UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

CIVN4005: Investigational Project

Capability of Permeable Pavement Systems in Johannesburg

Compiled By;

Hamzah Mohamed 1374118

Stephen Maycock 1429953

Supervised By:

Professor Anne Fitchett

Plagiarism Declaration

I _____Hamzah Mohamed_____________(student number:)__1374118______

am a registered student for ____Civil Engineering___ in the year___2020____.

I hereby declare the following:

- I am aware that plagiarism (an act or instance of using or closely imitating the language and thoughts of another author without authorization and the representation of that author's work as one's own, as by not crediting the original author) is wrong.
- I confirm that the work submitted for assessment for the above course is my own unaided work except where I have explicitly indicated otherwise.
- I have followed the required conventions in referencing the thoughts and ideas of others.
- I understand that the University of the Witwatersrand may take disciplinary action against me if there is a belief that this is not my own unaided work or that I have failed to acknowledge the source of the ideas or words in my writing.

Signature: ___________________________ Date: ___________

I _____Stephen Maycock_____________(student number:)__1429953

am a registered student for ____Civil Engineering___ in the year___2020____.

I hereby declare the following:

- I am aware that plagiarism (an act or instance of using or closely imitating the language and thoughts of another author without authorization and the representation of that author's work as one's own, as by not crediting the original author) is wrong.
- I confirm that the work submitted for assessment for the above course is my own unaided work except where I have explicitly indicated otherwise.
- I have followed the required conventions in referencing the thoughts and ideas of others.
- I understand that the University of the Witwatersrand may take disciplinary action against me if there is a belief that this is not my own unaided work or that I have failed to acknowledge the source of the ideas or words in my writing.

Signature: ___________________________ Date: __________

Executive Summary

The following is a report supplementing research conducted by the University of Cape Town as presented in Barnard (2019) to determine the capabilities of permeable paving systems (PPS) across South Africa. This is to build a catalogue of data to create a manual detailing the necessary maintenance procedures and regularity needed for PPS to remain efficient over its lifetime. Maintenance of PPS has proven to be of issue due to time and economic constraints and thus a modified stormwater infiltration field test (SWIFT) test was adopted based on the findings presented in Barnard (2019), to be used as this would prove efficient and easy for future use for property owners.

The report details the findings of infiltration rates of permeable interlocking concrete paving (PICP) systems across four sites in Johannesburg. This was achieved using the SWIFT test. Two primary types of PICP were investigated and the results documented and compared. Stormwater design rainfall was obtained and used to ascertain whether the PICP investigated had retained its design capability to deal with peak storm flow.

The results indicated that using the SWIFT test, open-block grass paving proved to be vastly more capable than standard PICP, however the testing method may not be reliable due to the retentive nature of open-block pavers. It was further determined the clear benefit of maintenance in improving the infiltration rates as well as the surface area of the individual brick in the PICP system.

The purpose of this research is to contribute to the limited source material on infiltration capability and relevant testing methods of permeable pavement systems in South Africa and thus further promote sustainable solutions to the rapid urbanisation problem faced in South Africa. This can in turn play a role in solving South Africa’s current water management, pollution and shortage problems.

Table of Contents

List of Figures

List of Tables

Glossary

Absorption is the combination of one substance into another substance.

Adsorption is the physical adhesion or bonding of atoms, ions or molecules onto a surface.

Attenuation is the reduction of peak discharge (stormwater flow).

Catchment is the collection of rainfall over a natural drainage area.

Design period is the number of years that a structure or asset will be expected to be safely usable.

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

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

Filtration is the removal of pollutants which are mixed into the stormwater during stormwater runoff.

Geotextile is a textile or plastic fabric designed to separate different fill materials.

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

Permeable Interlocking Concrete Paving (PICP) is a type of PPS separated by joints filled with small aggregate. Water enters the joints between the pavers and into an "open-graded" base-crushed stone layer with no small or fine particles.

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

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

1. Introduction

1.1 Background

Urbanisation is one of the fastest growing trends of the 21st century. This growing trend results in an increase in the amount of impervious landscapes (building rooftops, roadways etc.) (Armitage, et al., 2013; Pratt, et al., 1999) as well as an increase in the removal of natural vegetation. This will result in stormwater (rainfall collected on impervious surfaces) having reduced levels of infiltration and therefore resulting in greater surface runoff volumes that may carry waste and pollutants present in urban areas and may also lead to higher flood peaks as well as increased levels of erosion (Armitage, et al., 2013; Pratt, et al., 1999; Barbosa, et al., 2012; Mcgrane, 2016).

Stormwater management is created in order to mitigate these issues. Modern stormwater management has slowly moved towards a system which favours the quality of water as opposed to the quantity of water (Debo & Reese, 2003). However, in South Africa, stormwater management still focuses on methods which handle the quantity of stormwater, therefore resulting in problems such as: erosion; siltation and pollution still being prevalent in the stormwater systems (Armitage, et al., 2013; Armitage & Fisher-Jeffres, 2012). It is clear that the modern stormwater management in South Africa is insufficient and therefore improvements are required in order to provide environmental sustainability. The solution to these improvements are found in the form of Sustainable Urban Drainage Systems (SUDS).

SUDS is a form of drainage system which focuses on the quality of stormwater while still allowing for consideration regarding the quantity. SUDS does this by focusing primarily on emulating the natural hydrological cycle processes: retention, infiltration, evaporation, transpiration and conveyance of stormwater in the urban infrastructure (Fryd, et al., 2012). SUDS also have the benefits of improving aesthetics as well as regulating building temperatures; reducing heat island effects and reducing soil erosion (Armitage, et al., 2013; Woods-Ballard, et al., 2015). It is imperative that, if a SUDS is to work properly and efficiently, proper design, construction and maintenance are all done which will allow the SUDS to perform its function adequately and consistently.

The SUDS focused on in this research paper is permeable paving systems (PPS). PPS are a form of SUDS which allow for the infiltration of stormwater while still being able to adequately support/withstand loadings such as vehicles (Armitage, et al., 2013). PPS also have, by design, a means to deal with pollutants (due to the PPS' filtration capabilities) as well as: reduce soil erosion; increase groundwater recharge and allow for the retention and reuse of stormwater (Abbott & Comino-Mateos, 2003; Bruinsma, 2017; Scholz & Grabowiecki, 2007). The design of PPS focuses on two types of structural elements: monolith and modular. Both elements are considered 'load-bearing' materials and are built on a sub-base of coarse gravel which allows infiltration into groundwater (Armitage, et al., 2013). The performance of PPS can be summarised as being somewhat efficient in both the infiltration and filtration/removal of pollutants however this efficiency will drop off with time. In order to prevent this efficiency drop off, frequent maintenance is required to prevent the degradation of the PPS. The main cause of this degradation is the clogging of the system where fine sediments get trapped either on the pavement surface or between the surface joints therefore preventing infiltration through the PPS and thus resulting in the failure of the system (Armitage, et al., 2013; Abbott & Comino-Mateos, 2003). Therefore, maintenance methods such as vacuum-sweeping and/or high pressure jet-washing are suggested, and should be used roughly 4 times a year (Armitage, et al., 2013).

Testing methods to determine the efficiency of the PPS can also be done. Testing methods such as infiltrometer tests and simple infiltration tests can be done to determine the infiltration of a PPS. This research paper focuses solely on the stormwater infiltration field test (SWIFT) to determine the infiltration, and therefore the efficiency, of PPS around Johannesburg.

1.2 Objectives

This research is aimed to:

- Supplement the research conducted by Cole Barnard's 2019 research paper from the University of Cape Town, supervised by Professor Neil Armitage.
- Determine the infiltration and efficiency of PPS around Johannesburg using the SWIFT method.
- Determine the factors (such as age; number/type of maintenance; environment etc.) which affect the efficiency of the PPS.
- Determine and compare the efficiency of different types of PPS

1.3 Limitations

- Due to the Covid-19 pandemic, not all Johannesburg sites were accessible and therefore could not be tested.
- The SWIFT test does not simulate a full, intense rainfall period.
- The infiltration rates obtained from the SWIFT test are done by using a correlated result as presented in Barnard (2019), and thus may not be 100% accurate or reliable given the fact that the SWIFT test in theory only determines the wetted area of bricks.
- Different types of PPS were tested and therefore an issue of control in testing may arise.
- This research only focuses on the performance of PPS in terms of infiltration rates. The performance of the PPS in terms of water quality is not considered.

2. Literature Review

2.1 Introduction

This literature review will provide a brief overview of the research undertaken in order to contextualize and understand the role of urbanisation on stormwater management and the subsequent consequences that have led to the implementation of Sustainable Urban Drainage Systems (SUDS). One such SUDS, also the main focus of this paper's investigation, Permeable Paving Systems (PPS), will then be commented on with respect to previous research and the current state of knowledge regarding the design, construction, performance and maintenance. The Literature review will round off with examples of testing methods that have been used to assess the performance of PPS as well as a summary of previous testing methods including the primary method that will be used for this investigational project.

2.2 The Role of Urbanisation

Urbanisation is one of the fastest growing and significant trends of the 21st Century and marks the first time in history when the proportion of the world's population living in urban areas is larger than those living in rural areas (Brown, et al., 2009; McDonald, et al., 2014) with the next few decades forecasted to have the most rapid period of urban growth in human history (United Nations Population Division, 2011). These current and future urban dwellers will require water to sustain their lives as well as suitable urban water infrastructure to ensure secure water supply and the protection of water environments (Brown, et al., 2009). More specifically, due to the global increase of urbanisation there is the corresponding result of the expansion of impervious landscapes (building rooftops, roadways etc.) (Armitage, et al., 2013; Pratt, et al., 1999) as well as the removal of vegetation, reducing the natural stormwater buffering processes (Armitage, et al., 2013b).

This increase in total impervious areas causes a larger surface runoff volume due to a lack of infiltration, thus interfering with the natural water cycle and therefore inhibiting groundwater recharge (Mcgrane, 2016; Armitage, et al., 2013). This larger surface runoff volume also has an adverse effect on flooding due to higher and more rapid peak discharges that can overwhelm stormwater systems (Armitage, et al., 2013; Pratt, et al., 1999) as well as posing pollution problems to water bodies in and around urban areas due to the increase in anthropogenic activities found in urban areas where large quantities of waste and pollutants are present on these surfaces and subsequently caught in this large surface runoff (Barbosa, et al., 2012; Mcgrane, 2016; Pratt, et al., 1999). In essence, urbanisation increases flooding, pollution and erosion problems (Woods-Ballard, et al., 2015). A visual depiction of this can be seen in the Figure 2-1, demonstrating the effects of urbanisation (synonymous here to post-development).

