573-062X. Retrieved April 3, 2014 from http://www.tandfonline.com/doi/abs/10.1080/1573062X.2012.654802

Gnecco, I., Berretta, C., Lanza, L. G., & La Barbera, P. (2005). Storm water pollution in the urban environment of Genoa, Italy. *Atmospheric Research*, *77*(1-4), 60–73. doi:10.1016/j.atmosres.2004.10.017. ISSN:01698095. Retrieved April 3, 2014 from http://linkinghub.elsevier.com/retrieve/pii/S0169809505000888

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. Retrieved April 30, 2014 from http://www.ncbi.nlm.nih.gov/pubmed/17174006

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. doi:10.1080/15730620701723538. ISSN:1573-062X. Retrieved August 20, 2014 from http://www.tandfonline.com/doi/abs/10.1080/15730620701723538

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. doi:10.1016/j.jenvman.2004.08.006. ISSN:0301-4797. Retrieved April 3, 2014 from http://www.ncbi.nlm.nih.gov/pubmed/15572079

Goonrey, C. M., Perera, B. J. C., Lechte, P., Maheepala, S., & Mitchell, V. G. (2009). A technical decision-making framework: stormwater as an alternative supply source. *Urban Water Journal*, *6*(6), 417–429. doi:10.1080/15730620903089787. ISSN:1573-062X. Retrieved August 20, 2014 from http://www.tandfonline.com/doi/abs/10.1080/15730620903089787

Grabowiecki, P., Tota-Maharaj, K., Scholz, M., & Coupe, S. (2008). Combined permeable pavement and ground source heat pump system to treat urban runoff during storms and recycle energy, 1–10. Retrieved from http://events.exeter.ac.uk/bhs2008/index.php/bhs/

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*, 201–211. doi:10.1016/j.jhydrol.2013.01.001. ISBN: 0022-1694. ISSN:00221694. Retrieved from http://dx.doi.org/10.1016/j.jhydrol.2013.01.001

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. doi:10.2166/wst.2013.772. ISSN:0273-1223. Retrieved November 11, 2014 from http://www.ncbi.nlm.nih.gov/pubmed/24569271

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. doi:10.1016/j.jenvman.2005.09.019. ISSN:0301-4797.

Haskins, C. A. (2012). Cape Town's sustainable approach to urban stormwater management. Retrieved January 30, 2016, from http://www.capetown.gov.za/en/CSRM/Documents/CTsustainableApproachToUrbanStormwaterManagement.pdf

Hatt, B. E., Fletcher, T. T. D., Walsh, C. J. C., & Taylor, S. L. S. (2004). The Influence of Urban Density and Drainage Infrastructure on the Concentrations and Loads of Pollutants in Small Streams. *Environmental Management*, *34*(1), 112–124. doi:10.1007/s00267-004-0221-8. ISSN:0364-152X. Retrieved July 21, 2014 from http://link.springer.com/10.1007/s00267-004-0221-8

Heal, K., Mclean, N., & D'Arcy, B. (2004). SUDS and Sustainability. *[Online]*, (September), 1–9. Retrieved from http://www.geos.ed.ac.uk/homes/kheal/suds_sustainability.pdf

Heal, K. V., Bray, R., Willingale, S. A. J., Briers, M., Napier, F., Jefferies, C., & Fogg, P. (2009). Medium-term performance and maintenance of SUDS: A case-study of Hopwood Park Motorway Service Area, UK. *Water Science and Technology*, *59*(12), 2485–2494. doi:10.2166/wst.2009.288. ISSN:02731223. Retrieved February 11, 2016 from https://repository.abertay.ac.uk/jspui/bitstream/handle/10373/979/JefferiesWST59%2812%29Author2009.pdf?sequence=2&isAllowed=y

Houle, J. J., Roseen, R. M., Ballestero, T. P., Puls, T. a., & Sherrard, J. (2013). Comparison of maintenance cost, labor demands, and system performance for LID and conventional stormwater management. *Journal of Environmental Engineering (United States)*, *139*(July), 932–938. doi:10.1061/(ASCE)EE.1943-7870.0000698. ISBN: 6038623957. ISSN:07339372 (ISSN). Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-84879123187&partnerID=40&md5=2ecb752402e842a9e2471c5a808884cf

Imran, H. M., Akib, S., & Karim, M. R. (2013). Permeable pavement and stormwater management systems: a review. *Environmental Technology*, *34*(17-20), 2649–56. doi:10.1080/09593330.2013.782573. ISSN:0959-3330. Retrieved October 23, 2014 from http://www.ncbi.nlm.nih.gov/pubmed/24527626

Inca Concrete Products. (n.d.). Inca Permeable Pavement Information Brochure. Retrieved January 30, 2016, from http://www.incaconcrete.co.za/pdf/Inca_Permeable_Paving_Information_Brochure.pdf

James, W., & Von Langsdorff, H. (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). doi:0-958-46091-4. ISBN: 0958460914.