Given this information, one can conclude that urbanisation plays a key role in the need for suitable stormwater management that will mitigate floods and pollution problems that lead to negative effects on the natural environment and human well-being.

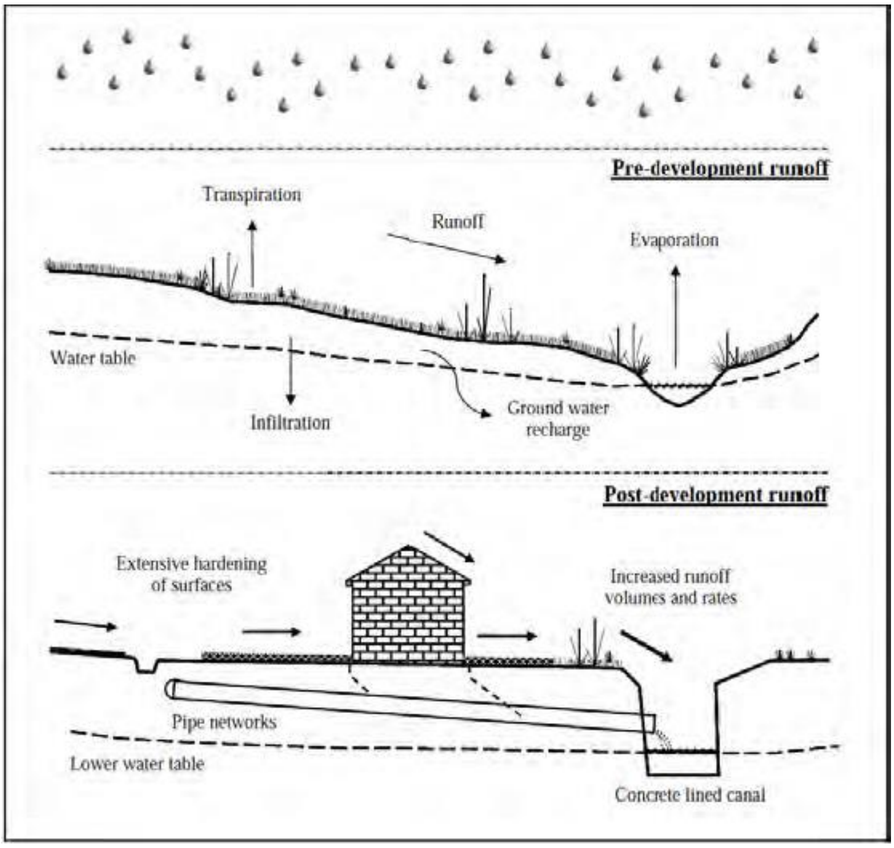

Figure 2-1: Typical pre- and post-development scenarios with the conventional approach to stormwater management (Armitage, et al., 2013)

2.3 Stormwater in an Urban Context

2.3.1 Characterisation of Stormwater

Stormwater is classified as rainfall that collects on any roofs, driveways, roads and other paved areas (Environmental Protection Authority, 2003). Stormwater which lands on such impervious surfaces is subject to runoff and it is necessary to collect and transport this stormwater to mitigate damages (e.g. from flooding). Hence, stormwater drainage systems (natural and man-made) are used (CSIR Building and Construction Technology, 2005). Stormwater poses an issue in urban areas due to the resulting runoff, which can result in erosion, sedimentation and, most harmful, pollution (Armitage, et al., 2013). One of the biggest concerns with regards to stormwater is its potential to carry pollutants (generally man-made pollutants) therefore resulting in stormwater pollution (CSIR Building and Construction Technology, 2005).

2.3.1 Stormwater Pollution

Stormwater pollution is a major concern in urban environments and it is the main factor that contributes to the deterioration of water quality in urban aquatic systems (Armitage & Fisher-Jeffres, 2012). As mentioned above, stormwater pollution arises from the stormwater's ability to carry pollutants which arise from a variety of different sources, such as: natural pollutants (organic material such as sediments), chemical pollutants (fertilisers, oils, detergents) and litter (plastics, cigarettes etc.) (CSIR Building and Construction Technology, 2005; Clean Water Action, 2020; Environmental Protection Authority, 2003). These pollutants primarily result in water systems/sources being polluted which can result in harm to plants, animals and humans (Clean Water Action, 2020; Environmental Protection Authority, 2003). Stormwater quality may also be poor due to the quality of the rainwater. An example of this is the rainfall in industrial areas that will result in poor stormwater quality due to the pollution introduced into the atmosphere by the industrial activities (Wanielista & Yousef, 1993). It is therefore important to manage stormwater in order to prevent these adverse effects.

2.4 Stormwater Management

2.4.1 Stormwater Management General

Stormwater pollution is major concern due to stormwater's capacity to carry waste and pollutants. It is therefore important to manage the quantity and the quality of stormwater in order to mitigate potential harm to public health and the natural environment (Barbosa, et al., 2012). Stormwater management has existed since the 1800s, with the very first iteration of management involving the use of ditches (Debo & Reese, 2003). This management slowly evolved over the years, with each iteration fixing the immediate problems of the previous. The evolution started in ditches and slowly continued: firstly with the introduction of stormwater pipes; then the need to mitigate flooding and finally evolving into the need to reduce pollution/improve water quality sustainability (Debo & Reese, 2003). As can be seen, modern stormwater management has slowly shifted focus from a quantity perspective, to a quality perspective.

In order to show how the modern perspective of stormwater management has changed, three methods are considered when managing stormwater: permit, structural, non-structural (Wanielista & Yousef, 1993). The permit method is primarily used for large urban sources or for concentrated rural sources (Wanielista & Yousef, 1993). The structural method modifies the hydrological process, usually by changing the flow transport system and is broken into two classifications: off-site (after water is in the drainage system – e.g. wet-detention pods) and on-site (before water is in the drainage system – e.g. pollutant reduction) (Wanielista & Yousef, 1993). The non-structural approach involves surface sanitation, chemical use control, use of natural drainage etc. (Wanielista & Yousef, 1993).

Many countries focus on the management of stormwater by controlling the quantity of stormwater, however more consideration for: quality, amenity and biodiversity management is needed (Armitage, et al., 2013).

2.4.2 Stormwater Management in South Africa

Stormwater poses a threat to many urban areas, including urban areas in South Africa. South African stormwater management has previously, and continues to, use methods intended to collect the stormwater runoff and direct it towards the nearest watercourse (Armitage, et al., 2013). This approach is effective in handling the quantity of stormwater, however the approach ignores the quality of the stormwater which does little for environmental preservation, mainly due to erosion, siltation and pollution (Armitage, et al., 2013; Armitage & Fisher-Jeffres, 2012). The current approach will also require maintenance and repairs due to the resultant flooding and erosion (Botha, 2005).

It is evident that current stormwater management is insufficient, therefore considerations that need to be taken into account are: communities, sanitation, treatment of contaminates/pollutants and drainage (Armitage, et al., 2013). These considerations lead to the concept of Sustainable Urban Drainage Systems (SUDS).

2.4.3 Factors Hindering Stormwater Management

Stormwater management is often intended to minimise flooding and is therefore designed to dispose of the stormwater as quickly as possible (Armitage & Fisher-Jeffres, 2012). However, by focusing on the quantity of stormwater removed, the quality is overlooked (Armitage & Fisher-Jeffres, 2012) and therefore, potential considerations to include the quality of stormwater management (i.e. to allow the water to be reusable) should be made. Armitage &

Fisher-Jeffres (2012) claim another mitigating factor in stormwater management is funding. They propose that taxes (similar to those for water and electricity) are to be imposed so as to have adequate funding to produce stormwater management systems that are sufficient in handling the quantity, whilst also improving the quality, of stormwater.

Other factors hindering stormwater management include the lack of maintenance of these systems (inspections done only once complaints of flooding have been made), poor/inadequate designs (either due to ineptitude of the designer/methodology and/or incomplete data), poor planning (e.g. home located in unregulated floodplains) (Debo & Reese, 2003).

2.5 Sustainable Urban Drainage Systems (SUDS)

As discussed previously, the increased urbanisation rates combined with conventional stormwater management that had always prioritised quantity removal over the quality of the water have led to increased pressure on the urban water cycle. To combat this, one such solution proposed and implemented around the world is that of Sustainable Urban Drainage Systems (SUDS). In contrast to the conventional drainage systems, whose primary objectives are that of mitigating floods and protecting road surfaces (Armitage, et al., 2013b), SUDS focus on emulating the natural hydrological cycle processes: retention, infiltration, evaporation, transpiration and conveyance of stormwater in the urban infrastructure (Fryd, et al., 2012). In short, SUDS should be implemented ensuring the effective management of stormwater quantity and quality, and associated amenity and biodiversity of the urban drainage systems (Armitage, et al., 2013b; Armitage, et al., 2013; Woods-Ballard, et al., 2015).

SUDS provide a wide range of other advantages including enhanced aesthetics if designed and maintained properly (thus impacting property value) (Armitage, et al., 2013b) as well as carbon capture, regulating building temperatures, reducing heat island effects and soil erosion as well as addressing climate change challenges and can often cost less when designed to make efficient use of less space available (Armitage, et al., 2013; Woods-Ballard, et al., 2015).

The effectiveness of SUDS, specifically regarding stormwater management and the removal of pollutants, is dependent on a so-called treatment train, or series of unit processes (Armitage, et al., 2013b; Armitage, et al., 2013; Wilson, et al., 2004). Each process has particular capabilities with respect to water quality treatment, attenuation and reduction of volumes and so a series of processes or trains are usually required to meet all the design criteria. Treatment train options may be combined in any order but have broadly been categorised into four categories: good housekeeping, source controls, local controls and regional controls, as seen in Figure 1-2.

To attain maximum benefits of SUDS, it is of utmost importance to ensure proper design, construction and maintenance throughout the design life and if implemented with all factors considered, particularly a thoroughly thought out treatment train, will have a positive effect on all aspects of the focus of stormwater management (quantity, quality, amenity and biodiversity) as well as providing the benefits mentioned as opposed to conventional drainage systems that focused primarily on the preservation of public safety.