Jefferies, C., Duffy, A., Berwick, N., Mclean, N., & Hemmingway, A. (2008). SUDS Treatment Train Assessment Tool, 1–10.

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*(1-3), 178–84. doi:10.1016/j.scitotenv.2006.12.053. ISSN:0048-9697. Retrieved May 2, 2014 from http://www.ncbi.nlm.nih.gov/pubmed/17320154

Kim, L.-H., Kayhanian, M., Zoh, K.-D., & Stenstrom, M. K. (2005). Modeling of highway stormwater runoff. *The Science of the Total Environment*, *348*(1-3), 1–18. doi:10.1016/j.scitotenv.2004.12.063. ISSN:0048-9697. Retrieved May 2, 2014 from http://www.ncbi.nlm.nih.gov/pubmed/16162310

Lariyah, M. S., Mohamed Roseli, R., Zulkefli, M., & Amirah Hanim, M. P. (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, Sarawak, Malaysia* (pp. 1–10).

Lee, J. H., Bang, K. W., Ketchum, L. H., Choe, J. S., & Yu, M. J. (2002). First flush analysis of urban storm runoff. *The Science of the Total Environment*, *293*(1-3), 163–75. ISSN:0048-9697. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12109470

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 : A Journal of the International Association on Water Pollution Research*, *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. doi:10.1016/0048-9697(96)05228-X. ISSN:00489697. Retrieved from http://linkinghub.elsevier.com/retrieve/pii/004896979605228X

Li, L.-Q., Yin, C.-Q., He, Q.-C., & Kong, L.-L. (2007). First flush of storm runoff pollution from an urban catchment in China. *Journal of Environmental Sciences (China)*, *19*(3), 295–9. ISSN:1001-0742. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/17918590

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* (pp. 11–16).

Luo, H., Luo, L., Huang, G., Liu, P., Li, J., Hu, S., Wang, F., Xu, R., & Huang, X. (2009). Total pollution effect of urban surface runoff. *Journal of Environmental Sciences*, *21*(9), 1186–1193. doi:10.1016/S1001-0742(08)62402-X. ISSN:10010742. Retrieved May 2, 2014 from http://linkinghub.elsevier.com/retrieve/pii/S100107420862402X

Maniquiz, M. C., Lee, S., & Kim, L. (2010). Multiple linear regression models of urban runoff pollutant load and event mean concentration considering rainfall variables. *Journal of Environmental Sciences*, *22*(6), 946–952. doi:10.1016/S1001-0742(09)60203-5. ISSN:10010742. Retrieved May 2, 2014 from http://linkinghub.elsevier.com/retrieve/pii/S1001074209602035

Meybeck, M., Laroche, L., Dürr, H., & Syvitski, J. (2003). Global variability of daily total suspended solids and their fluxes in rivers. *Global and Planetary Change*, *39*(1-2), 65–93. doi:10.1016/S0921-8181(03)00018-3. ISSN:09218181. Retrieved February 11, 2016 from http://www.sciencedirect.com/science/article/pii/S0921818103000183

Minton, G. R. (2002). *Stormwater Treatment: Biological, Chemical, and Engineering Principles*. Seattle, Washington.

Mitchell, G. (2005). Mapping hazard from urban non-point pollution: a screening model to support sustainable urban drainage planning. *Journal of Environmental Management*, *74*(1), 1–9. doi:10.1016/j.jenvman.2004.08.002. ISSN:0301-4797. Retrieved March 19, 2014 from http://www.ncbi.nlm.nih.gov/pubmed/15572076

Mitchell, V. G. (2006). Applying Integrated Urban Water Management Concepts: A Review of Australian Experience. *Environmental Management*, *37*(5), 589–605. doi:10.1007/s00267-004-0252-1. ISSN:1432-1009. Retrieved from http://dx.doi.org/10.1007/s00267-004-0252-1

Mitchell, V. G., Deletic, A., Fletcher, T. D., Hatt, B. E., & McCarthy, D. T. (2006). Achieving multiple benefits from stormwater harvesting. In *7th International Conference on Urban Drainage Modelling and the 4th International Conference on Water Sensitive Urban Design; Book of Proceedings* (p. 912). Monash University.

Mullaney, J., Jefferies, C., & Mackinnon, E. (2011). The Performance of Block Paving With and without Geotextile in the Sub-base. In *12nd International Conference on Urban Drainage, Porto Alegre/Brazil, 11-15 September 2011*.

Mullaney, J., & Lucke, T. (2014). The Implications of Using Permeable Pavements to Enhance Street Tree Health and Reduce Pavement Damage — Effects on Soil Conditions. In *13th International Conference on Urban Drainage* (pp. 1–8).

Mwenge Kahinda, J., Taigbenu, A. E., & Boroto, R. J. (2010). Domestic rainwater harvesting as an adaptation measure to climate change in South Africa. *Physics and Chemistry of the Earth, Parts A/B/C*, *35*(13-14), 742–751. doi:10.1016/j.pce.2010.07.004. ISSN:14747065. Retrieved February 10, 2016 from http://www.sciencedirect.com/science/article/pii/S1474706510001336

Nel, N., Parker, A, & P, S. (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. P., Aitken, D., & Antizar-Ladislao, B. (2013). Stormwater quality performance of a macro-pervious pavementcar park installation equipped with channel drainbased oil and silt retention devices. *Water Research*, *47*(20), 7327–7336. doi:10.1016/j.watres.2013.05.061. ISBN: 0043-1354. ISSN:00431354. Retrieved from http://dx.doi.org/10.1016/j.watres.2013.05.061

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* (pp. 1–12). Portland, Oregon.

Newman, A. P., Coupe, S. J., Smith, H. G., Puehmeir, T., & Bond, P. (2006). The microbiology of permeable pavements. In *8th International Conference on Concrete Block Paving, November 6-8, 2006 San Francisco, California USA* (pp. 181–191).

Nichols, P. W. B., Lucke, T., Dierkes, C., Keeshan, G., & Denny, L. (2014). Permeable Pavements : Particle Size Distributions , Infiltration and Clogging The Road to Durable Performance, 1–7.

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. doi:10.1080/10298436.2014.893325. ISSN:1029-8436. Retrieved October 23, 2014 from http://www.tandfonline.com/doi/abs/10.1080/10298436.2014.893325

Nnadi, E. O., Newman, A. P., & Puehmeier, T. (2008). An Evaluation of the Use Of Stored Water Derived From Permeable Paving Systems for Irrigation Purposes. In *International Conference on Urban Drainage* (pp. 1–10).

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. doi:10.1080/1573062X.2012.750372. ISSN:1573-062X. Retrieved April 3, 2014 from http://www.tandfonline.com/doi/abs/10.1080/1573062X.2012.750372

Page, J. L., Winston, R. J., & Hunt, 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, Sarawak, Malaysia (pp. 1–9).

Pagotto, C., Legret, M., & Cloirec, P. L. E. (2000). Comparison of the Hydraulic Behaviour and the Quality of Highway Runoff Water. *Water Research*, *34*(18), 4446–4454.

Paul, M. J., & Meyer, J. L. (2001). Streams in the Urban Landscape. *Annual Review of Ecology and Systematics*, *32*(2001), 333–365. doi:doi:10.1146/annurev.ecolsys.32.081501.114040. ISBN: 978-0-387-73411-8. ISSN:0066-4162.

Petrucci, G., Deroubaix, J.-F., de Gouvello, B., Deutsch, J.-C., Bompard, P., & Tassin, B. (2012). Rainwater harvesting to control stormwater runoff in suburban areas. An experimental case-study. *Urban Water Journal*, *9*(1), 45–55. doi:10.1080/1573062X.2011.633610. ISSN:1573-062X. Retrieved March 25, 2014 from http://www.tandfonline.com/doi/abs/10.1080/1573062X.2011.633610

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. doi:10.1016/j.jhydrol.2012.06.018. ISBN: 0022-1694. ISSN:00221694. Retrieved from http://dx.doi.org/10.1016/j.jhydrol.2012.06.018