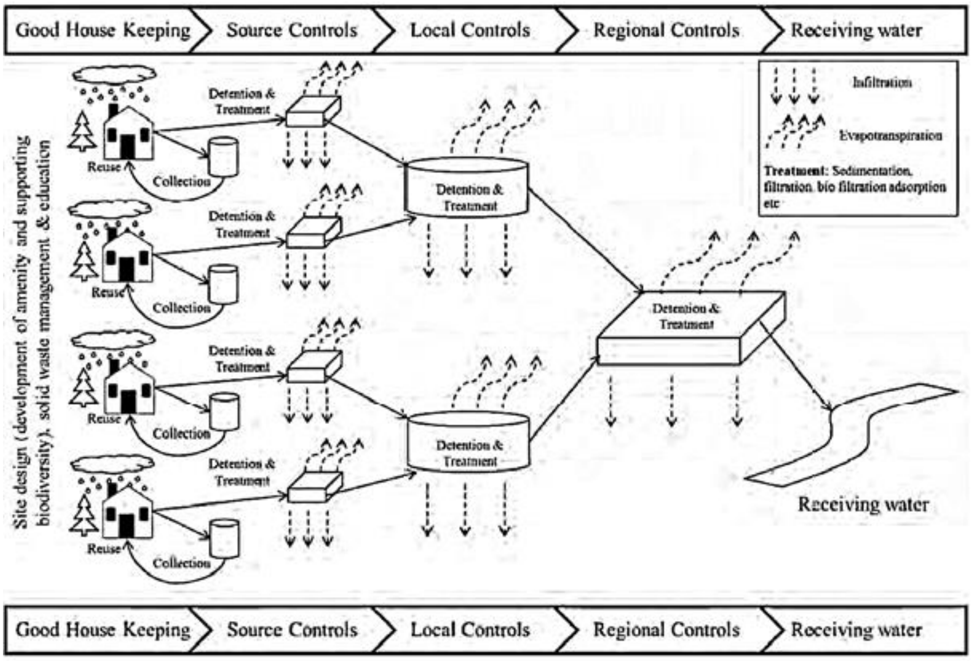

Figure 2-2: Treatment Train Schematic (Armitage, et al., 2013)

2.6 Permeable Paving Systems (PPS)

Permeable paving systems are a type of SUDS and are considered to be very effective in dealing with stormwater, both in terms of quality and quantity (Tarde, et al., 2019) as a result of minimising runoff by allowing for infiltration while adequately supporting/withstanding expected loadings (due to pedestrians, vehicles etc.) (Armitage, et al., 2013) and dealing with the pollutant problems mentioned in the previous sections due to its natural ability to treat these pollutants by acting as a filter (Abbott & Comino-Mateos, 2003). The use of PPS also reduces soil erosion as the infiltrated water is usually stored and discharged into the soil at a controlled rate (Abbott & Comino-Mateos, 2003; Bruinsma, 2017; Scholz & Grabowiecki, 2007). Further benefits of PPS include the potential retention of stormwater for reuse, increasing groundwater recharge and the reduction of the urban heat island effect (Scholz & Grabowiecki, 2007). Typically, PPS are designed for low volume traffic, such as: driveways, parking lots and loading areas (Lucke, et al., 2013; Scholz & Grabowiecki, 2007) and should be built on gentle slopes of less than 5 degrees. (Armitage, et al., 2013).

2.6.1 Design of PPS

PPS involve two types of structural elements: monolith (infiltration through the pavement surface only) and modular (infiltration through surface joints) (Lucke, et al., 2013). These structural elements (also considered load-bearing surface materials) include: ‘porous pavement’ (porous concrete/asphalt), brick or permeable concrete block pavers, gravel and even just grass (very low traffic loading) (Armitage, et al., 2013). These materials are built on a sub-base of coarse gravel (which allows infiltration into groundwater) (Armitage, et al., 2013).

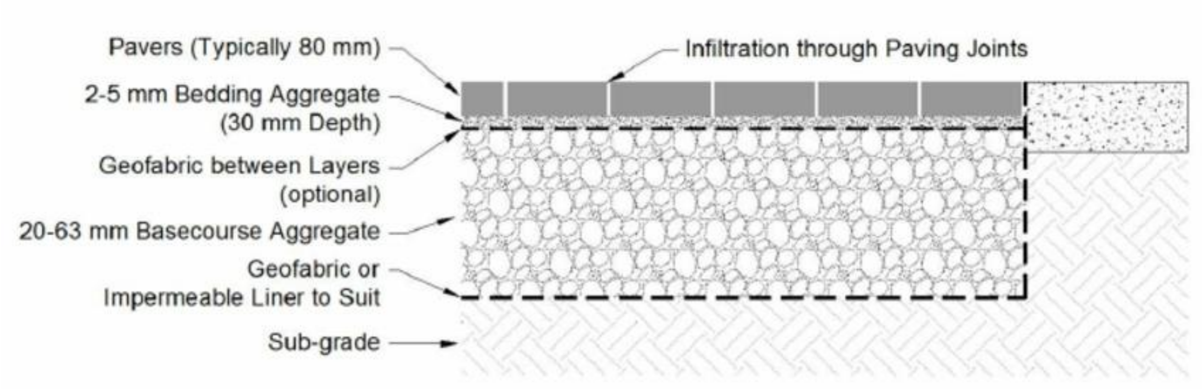

Figure 2-3: Standard Layout of a PPS (Lucke, et al., 2013)

2.6.2 Performance of PPS

PPS have a very high potential for reducing surface runoff and peak stormwater flows (Abbott & Comino-Mateos, 2003; Andersen, et al., 1999; Drake, et al., 2013) and, as expected, are typically far more effective during small rainfall events with a slight loss in efficiency during high rainfall intensities and saturated soil conditions (Andersen, et al., 1999). Past observations (Shackel, et al., 2003; Abbott & Comino-Mateos, 2003; Drake, et al., 2013) have indicated a reduction of total surface flow volumes from 24% to 93% whilst achieving peak flow reductions of at least 30%. Without going into great depth of past observation results, it is evident that PPS have a high hydrological performance potential. Actual quantitative measurements for the hydrological performance of PPS vary greatly as a result of due to variable designs and testing methods as well as environmental conditions, and therefore observation and test results should be taken qualitatively.

Another performance aspect of PPS to consider is its ability to filter and remove pollutants. Past results collected by (Legret & Colandini, 1999) and (Yong, et al., 2008) indicated that at least 50% of Total Suspended Solids were removed with the latter being as high as 90%, proving that PPS have a high potential for pollutant removal, especially when compared to the conventional systems.

The performance of PPS has been shown have very high potentials, however in most cases this potential decreases with time and for the performance potential of PPS to be fully realised, adequate and thorough maintenance is of utmost importance.

2.6.3 Maintenance of PPS

PPS require regular maintenance in order to function adequately and as designed. The main cause of failure of PPS is the clogging of the system, mainly due to fine sediments (Armitage, et al., 2013; Abbott & Comino-Mateos, 2003) which results in reduced infiltration therefore making the system a failure. The fine stone aggregate located between the surface materials of these aggregates also lead to blockage as well as trap pollutants (Armitage, et al., 2013). A vacuum-sweeping and/or high pressure jet-washing is one such method suggested, and should be used roughly 4 times a year (Armitage, et al., 2013).

2.7 Testing Methods

PPS is a very useful type of SUDS, however the system requires adequate design, construction and maintenance. In order to test the performance of a PPS, several testing apparatuses have been created. The more popular testing involves measuring the infiltration rate/capacity of the PPS, with the main testing methods comprising of either the single or double ring infiltrometer tests (Lucke, et al., 2013; Bean, et al., 2007). A ring infiltrometer test is used to determine the hydraulic conductivity of in situ soils (while the double ring was introduced to improve accuracy by reducing errors caused by lateral flow which seeps through under the rings) (Lucke, et al., 2013). The constant and falling head methods are the most popular methods used to calculate the infiltration rate when using the single/double ring infiltrometer (Lucke, et al., 2013; Bean, et al., 2007; Boogaard, et al., 2014). The main hindrance to using the infiltrometer methods is that the test rings cannot penetrate the concrete surface being tested, therefore some sort of adhesive is required to prevent/minimise lateral water flow through the rings (Lucke, et al., 2013). The two main parameters followed by these methods are described in ASTM C1701 and NCAT (Li, et al., 2013; Boogaard, et al., 2014).

A simple infiltration test can be used whereby a square made of simple wooden planks is stuck to the concrete surface (which is being tested) using a type of adhesive. 20L of water is poured into the square and a time is taken to measure how quickly the PPS allows for infiltration (Bernard, 2019; Winston, et al., 2016).

A simpler infiltration test can be done: the stormwater infiltration field test (SWIFT) which makes use of a 20L bucket with a 4mm diameter hole in the centre of the bottom of the bucket. The hole is plugged, the bucket is filled with 6L of water and raised about 60mm. The plug is removed and the number of fully wetted bricks is counted to determine blockage (Bernard, 2019; Lucke, et al., 2015).

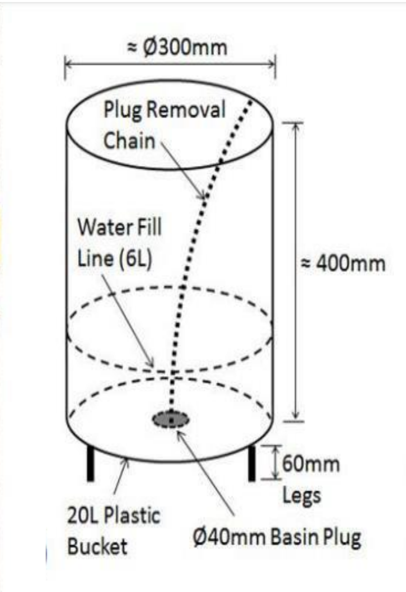

Figure 2-4: Stormwater Infiltration Field Test (SWIFT) Infiltrometer (Lucke et al., 2015)

2.8 Summary

Conventional stormwater management and drainage systems are progressively becoming more problematic due to the rapid increase of urbanisation and their inabilities to continue to control increased surface runoff volumes, peak flow volumes and the pollution issues that arise as a result. Therefore, a paradigm shift is needed in order to counter these problems in a sustainable way. SUDS are one such alternatives to the conventional methods in place. The effective use of SUDS directly addresses the problems that the conventional methods are facing, whilst also providing additional benefits towards the quality of life in implemented areas.

PPS are one such SUDS and are being implemented due to their high-performance potential in the problem areas faced by the conventional stormwater practices due to their ability to reduce surface runoff and peak flows as well as transported pollutants via infiltration of stormwater into their porous structures whilst being able to withstand road and pedestrian traffic.

3. Research Method

This research paper aims to investigate the rate of infiltration of permeable pavement systems in Johannesburg, specifically permeable interlocking concrete paving (PICP). Further results for PICP in Cape Town are obtained from a study conducted by the University of Cape Town as presented in Barnard, (2019) and can be seen in Appendix B.