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

Revitt, D. M., Lundy, L., & Ellis, J. B. (2014). An Impact Assessment Approach for Car Park Runoff (pp. 7–12). Retrieved from http://www.13icud2014.com/fullpaper/Oral Presentations/Storm Water Source Control and Best Management Practices/ID-2493109 An Impact Assessment Approach for Car Park Runoff.pdf

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. doi:10.1016/j.watres.2005.07.041. ISSN:0043-1354. Retrieved April 3, 2014 from http://www.ncbi.nlm.nih.gov/pubmed/16182336

Roux, D., Kempster, P., Kleynhans, C., Van Vliet, H. R., & Du Preez, H. H. (1999). Integrating Stressor and Response Monitoring into a Resource-Based Water-Quality Assessment Framework. *Environmental Management*, *23*(1), 15–30. ISSN:1432-1009. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/9817769

Roy, A. H., Wenger, S. J., Fletcher, T. D., Walsh, C. J., Ladson, A. R., Shuster, W. D., Thurston, H. W., & Brown, R. R. (2008). Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. *Environmental Management*, *42*(2), 344–59. doi:10.1007/s00267-008-9119-1. ISBN: 0026700891. ISSN:0364-152X. Retrieved March 26, 2014 from http://www.ncbi.nlm.nih.gov/pubmed/18446406

Rushton, B. T. (2001). Low-Impact Parking Lot Design Reduces Runoff Pollutant Loads. *J. Water Resours. Plann. Manage.*, *127*(June), 172–179.

Scholz, M. (2013). Water Quality Improvement Performance of Geotextiles Within Permeable Pavement Systems: A Critical Review. *Water*, *5*, 462–479.

doi:10.3390/w5020462. ISSN:2073-4441. Retrieved from http://www.mdpi.com/2073-4441/5/2/462/

Scholz, M., & Grabowiecki, P. (2007). Review of permeable pavement systems. *Building and Environment*, *42*(11), 3830–3836. doi:10.1016/j.buildenv.2006.11.016. ISSN:03601323. Retrieved July 17, 2014 from http://linkinghub.elsevier.com/retrieve/pii/S0360132306004227

Scholz, M., & Grabowiecki, P. (2009). Combined permeable pavement and ground source heat pump systems to treat urban runoff. *Journal of Chemical Technology and Biotechnology*, *84*(August 2008), 405–413. doi:10.1002/jctb.2054. ISBN: 0268-2575. ISSN:02682575.

Shackel, B. (2006). Design of permeable paving subject to traffic. In *International Conference on Concrete Block Paving* (pp. 51–60).

Shackel, B., Ball, J., & Mearing, M. (2003). Using Permeable Eco-Paving To Achieve Improved Water Quality for Urban Pavements. In *International Conference on Concrete Block Paving*. ISBN: 0958460914.

Shackel, B., Kaligis, J. O., Muktiarto, Y., & Pamudji. (1996). Infiltration and structural tests of permeable eco-paving. In *Proc. 5th Int. Conf. on Concrete Block Paving*. Tel Aviv, Israel.

Shuster, W. D., Bonta, J., Thurston, H., Warnemuende, E., & Smith, D. R. (2005). Impacts of impervious surface on watershed hydrology: A review. *Urban Water Journal*, *2*(4), 263–275. doi:10.1080/15730620500386529. ISSN:1573-062X. Retrieved July 29, 2014 from http://www.tandfonline.com/doi/abs/10.1080/15730620500386529

Siegle, D. (2015). r Critical Value Table | Educational Research Basics by Del Siegle. Retrieved February 15, 2016, from http://researchbasics.education.uconn.edu/r_critical_value_table/

Strecker, E. W., Quigley, M. M., Urbonas, B. R., Jones, J. E., & Clary, J. K. (2001). Determining Urban Storm Water BMP Effectiveness. *Journal of Water Resources Planning and Management*, *127*(June), 144–149.

Taebi, A., & Droste, R. L. (2004). Pollution loads in urban runoff and sanitary wastewater. *The Science of the Total Environment*, *327*(1-3), 175–84. doi:10.1016/j.scitotenv.2003.11.015. ISSN:0048-9697. Retrieved April 29, 2014 from http://www.ncbi.nlm.nih.gov/pubmed/15172580

Tennis, P. D., Leming, M. L., & Akers, D. J. (2004). *Pervious Concrete Pavements*. ISBN: 0893122424.

Tota Maharaj, K., Grabowiecki, P., Scholz, M., & Coupe, S. J. (2009). Hybrid Urban Runoff Treatment System Incorporating Permeable Pavements and Geothermal Pumps. In *National Telford Institute Workshop* (pp. 1–6).

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 *Sixteenth International Water Technology Conference, IWTC 16 2012, Istanbul, Turkey* (pp. 1–13). Turkey.

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. doi:10.1002/ep.10418. ISSN:19447442. Retrieved from http://doi.wiley.com/10.1002/ep.10418

Tota-Maharaj, K., Scholz, M., Ahmed, T., French, C., & Pagaling, E. (2010). The synergy of permeable pavements and geothermal heat pumps for stormwater treatment and reuse. *Environmental Technology*, *31*(14), 1517–31. doi:10.1080/09593331003782409. ISSN:0959-3330. Retrieved October 23, 2014 from http://www.ncbi.nlm.nih.gov/pubmed/21275249

Transport Roads & Stormwater Directorate. (2002). *Stormwater Management Planning and Design Guidelines for New Developments*. City of Cape Town. Retrieved January 30, 2016, from https://www.capetown.gov.za/en/CSRM/Documents/SW_Plan_Guidelines_new_develop.pdf

Urrutiaguer, M., Rossrakehs, S., Potter, M., Ladson, A., & Walsh, C. J. (2012). Using directly connected imperviousness mapping to inform stormwater management strategies. *7th International* .... Retrieved from http://www.urbanstreams.unimelb.edu.au/cwalsh/docs/urrutiaguer_et_al_2012.pdf

USEPA. (n.d.). Three Keys to BMP Performance: Concentration, Volume, and Total Load. Retrieved February 10, 2016, from http://www.epa.gov/npdes/three-keys-bmp-performance-concentration-volume-and-total-load

USEPA. (2009). *Industrial Stormwater Monitoring and Sampling Guide*. Washington D.C.

Walsh, C., Fletcher, T. D., & Burns, M. J. (2012). Urban stormwater runoff: a new class of environmental flow problem. *PloS One*, *7*(9), e45814. doi:10.1371/journal.pone.0045814. ISSN:1932-6203. Retrieved August 8, 2014 from http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3446928&tool=pmcentrez&rendertype=abstract

Walsh, C. J. (2000). Urban impacts on the ecology of receiving waters : a framework for assessment , conservation and restoration. *Hydrobiologia*, (431), 107–114.

Walsh, C. J., & Kunapo, J. (2009). The importance of upland flow paths in determining urban effects on stream ecosystems. *Journal of the North American Benthological Society*, *28*(4), 977–990. doi:10.1899/08-161.1. ISSN:0887-3593. Retrieved July 16, 2014 from http://www.bioone.org/doi/abs/10.1899/08-161.1

Water Sensitive Urban Design (WSUD) | WITS Parking Lot. (n.d.). Retrieved February 10, 2016, from http://wsud.co.za/wsud-sites-in-south-africa/wits-parking-lot/

Winter, K., & Mgese, S. (2011). Stormwater drainage : a convenient conduit for the discharge of urban effluent into the Berg River , South Africa, (September), 11–16.

Woods-Ballard, B., Kellagher, R., Martin, P., Jefferies, C., Bray, R., & Shaffer, P. (2007). *The SUDS Manual*. CIRIA. London.

Wright Water Engineers and Geosyntec Consultants. (2007). Frequently Asked Questions

Fact Sheet for the International Stormwater BMP Database: Why does the International Stormwater BMP Database Project omit percent removal as a measure of BMP performance? Retrieved January 25, 2016, from http://www.bmpdatabase.org/Docs/FAQPercentRemoval.pdf

Yong, C., & Deletic, A. (2008). The clogging behaviour and treatment efficiency of a range of porous pavements. In *11th International Conference on Urban Drainage, Edinburgh, Scotland, UK*.

Yong, C. F., McCarthy, D. T., & Deletic, a. (2013). Predicting physical clogging of porous and permeable pavements. *Journal of Hydrology*, *481*, 48–55. doi:10.1016/j.jhydrol.2012.12.009. ISSN:00221694. Retrieved from http://dx.doi.org/10.1016/j.jhydrol.2012.12.009

APPENDIX A

This appendix contains correlation matrixes for inter-event averages from NEB-B, as well as summaries and event progression from the pilot study.