This research paper also considers possible factors which hinder the performance of the PICP, specifically in terms of infiltration. These factors include: lack of or poor maintenance; vegetation in and around the testing site; slope of the site; age of the PICP; design of the PICP.

3.1 Description of Sites

Several sites around Johannesburg were identified having PPS in operation. Only three sites were accessible due to the COVID-19 pandemic, with one site having two locations tested individually. The sites are shown in Figure 3-1. For all locations tested, there was no prior record of previous testing with only one site undergoing any form of maintenance in its years of operation. Site investigations were conducted on arrival to determine the most suitable location for spot tests with regards to any physical attributes that may have an effect on the capability and performance of the paving.

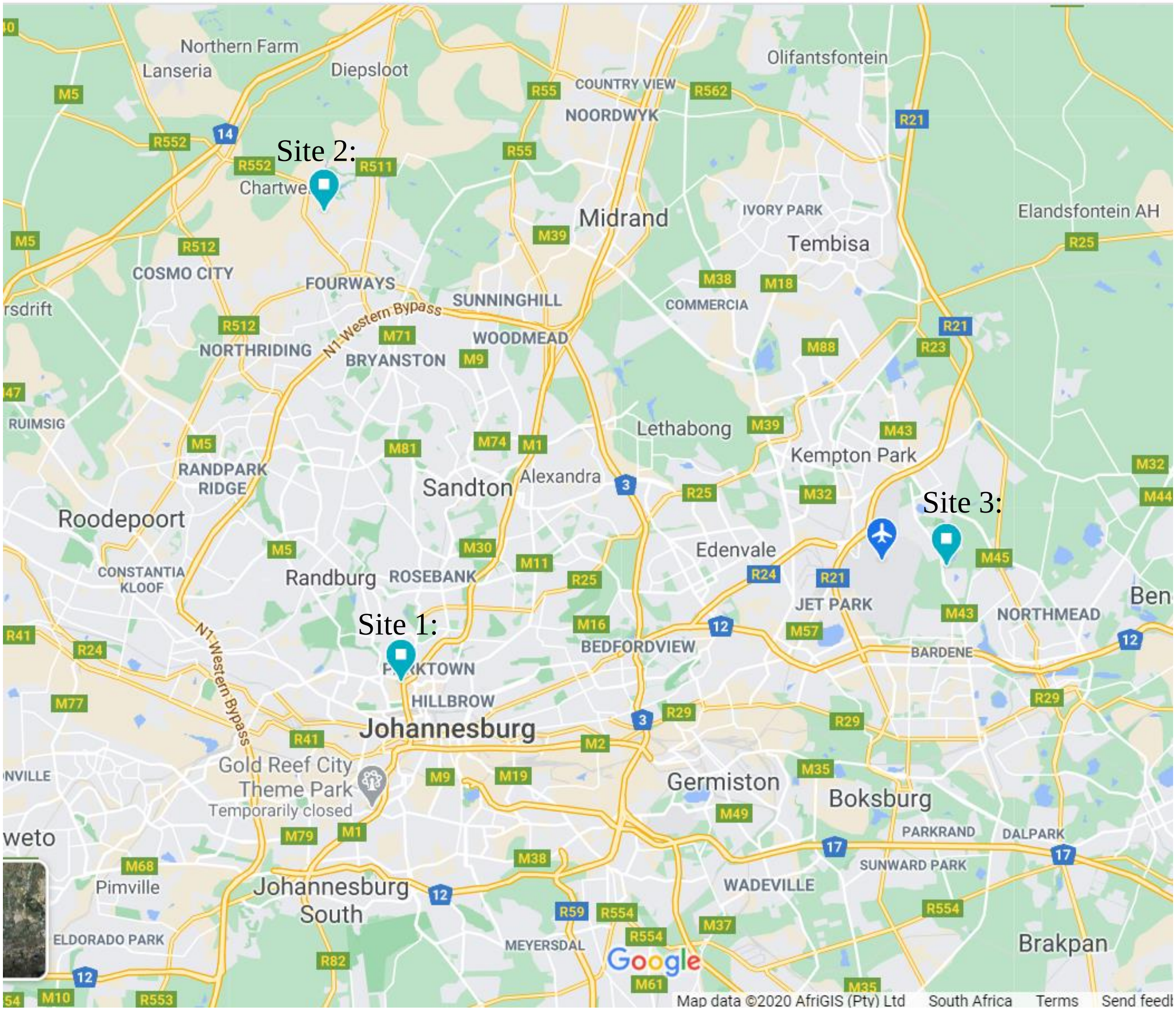

Figure 3-2: Test Locations: Site 1 (University of the Witwatersrand); Site 2 (Broadacres Academy); Site 3 (Toyota Parts Distribution Centre) (Google Maps, 2020)

3.2 Apparatus

Figure 3-2 shows the apparatus used for all spot tests conducted. 6l of water was measured and marked clearly inside the bucket to ensure all tests were done with 6l of water. The bucket was raised 60mm and had a 40mm diameter hole at the bottom for the water to flow out once unplugged.

Figure 3-2: SWIFT apparatus used

A sustainable source of water was used for all spot tests and was sourced from a recirculating pond at one of the researcher's homes. This water was transported to each site using old buckets and jerry cans.

3.3 Methodology

As this research's primary objective is to supplement research completed by the University of Cape Town, the testing used to determine the infiltration rates at each site was the modified SWIFT test presented in Barnard (2019). This modified test deviates from the original by using an approximated area of an ellipse to estimate the wetted area directly instead of counting the number of wetted bricks. This is done by taking two lengths perpendicular to each other and using the following formula:

$$A = \frac{ab\pi}{4} \tag{3.1}$$

Where:

A = Area (m2); a = Length (m); b = Breadth (m)

The infiltration capacity of the PPS for each site was then determined by using the equation presented in Barnard (2019) found by correlating results from the ASTM Standard test and the modified SWIFT test. The graph giving this correlation can be found in Appendix B.

$$y = -1056\ln(x) + 1958.3 \tag{3.2}$$

Where:

y = Infiltration Rate (mm/hr)
x = Wetted Area (m2)

For the tests conducted in this report, some infiltration rates calculated using equation 3.2 resulted in negative values and were consequently changed to return a value of 0mm/hr as this is more suitable for this study.

To determine the capability of each site with regards to its performance in a storm event, the area that the PICP services at each site (respective catchment areas) was calculated using the area function on google earth and subsequently calculating a run-on-ratio (r) factor using equation 3.3.

$$r = \frac{Total\ Area}{Permeable\ Area} \quad (3.3)$$

This factor was then used with the effective rainfall for a 1-hr storm, found by extrapolating a 5-minute storm duration for 50-year, 100-year and 200-year return periods, to obtain the infiltration requirements of the PICP at the site in question. The return periods used as well as the extrapolation of the 5-minute storm duration was done for the sake of maintaining uniformity between this research and that of Barnard (2019) as it was deemed that this was the worst-case scenario that the PPS capability should be compared against. The design rainfall for each of the return periods was found using a software developed by J C Smithers and R E Schulze and the University of KwaZulu-Natal for the Water Research Commission, and can be found in Appendix C. The software was developed based on the findings and research presented in Smithers and Schulze (2002) and required the following as inputs: coordinates; storm duration; desired return periods.

3.4 Paving Types

It should be noted that this research presents the findings of tests performed on two major types of PICP, namely open-block paving and the more standard type resembling typical paving. Therefore, results were differentiated between each type found at sites utilising multiple PICP and comparisons between the performance of similar paving types as well as the different types are made with regards to this report and Barnard (2019). Visuals for the types found at each site can be seen below, labelled as found in the Results and Analysis results.

3.4.1 University of the Witwatersrand Parking

Figure 3-3: Wits Parking Paving Type – similar type used for both upper and lower parking lots.

3.4.2 Broadacres Academy

Figure 3-4: Broadacres Academy Type 1

Figure 3-5: Broadacres Academy Type 2

3.4.3 Toyota Parts Distribution Centre

Figure 3-6: Toyota Type 1 - also indicating slope towards multiple drainage points