A.I Pilot Study

The results of the pilot study are shown below. In total, 22 samples were taken from RPPS and 7 from RTS. All samples were taken from RTS 1, as the distinction between the two sites was only realised after the pilot study. Significantly fewer results were obtained from RTS due to the ephemeral nature of surface runoff. Only three events were sampled, and each of these events displayed a total event rainfall of between 11 and 19mm.

Table A-1: Summary statistics of results from RPPS Pilot Study

	EC (µS/cm)		pH		Orthophosphate (mg/l)		Ammonia (mg/l)	
	Average:	SE:	Average:	SE:	Average:	SE:	Average:	SE:
RTS 2	165.000	34.995	8.786	0.135	0.869	0.265	1.126	0.160
RPPS	235.570	11.165	8.652	0.113	0.263	0.037	0.197	0.041

Table A-1 above shows clear contrasts between RTS and RPPS. EC levels of RPPS are significantly higher, with less variability. Orthophosphate levels in RPPS were about one-third those of RTS, while Ammonia levels where more than five times higher in RTS than in RPPS. Indeed, RTS Ammonia levels were consistently above the 0.5 mg/l accuracy threshold.

A.I.i **Event-Specific Results**

The following four plots show the event-specific averages and standard error for each parameter along with rainfall characteristics. EC is the only parameter to show any clear progression in such a small dataset. Orthophosphate appears to vary inversely with event rainfall, but the error bars highlight significant variability. The high initial ammonia levels are of interest, as these were not seen at this site in the remainder of the study. A potential cause of this could be that significant organic material had accumulated in stormwater chamber from which the samples were taken. During the winter study, this had been washed away.

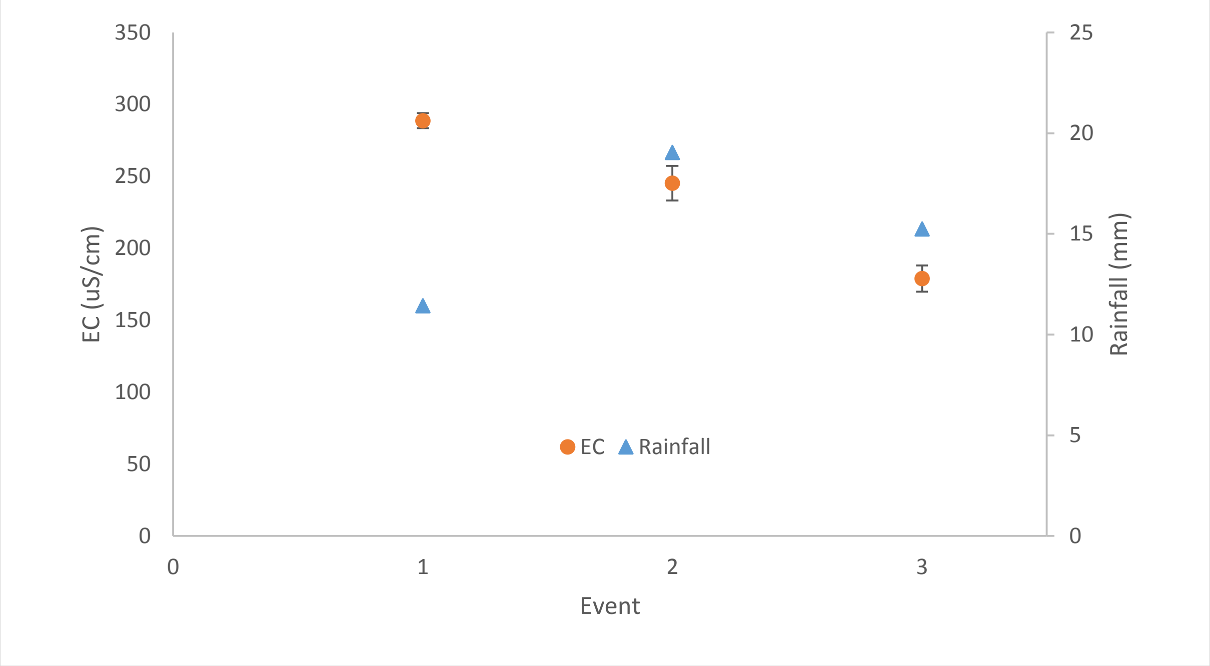


Figure A-8-1: Pilot study EC results show decreasing EC with each event

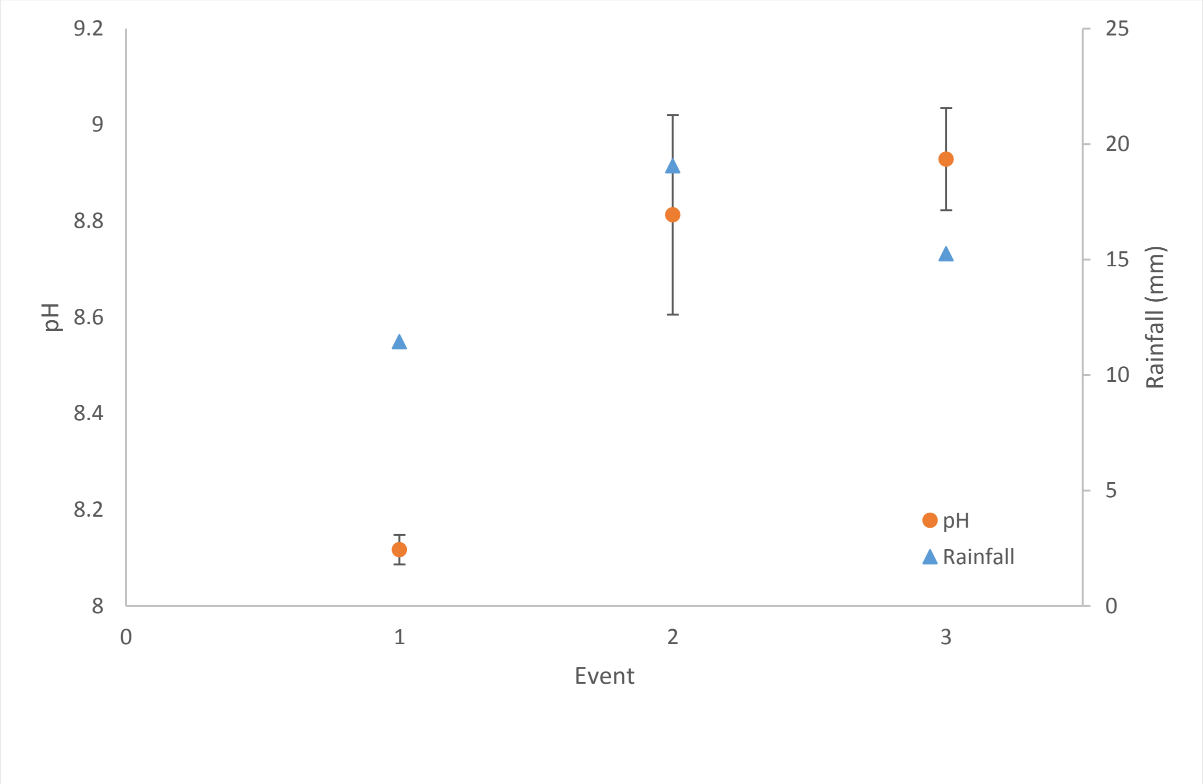


Figure A-8-2: Pilot study pH results

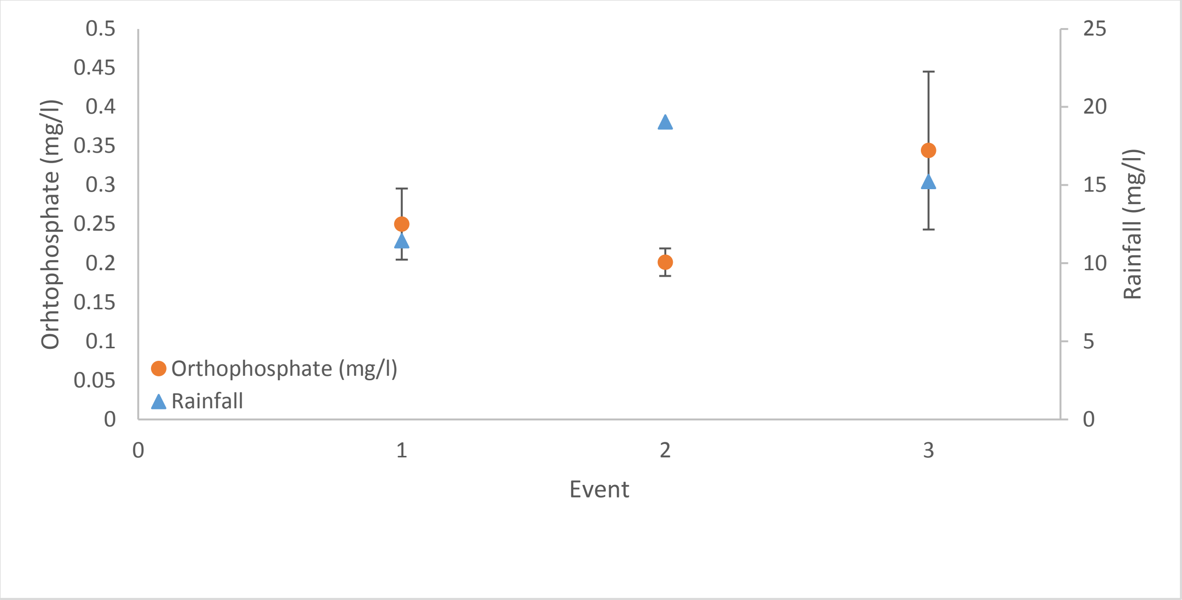