Figure 3-7: Toyota Type 2

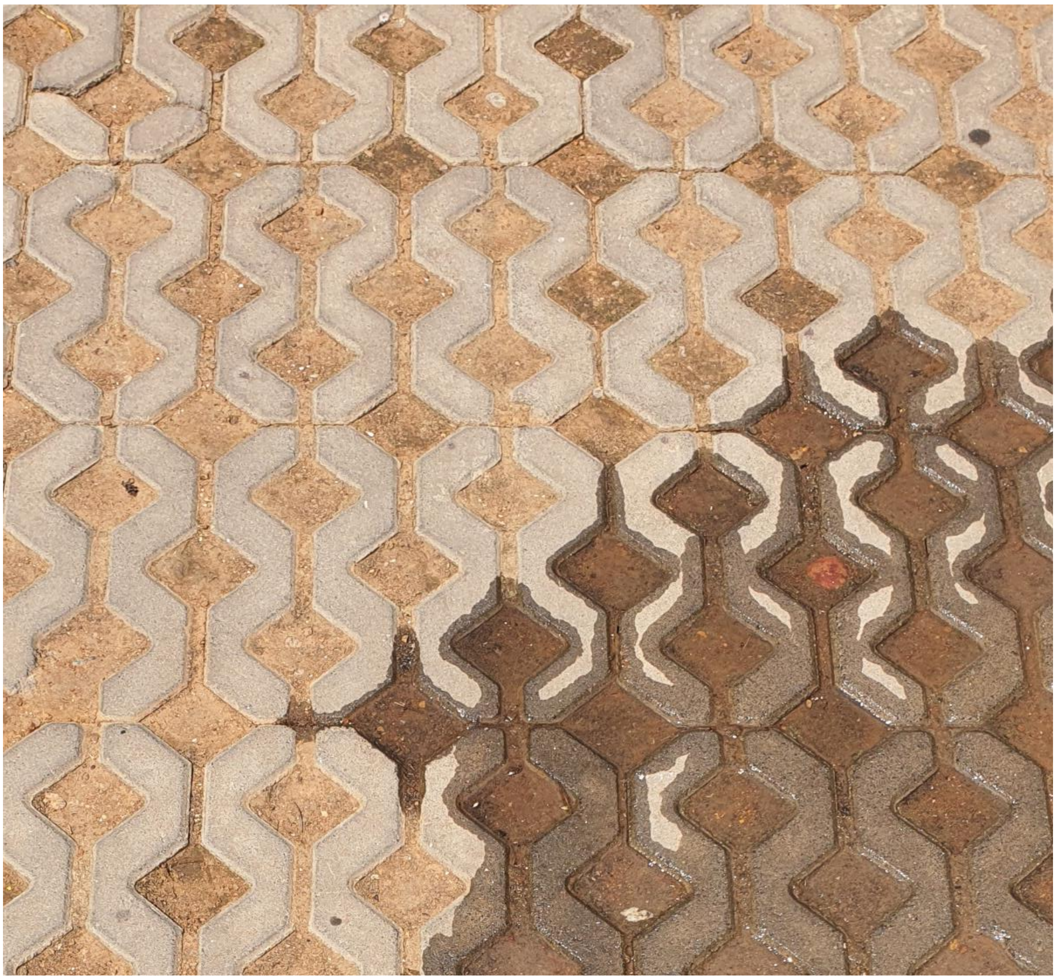

Figure 3-8: Toyota Type 3

4. Results and Analysis

4.1 University of the Witwatersrand Lower Parking

The University of the Witwatersrand's (Wits) permeable paving is found at two parking lots at the very northern end of the Braamfontein campus. The lower parking has been in operation since 2013 and has had no maintenance since instalment. The entire lot consists of PICP with scattered trees throughout. A small embankment marks the eastern border of the lot (above which the upper parking is situated) and can be seen in Figure 3-3. Tests were performed at the main driving lanes of the parking as this was deemed to have most traffic and thus would provide a more accurate representation of the deterioration of the PICP throughout its use. The location of these spot tests is shown in Figure 4-1 and the results can be seen in Table 4-1.

Figure 4-1: Wits Lower Parking test sites.

Table 4-1: Wits Lower Parking Test Results

University of the Witwatersrand Lower Parking				
Test Site	Measured Area (Length x Width) (m2)	Area (m2)	Infiltration Rate (mm/hr)	Infiltration Rate (mm/hr)
1	10.07	7.91	-225.50	0.00
2	9.25	7.26	-135.81	0.00
3	3.68	2.89	837.52	837.52
4	6.96	5.47	164.56	164.56
5	7.47	5.87	89.89	89.89
6	6.84	5.37	182.93	182.93
7	7.75	6.09	51.03	51.03
8	6.40	5.03	253.14	253.14
9	6.44	5.06	246.56	246.56
10	5.69	4.47	377.31	377.31
11	8.05	6.32	10.92	10.92
12	8.79	6.90	-81.95	0.00
13	7.59	5.96	73.06	73.06
14	7.64	6.00	66.12	66.12
15	6.14	4.82	296.94	296.94
16	10.00	7.85	-218.14	0.00
17	7.54	5.92	80.04	80.04
		Average	121.68	160.59

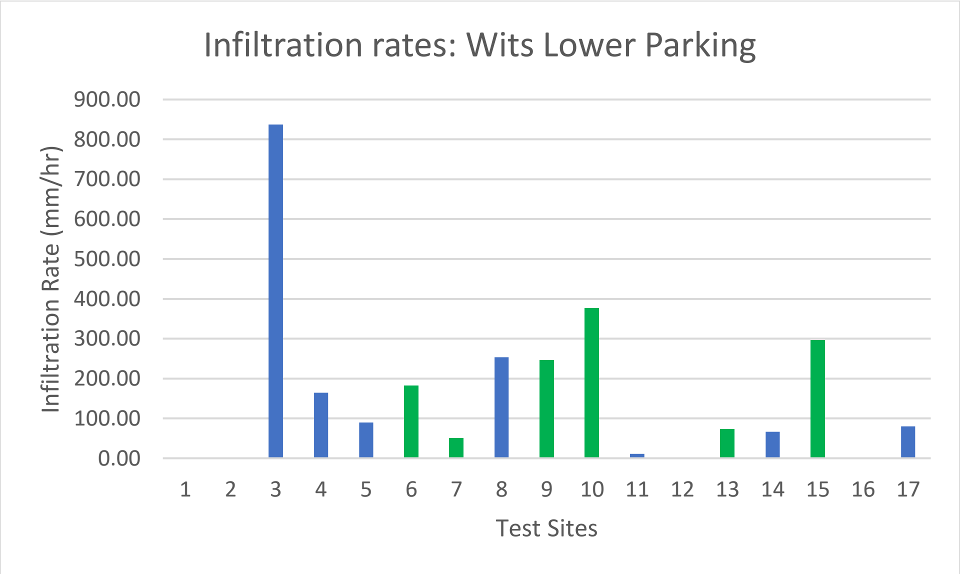

Figure 4-2: Wits Lower Parking Test Results

One of the factors investigated at this specific site, was that of a blocking wave. This is due to the assumption that the embankment present would aid in the transportation of sediments onto the paving and thus it was investigated as to whether the paving's infiltration capacity gradually worsened as it approached the embankment. Test sites 1-4, closest to the embankment, show no evidence of this being a true assumption when compared with other test sites. However, there are many factors that could have influenced the results such as the lack of maintenance and presence of vegetation throughout the site as can be seen in Appendix A. Thus, it is difficult to accurately analyse for any such patterns given the state of the system.

The presence of trees was also investigated, and all sites tested within the vicinity of trees are filled in green on Figure 4-2. Once again, no direct correlation can be made as there is no pattern visible from these results.

Table 4-2 shows the infiltration rate required for the paving to perform acceptably in a worst-case scenario design storm. The contributing catchment area can be taken solely as the permeable paving area as there is no major runoff from any surrounding areas. It can be seen that the permeable paving is not capable to perform in any of the storm events.

Table 4-2: Design Rainfall Lower Parking: Comparing design rates to the average rate obtained by test results

Wits Lower Parking			
Design Rainfall	Total Catchment Area	Permeable Paving Area	Run-on-ratio
	5314	5314	1
	50-yr	**100-yr**	**200-yr**
5-min (mm/hr)	21.7	25.1	28.8
1-hr extrapolation (mm/hr)	260.4	301.2	345.6
Infiltration Requirement (mm/hr)	260.4	301.2	345.6
Test Average Infiltration Rate (mm/hr)	160.6		

4.2 University of the Witwatersrand Upper Parking

The upper parking has also been in operation since 2013 but has had maintenance in the form of replacement in 2017. It has a similar layout to the lower parking in the sense that the entire lot consists of PICP with scattered trees throughout. Tests were performed at the main driving lanes of the parking for the same reason as previously mentioned. The location of these spot tests is shown in Figure 4-3 and the results can be seen in Table 4-3.

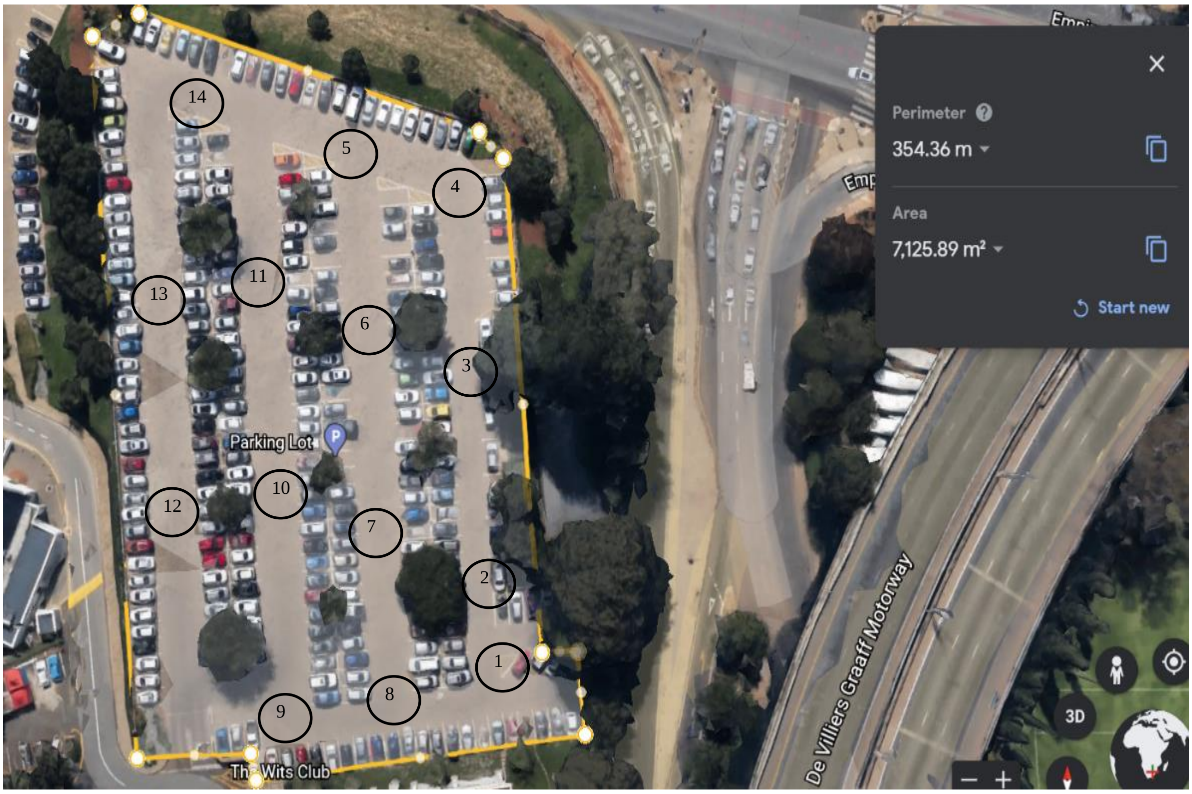

Figure 4-3: Wits Upper Parking test sites

Table 4-3: Wits Upper Parking Test Results

University of the Witwatersrand Upper Parking				
Test Site	Measured Area (Length x Width) (m2)	Area (m2)	Infiltration Rate (mm/hr)	Infiltration Rate (mm/hr)
1	9.05	7.11	-112.73	0.00
2	5.65	4.44	384.76	384.76
3	8.97	7.05	-103.35	0.00
4	7.62	5.98	68.89	68.89
5	4.40	3.46	648.82	648.82
6	8.32	6.53	-23.92	0.00
7	6.31	4.96	268.10	268.10
8	4.92	3.86	530.86	530.86
9	6.00	4.71	321.29	321.29
10	2.44	1.92	1271.44	1271.44
11	7.59	5.96	73.06	73.06
12	4.00	3.14	749.47	749.47
13	6.86	5.39	179.85	179.85
14	3.98	3.12	756.09	756.09
		Average	358.04	375.19

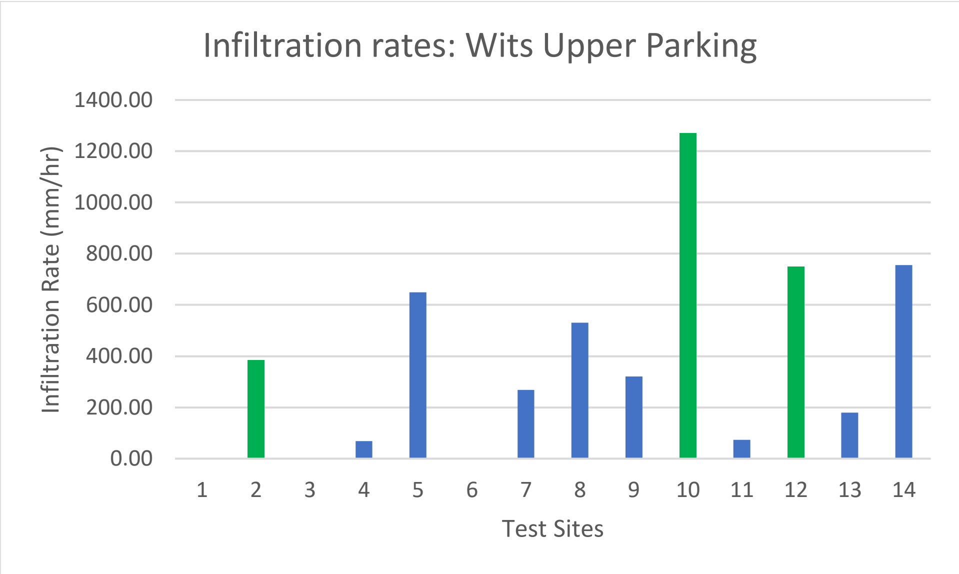

Figure 4-4: Wits Upper Parking Test Results

No blocking wave phenomenon was investigated due to the absence of any boundary controls. The presence of trees was once more investigated and the tests occurring within the vicinity of trees are filled in green in Figure 4-4 (Test Site 6 displaying a value of 0 also being one of these tests). Once again it can be seen that no visible pattern emerges, and the presence of trees cannot be taken to have a direct noticeable impact on the capability of permeable paving nearby. Poor maintenance was also observed in the form of major blockage as a result of fallen foliage and vegetation as can be seen in Appendix A.

Comparing the average infiltration rate obtained for both lower and upper parking lots, the upper parking lot performs better with an average infiltration rate double that of the lower parking. This can possibly be attributed to the fact that the upper parking had maintenance conducted in its lifetime, unlike the lower parking.

However, it should be noted that the maintenance construction of the upper parking paving is poor as can be seen in Appendix A, with major gaps between poor placements of paving. These gaps may contribute to an increased infiltration rate as water will flow more readily than if placed adequately and thus may not accurately reflect the infiltration capabilities of the pavement itself.

Table 4-4: Design Rainfall Upper Parking: Comparing design rates to the average rate obtained by test results

Wits Upper Parking			
Design Rainfall	Total Catchment Area	Permeable Paving Area	Run-on-ratio
	7126	7126	1
	50-yr	**100-yr**	**200-yr**
5-min (mm/hr)	21.7	25.1	28.8
1-hr extrapolation (mm/hr)	260.4	301.2	345.6
Infiltration Requirement (mm/hr)	260.4	301.2	345.6
Test Average Infiltration Rate (mm/hr)	375.2		

Table 4.4 shows the infiltration rate required for the paving to perform acceptably in a worst-case scenario design storm. The contributing catchment area can be taken solely as the permeable paving area as there is no major runoff from any surrounding areas. It can be seen that the permeable paving is capable to perform in all of the storm events. However, once more the poor construction should be taken into account when analysing this site.

4.3 Broadacres Academy

The PPS in operation at Broadacres consists of open-block grass paving. Two types were observed and can be referred to in Section 3.3. Test sites 1-5 are type 1 and were installed midway through 2018 whilst test sites 6-9 are type 2 and were installed at the beginning of 2020. The PPS were located only at the parking bays whilst the surrounding access roads were of normal paving. The site had a gentle slope, sloping towards a drainage area marked "D" in Figure 4-5. The spot test sites are also shown in Figure 4-5 with the results shown in Table 4-5.

Figure 4-5: Broadacres test sites.

Table 4-5: Broadacres Academy Test Results

Broadacres Academy			
Test Site	Measured Area (Length x Width) (m2)	Area (m2)	Infiltration Rate (mm/hr)
1	2.60	2.042035	1204.372
2	3.08	2.419026	1025.466431
3	3.25	2.552544	968.7324097
4	1.40	1.099557	1858.077404
5	1.50	1.178097	1785.220932
6	0.41	0.322013	3154.9197
7	1.80	1.413717	1592.689368
8	2.44	1.916372	1271.442156
9	0.72	0.565487	2560.292381
		Average	1713.468087

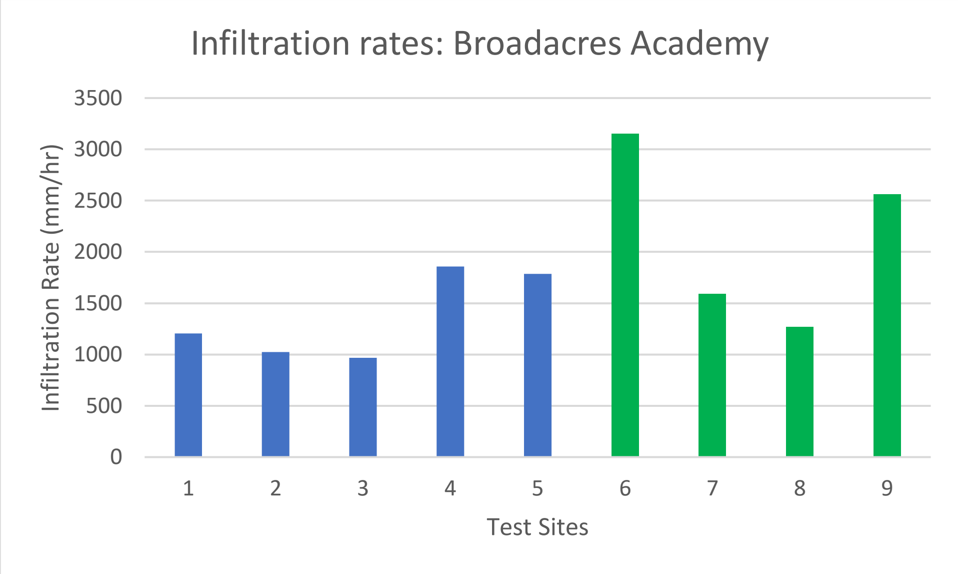

Figure 4-6: Broadacres Academy Test Results

The site was fairly uniform throughout with the only differences being that of the slightly different paving used as mentioned and therefore nothing in particular in terms of physical factors, was investigated. Those installed in 2020 (Type 2) are filled in green on Figure 4-6 and had an average infiltration rate of 2145mm/hr compared to the 2018 installations (Type 1) of 1368mm/hr. It can be estimated that the paving's capability has therefore deteriorated by 32% over one and a half years.

A potential limitation using the SWIFT testing method for this type of PICP was identified as it was noted that in some instances the water would collect in pools within the open blocks of the paving. Thus, using the wetted area may have resulted in testing the paving's retention capabilities as opposed to its permeable capabilities.

Table 4-6: Design Rainfall Broadacres Academy: Comparing design rates to the average rate obtained by test results

Broadacres Academy			
Design Rainfall	Total Catchment Area	Permeable Paving Area	Run-on-ratio
	3330	1341	2.483221
	50-yr	**100-yr**	**200-yr**
5-min (mm/hr)	22.3	25.8	29.6
1-hr extrapolation (mm/hr)	267.6	309.6	355.2
Infiltration Requirement (mm/hr)	664.5100671	768.8053691	882.0403
Test Average Infiltration Rate (mm/hr)	1713.5		

Table 4.6 shows the infiltration rate required for the paving to perform acceptably in a worst-case scenario design storm. The contributing catchment area was converted into a run-on-ratio using Equation 3.3 so as to incorporate the runoff from the surrounding impervious surfaces. It can be seen that the permeable paving is capable to perform in all of the storm events.

4.4 Toyota Parts Distribution Centre

The PICP found at Toyota consisted of three types which can be seen upon referring to Section 3.3. All three types were constructed in 2013 with no record of maintenance. Figure 4-7 depicts the entire site and Figure 4-8 (section marked in black on Figure 4-7) displays the three types in use that were made accessible, with types 1 and 2 (shown in orange and yellow respectively) being of a standard type of PICP and type 3 (shown in green) an open-block grass paving similar to those found at Broadacres Academy. The lower orange section (Figure 4-8) was sloped towards the left towards multiple drainage points (shown in Figure 3-6), and thus potentially having an effect on the testing as the water would flow immediately towards the drainage points, as the roadway was not very wide, resulting in some tests losing accuracy as the wetted area was restricted due to the exit point being provided. Therefore, some of the tests may have resulted in a higher infiltration rate due to its low wetted area being reported. The test results are shown in Table 4-7.

Figure 4-7: Toyota Site. Black outline indicates the PICP tested. Blue outline indicates PICP not tested.