Figure A-8-3: Pilot study Orthophosphate results are relatively high, with most error bars overlapping

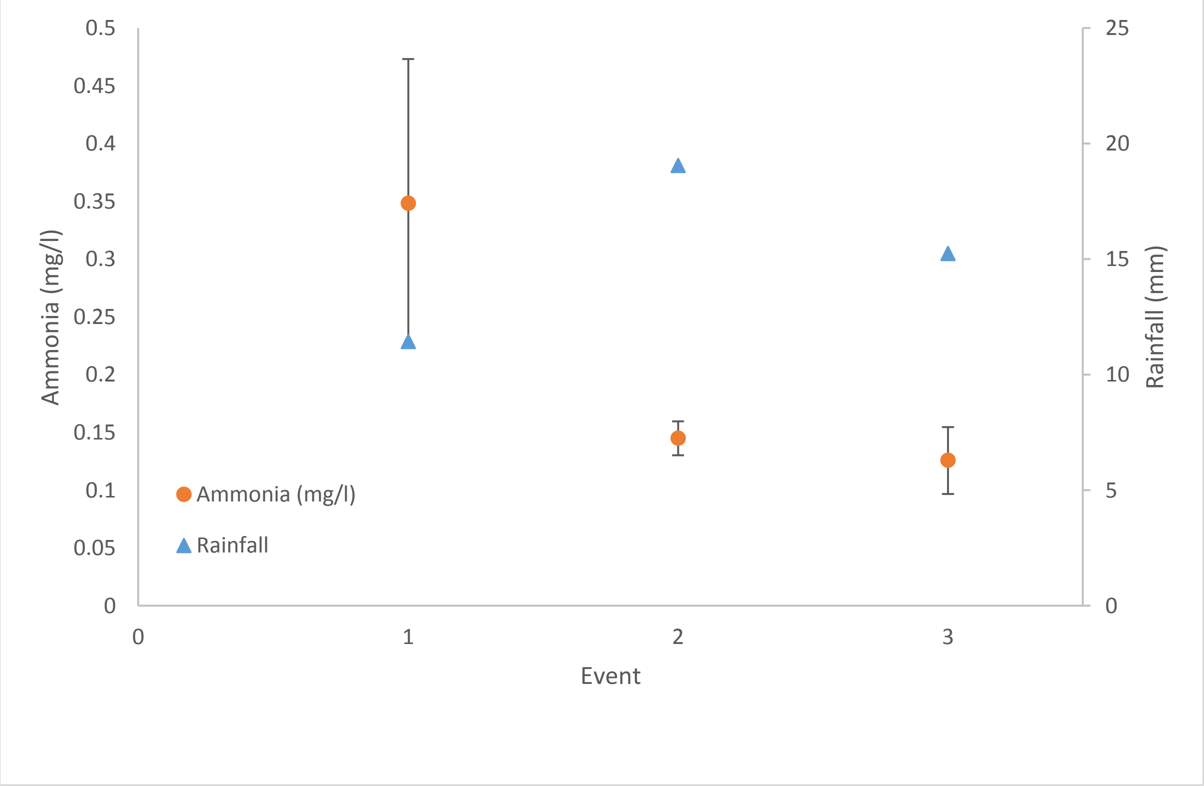


Figure A-8-4: Pilot study Ammonia results show initially high ammonia, with significant variabil