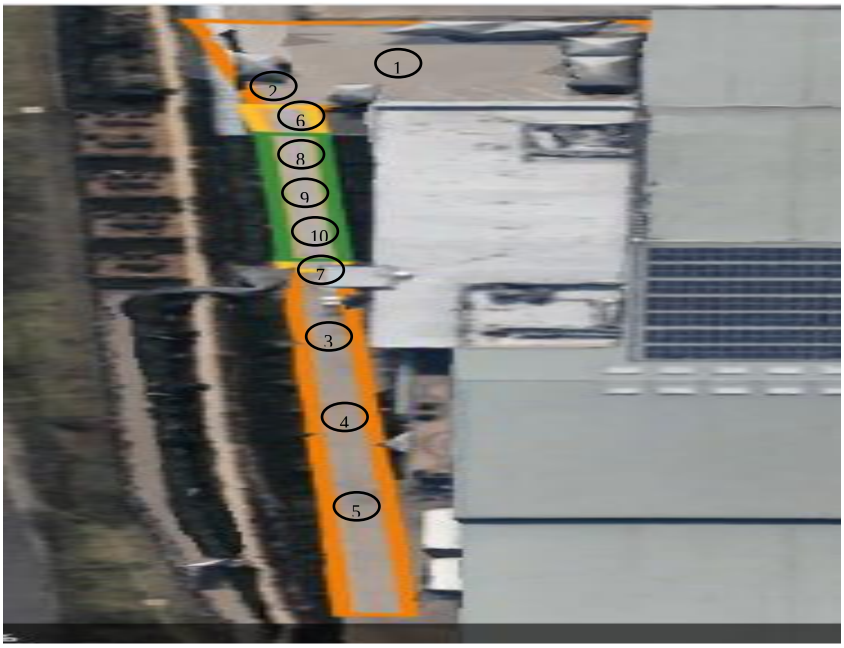

Figure 4-8: Toyota Test Sites

Table 4-7: Toyota Parts Distribution Centre Test Results

Toyota Parts Distribution Centre				
Test Site	Measured Area (Length x Width) (m2)	Area (m2)	Infiltration Rate (mm/hr)	Infiltration Rate (mm/hr)
Type 1				
Area: 1134m2				
1	8.28	6.503096793	-18.82608874	0.00
2	6.60	5.183627878	220.6465365	220.65
3	6.94	5.450663254	167.601412	167.60
4	6.63	5.207189823	215.8574127	215.86
5	4.53	3.55785368	618.0697178	618.07
		Average	240.669798	244.4350158
Type 2				
Area: 46m2				
6	7.88	6.188937528	33.4618194	
7	6.00	4.71238898	321.2940864	
		Average	177.3779529	
Type 3				
Area: 135m2				
8	1.97	1.547234382	1497.388665	
9	2.34	1.837831702	1315.632704	
10	2.73	2.144136986	1152.849587	
		Average	1321.956985	
Total Area (m2)	1315.00	**Weighted Average (mm/hr)**	352.71	

Unfortunately, due to COVID-19 restrictions, only a small portion of the site was open to testing and thus an accurate estimation of its capabilities compared to the design rainfall obtained could not be done as the total catchment areas incorporated would have to include a large area of PICP (type 1) that went untested (marked in blue on Figure 4-7). For analysis it was therefore assumed that the total catchment area shown in Figure 4-7 had no impact on the small area of PICP tested due to its geometric properties and a weighted average of the infiltration rates for each type with respect to their contributing areas was therefore used in determining the average infiltration rate for the site.

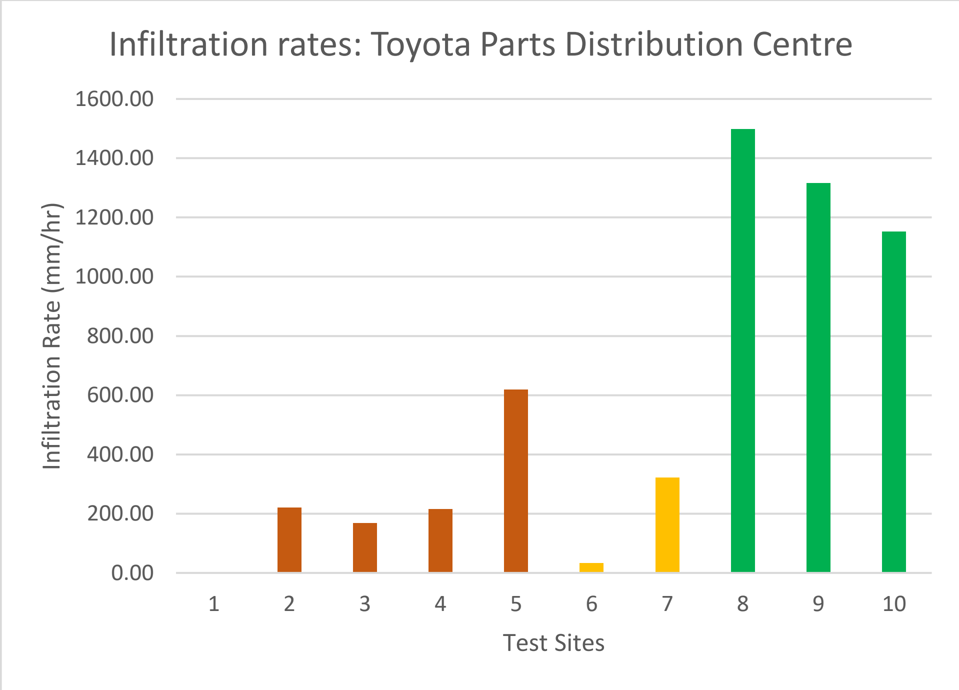

Figure 4-9: Toyota Parts Distribution Centre Test Results

Tests 1-5 were of type 1. Tests 6 and 7 were of type 2 paving, resembling those found at the Wits sites, the nature of which is similar to that of type 1 with each paving having a larger surface area. Tests 8-10 were of type 3 paving (open-block). It can be seen from Figure 4.8 that the open-block paving outperforms the other types by a large margin, however, as was observed at Broadacres Academy, the SWIFT test may not prove the most accurate testing method for this type of paving due to its retentive nature. At spot test 5, the drainage point problem mentioned was observed and thus an overestimated value of infiltration is recorded due to the water flowing into the drain.

Table 4-8 shows the infiltration rate required for the paving to perform acceptably in a worst-case scenario design storm. The contributing catchment area was taken as the combined area of each PICP with no extra runoff from the surrounding buildings as it was noted that their flow would flow away from the PICP tested. It can be seen that the permeable paving is capable to perform in all of the storm events.

Table 4-8: Design Rainfall Toyota Parts Distribution Centre: Comparing design rates to the average rate obtained by test results

Toyota Parts Distribution Centre			
Design Rainfall	Total Catchment Area	Permeable Paving Area	Run-on-ratio
	1315	1315	1
	50-yr	**100-yr**	**200-yr**
5-min (mm/hr)	20.6	23.8	27.3
1-hr extrapolation (mm/hr)	247.2	285.6	327.6
Infiltration Requirement (mm/hr)	247.2	285.6	327.6
Test Average Infiltration Rate (mm/hr)	352.7		

4.5 Comparison between Sites Tested

It is evident upon noting the results from Broadacres Academy and Type 3 of the Toyota Centre that the open-block grass paving outperforms all other types substantially. This should be taken with caution as the SWIFT testing method may not be the most reliable method with regards to the open-block paving. Comparison of the open-block paving between both sites show that Broadacres Academy's paving has an average infiltration rate higher than that of the Toyota Centre (2145mm/hr to 1322mm/hr). Later installation (2018 as opposed to 2013) could be a factor in this difference, as well as the traffic volumes each paving is subject to, as the Toyota Centre has high volumes of heavy trucks whereas the paving at Broadacres Academy is only subject to parked cars, thus less heavy traffic flow. It was also observed that the paving at Broadacres Academy had more vegetation growth in the individual block paving which once again can be attributed to the difference in traffic volume, and possibly also impacted the infiltration capacities.

Comparisons between the average infiltration rates of paving types 1 and 2 at the Toyota Centre (244mm/hr and 177mm/hr respectively) and the Wits lower parking (161mm/hr), can be done utilising the fact that installation occurred in the same year (2013). Type 1 outperforms type 2 as well as the paving found at the Wits lower parking. Noting that paving type 2 and the Wits paving are similar in terms of each individual brick having a larger surface area than that of type 1, it can be assumed that the surface area of the individual bricks possibly has an effect on the infiltration capacities of the paving as a whole, with a smaller surface area resulting in a higher infiltration capacity.

Paving type 2 at the Toyota Centre shows marginally higher infiltration rates than those at the lower parking lot at Wits. Given they are of similar type as well as being constructed in the same year with no subsequent maintenance, this difference can possibly be attributed to the presence of trees and vegetation present at Wits, resulting in more clogging as opposed to the lack of vegetation present at the Toyota Centre. However, the difference is not large enough to fully substantiate such an assumption. The maintenance performed at the Wits upper parking shows the positive effect of maintenance, as this site had double the infiltration capacity than the lower parking and substantially more when compared to the Toyota Centre. This higher infiltration rate can be attributed primarily to the maintenance performed given that the major difference between the three sites was this maintenance.

4.6 Comparison between Cape Town and Johannesburg

Appendix B shows a summary of results obtained by Barnard (2019) in the form of a graph. This same graph was used to obtain the relationship between the ASTM and SWIFT methods. Upon observing the values shown on the graph, it can be noted that the PICP capabilities found in the Cape Town tests are far better than that found in Johannesburg. This can mainly be attributed to the fact that most of the sites in Cape Town are newer, or were subject to maintenance throughout their design life as well as even being subject to previous testing, thus showing due diligence by the operators in ensuring the PICP retained its necessary capabilities.

Despite this, the results obtained in this report indicate that the PICP at each site are still capable for the worst-case design rainfall. Whilst their capabilities are far less than that found in the sites tested in Cape Town, they are adequate in dealing with their individual demands and thus prove to be successful, with the exception of the Wits lower parking.

5. Conclusion

The presence of permanent vegetation (trees) seemed to have no impactful effect on the overall capability of PICP when compared to sites with fewer or no permanent vegetation. Temporary vegetation that grow within the gaps (weeds) as well as general blocking due to sedimentation and the flow of aggregates over the PICP have clear negative impacts on the performance of PICP and thus require regular maintenance to ensure the build-up of these inevitable factors do not affect the performance of the PICP. This is substantiated as seen by the tested sites, specifically the difference between the two Wits sites. The maintenance of a PICP will increase its performance drastically whereas a lack of maintenance will reduce the performance to the point of incapability to deal with what it was designed for.

The surface area of individual bricks in a PICP system may also have an effect on the infiltration capacity of the system and should be further investigated.

The SWIFT test is an efficient and simple method of testing the capacity of most PICP, however certain PICP (specifically ‘open-block’) possibly require a more in-depth or tailored method due to some PICP having high retention qualities that are not taken into account with the SWIFT test.

It is clear that the design, construction and maintenance of PICP is essential for a consistent performance over the PICP’ design life. In order to ensure this are adhered to, a governing code is required so that engineers and contractors can follow a standard design and procedure for construction and regular maintenance.

PICP can be a viable solution to the improvement of stormwater management in South Africa, however proper design, construction and maintenance is required in order to ensure these PICP perform efficiently.

6. Recommendations

- Regular maintenance of existing and future PICP should be conducted in order to ensure the system performs adequately over its design life.
- Site owners who wish to install PICP should be willing to conduct regular maintenance in order to ensure consistent performance of the PICP. If a site owner is not willing to conduct maintenance, then they should be encouraged to not use a PICP.
- Further testing on the given sites should be done using different testing methods to ensure that the results found are adequate in predicting the performance of PICP, specifically in a high intensity storm. Further investigation for suitable testing methods is also required for the 'open-block' PICP due to the high retention capabilities of these PICP, therefore more than 6L of water may be required to assess the capabilities of these PICP.
- Further testing should also be done to ensure that the correlation found in Barnard (2019) between ASTM and SWIFT tests is reliable. Due to time and safety constraints, this was not possible in this research.
- Investigation on the possible correlation between surface area of individual bricks in a PICP system and infiltration capacities should be conducted.
- A South African code detailing design, construction and maintenance should be adopted to ensure PICP are efficient and safe. It is also important that all stakeholders involved are educated in the importance of proper design, construction and maintenance of PICP.

Appendix A: Site Photos

Wits Lower Parking

Figure A-1: Wits Lower Parking indicating clogging of the PPS..

Wits Upper Parking

Figure A-2: Wits Upper Parking indicating clogging and blockage of the PPS

Figure A-3: Wits Upper Parking indicating poor construction/maintenance resulting in failure of the PPS.

Appendix B: Correlation between ASTM and SWIFT Test

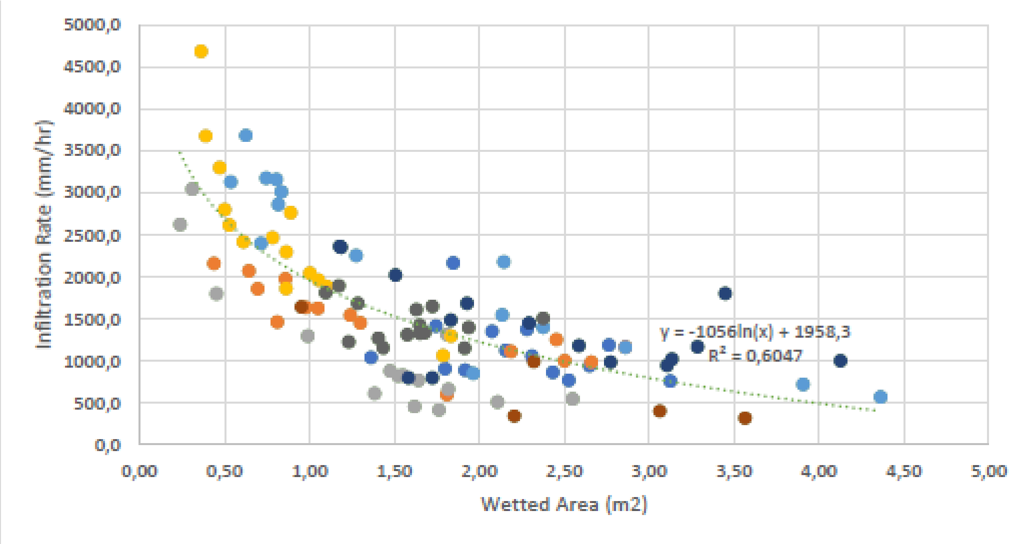

Figure B-1: Logarithmic correlation between infiltration rate to wetted area (Bernard, 2019)

Figure B-1 shows the correlation between the single ring infiltration test (as outlined in ASTM) and the SWIFT test. The infiltration rate is obtained using the single ring infiltration test and the wetted area is obtained using the SWIFT test. The two are then plotted and a correlation factor of R^2 is found. A logarithmic relationship was chosen as it showed the highest correlation between the two test types.

Appendix C: Design Rainfall

Table C-1: Design Rainfall used to determine PICP capabilities in section 4.

Location	Latitude (°) (')		Longitude (°) (')		Mean Annual Precipitation (mm)	Altitude (m)	Storm Duration	50	50L	50U	100	100L	100U	200	200L	200U
Wits	26	12	28	2	701	1720	5-minutes	21.7	17.3	26.1	25.1	19.9	30.3	28.8	22.8	35
Toyota	26	8	28	16	700	1660		20.6	16.4	24.9	23.8	18.9	28.9	27.3	21.6	33.3
Broadacres	26	0	28	0	664	1400		22.3	18.4	26.3	25.8	21.1	30.6	29.6	24.1	35.3

References

Abbott, C. & Comino-Mateos, L., 2003. IN-SITU HYDRAULIC PERFORMANCE OF A PERMEABLE PAVEMENT SUSTAINABLE URBAN DRAINAGE SYSTEM. *Journal of the Chartered Institution of Water and Environmental Management,* 17(3), pp. 187-190.

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), pp. 597-609.

Armitage, N. & Fisher-Jeffres, L., 2012. Charging for Stormwater in South Africa. In: *Water SA Vol. 39 No 3 WISA 2012 Special Edition 2013.* Cape Town: Water Institute of South Africa, pp. 429-430.

Armitage, N. et al., 2013b. *Alternative Technology for Stormwater Management: Sustainable Drainage Systems – Report and South African Case Studies,* Pretoria: Water Research Comimssion.

Armitage, N. et al., 2013. *The South African Guidelines for Sustainable Drainage Systems,* Pretoria: Water Research Commission.

Barbosa, A. E., Fernandes, J. N. & David, L. M., 2012. Key issues for sustainable urban stormwater management. In: *Water Research 46.* Lisbon: National Laboratory for Civil Engineering, pp. 6787-6798.

Bean, E. Z., Hunt, W. F. & Bidelspach, D. A., 2007. *Field Survey of Permeable Pavement Surface,* s.l.: JOURNAL OF IRRIGATION AND DRAINAGE ENGINEERING.

Bernard, C., 2019. *PERMEABLE PAVEMENT SYSTEMS,* Cape Town: University of Cape Town.

Boogaard, F., Lucke, T., Giesen, N. v. d. & Ven, F. v. d., 2014. *Evaluating the Infiltration Performance of Eight Dutch,* s.l.: Department of Water Management .

Botha, N., 2005. *Factors Hindering Stormwater Management,* Johannesburg: University of Johannesburg.

Brown, R., Keath, N. & Wong, T., 2009. Urban water management in cities: historical, current and future regimes. *Water Science and Technology*, 59(5), pp. 847-855.

Bruinsma, J., 2017. *Guidance for Usage of Permeable Pavements at Airports.* Washington: Transportation Research Board.

Clean Water Action, 2020. *Stormwater Pollution.* [Online] Available at: https://www.cleanwateraction.org/features/stormwater-pollution [Accessed 03 March 2020].

CSIR Building and Construction Technology, 2005. Guidelines for Human Settlement and Design Volume 2. In: Pretoria: CSIR Building and Construction Technology, pp. Chapter 6, 2.

Debo, T. N. & Reese, A., 2003. Introduction to Stormwater Management . In: *Municipal Stormwater Management Second Edition.* New York: Lewis Publishers, pp. 1-15.

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), p. 203.

Environmental Protection Authority, 2003. *Stormwater Pollution.* [Online] Available at: https://www.epa.sa.gov.au/search/documents?q=stormwater+pollution&published= [Accessed 10 March 2020].

Fryd, O., Dam, T. & Jensen, M., 2012. A planning framework for sustainable urban drainage systems. *Water Policy,* Volume 14, pp. 865-886.

Legret, M. & Colandini, V., 1999. Effects of a porous pavement with reservoir structure on runoff water: water quality and fate of heavy metals. *Water Science and Technology*, 39(2), pp. 111-117.

Li, H., Kayhanian, M. & Harvey, J. T., 2013. *Comparative field permeability measurement of permeable pavements using,* s.l.: Journal of Environmental Management.

Lucke, T., Boogaard, F. & Ven, F. v. d., 2013. *Evaluation of a new experimental test procedure to more accurately,* s.l.: Routledge.

Lucke, T., White, R., Nichols, P. & Borgwardt, S., 2015. *A Simple Field Test to Evaluate the Maintenance Requirements of Permeable Interlocking Concrete Pavements,* s.l.: Department of Water Management.

McDonald, R. et al., 2014. Water on an urban planet: Urbanization and the reach of urban water infrastructure. *Global Environmental Change,* Volume 27, pp. 96-105.

Mcgrane, S., 2016. Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. *Hydrological Sciences Journal,* 61(13), pp. 2295-2311.

Pratt, C., Newman, A. & Bond, P., 1999. Mineral Oil Bio-Degradation Within a Permeable Pavement: Long Term Observations. *Water Science and Technology,* 39(2), pp. 103-109.

Scholz, M. & Grabowiecki, P., 2007. Review of permeable pavement systems. *Building and Environment,* Volume 42, p. 3830–3836.

Shackel, B., Ball, J. & Mearing, M., 2003. *USING PERMEABLE ECO-PAVING TO ACHIEVE IMPROVED WATER QUALITY FOR URBAN PAVEMENTS.* Sun City, South Africa, Document Transformation Technologies.

Smither, J. & Schulze, R., 2002. *Design Rainfall Estimation.* [Online] Available at: http://ukzn-iis-02.ukzn.ac.za/unp/beeh/hydrorisk/RLMA%20and%20SI%20design%20rainfall.htm [Accessed 18 November 2020].

Smithers, J. & Shulze, R., 2002. *Design Rainfall and Flood Estimation in South Africa,* Pietermaritzburg: University of Natal.

Tarde, S., Shinde, S., Saindane, D. & Shaikh, M., 2019. *EXPRIMENTAL ANALYSIS OF PERMEABLE CONCRETE AND ITS APPLICATION OVER CONVENTIONAL METHOD.,* India: INTERNATIONAL RESEARCH JOURNAL OF ENGINEERING AND TECHNOLOGY.

United Nations Population Division, 2011. *World Urbanization Prospects: The 2011 Revision.,* New York: s.n.

Wanielista, M. P. & Yousef, Y. A., 1993. Stormwater Management Alternatives for Water Quality Improvement. In: *Stormwater Management.* USA: John Wiley & Sons, pp. 128, 216-219.

Wilson, S., Bray, R. & Cooper, P., 2004. *Sustainable Drainage Systems: Hydraulic, structural and water quality advice,* London: CIRIA C609.

Winston, R. J., Al-Rubaei, A. M., Blecken, G. T. & Hunt, W. F., 2016. *A Simple Infiltration Test for Determination of Permeable Paving Needs,* s.l.: J Environ. Eng..

Woods-Ballard, B. et al., 2015. *The SuDS Manual*, London: CIRIA 697.

Yong, C., Deletic, A., Fletcher, T. D. & Grace, M. R., 2008. The clogging behaviour and treatment efficiency of a range of porous pavements. *11th Int. Conference on Urban Drainage,* pp. 1-12.