DISSERTATION FOR THE DEGREE OF MASTER OF CIVIL ENGINEERING

The link between Permeable Interlocking Concrete Pavement (PICP) design and nutrient removal

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Abstract

Urbanisation, associated with the construction of 'hard' impermeable surfaces such as roofs and roads, results in increased stormwater runoff peak flows and volumes and their associated pollutants into downstream receiving waters compared with the pre-development state unless mitigated through Sustainable Drainage Systems (SuDS). Permeable Pavement Systems (PPS), one of the source control options in SuDS suite, are able to control stormwater runoff and reduce the discharge of pollutants (Armitage *et al.*, 2013). Urban runoff typically includes sediment, trash, heavy metals, organic matter, hydrocarbons and nutrients. PPS are able to remove a sizeable proportion of these through sedimentation, filtration, adsorption and biodegradation. The most commonly used PPS in South Africa are Permeable Interlocking Concrete Pavements (PICP) which comprise concrete pavers laid on selected stone layer works with surface infiltration enabled by the presence of carefully designed openings between the pavers filled with fine stone. The treatment performance of PICP systems appear to depend on various factors such as: the layout of the pavers; the size and condition of the stone aggregates; the presence and location of any geotextiles; the type of outlet; and the time period between rain events. While some research on the treatment of stormwater by PICP has been published, not enough is known about the relative performance of different PICP designs. This dissertation describes an investigation on the performance of 10 different PICP systems constructed in the civil engineering laboratory at the University of Cape Town (UCT) for the treatment of various nutrients (ammonia-nitrogen, orthophosphate-phosphorus and nitrate-nitrogen) commonly found in stormwater runoff.

Ten experimental cells each housing a different permeable pavement design were constructed in the NEB laboratory at the UCT. Infiltration tests (ASTM C1781) were first conducted to test the hydrological performance of each of the PICP cell. This was followed by 'clean water' tests to establish the 'base-line' pollutant values prior to the additional of any pollutants. Finally, typical Cape Town rainfall events were simulated using a synthetic stormwater mixture containing representative nutrients concentrations to test the treatment efficacy for each of the permeable pavement systems over the period of two years with intermittent dry and wet periods. The influent and effluent from all ten experimental cells were periodically collected and analyzed for pH, temperature, electrical conductivity and the effluent concentrations of ammonia-nitrogen, orthophosphate-phosphorus, nitrite-nitrogen and nitrate-nitrogen.

It was found that there is a reduction of ammonia-nitrogen for all experimental cells ranged from 27.5% to 78.7% compared with the average of 63.7% removal rate from other studies. However, the reduction in the ammonia-nitrogen effluent concentrations may not be true removal as the ammonia-nitrogen may have been converted into nitrite-nitrogen or nitrate-nitrogen through the nitrification process. It was also found that: the cells with geotextiles had higher ammonia-nitrogen reduction than those cells without; the cells with washed aggregates had higher ammonia-nitrogen reduction than those cells with unwashed aggregates; and the cell with a raised outlet (creating a 'sump' in the underlying stone aggregate) had the highest ammonia-

nitrogen reduction of all. The orthophosphate-phosphorus effluent concentrations ranged from 37% orthophosphate-phosphorus addition to 11% orthophosphate-phosphorus reduction compared with the average of 47.7% removal rate of orthophosphate-phosphorus in other studies. The presence of geotextile resulted in higher orthophosphate-phosphorus removal efficiencies than those cells without; the cells with washed aggregates had higher orthophosphate-phosphorus removal efficiency than those cells with unwashed aggregates. The cell with an elevated outlet (sump) had the least orthophosphate-phosphorus removal efficiency. In addition, it was found that all the experimental cells added significant quantities of nitrates having nitrate-nitrogen addition ranging from 160% to 2580% which may be due to the nitrification process of ammonia-nitrogen (NH_3) to nitrate-nitrogen (NO_3^-). The cell with the raised outlet had the highest nitrate-nitrogen addition which can be explained by its highest ammonia-nitrogen removal efficiency through the nitrification process. It was also found that the presence of geotextile has a negative impact on the nitrate-nitrogen removal efficiencies, possibly because geotextiles provide a habitat for the microbes that encourage nitrification. The nitrification process, promoting the reduction in ammonia-nitrogen effluent concentrations and the increase in nitrate-nitrogen effluent concentrations occurs when the pH is within the optimum range of 7.6-8.8 for growth of nitrifying bacteria, Lower pH results in higher nitrate-nitrogen concentrations. It was also found that the electrical conductivity – a measure of ionic strength – strongly depends on the length of the periods between rainfall ‘seasons’; it decreases rapidly during wet periods and increases during dry periods.

A field testing was also carried out on the New Engineering Building (NEB) parking lot at the UCT to confirm the true treatment performance of PPS. The results show the PICP are efficiently removing TSS, ammonia-nitrogen and orthophosphate-phosphorus. The PICP with geotextile was found to have positive impact on TSS, ammonia-nitrogen and orthophosphate-phosphorus removal than the one without. It was also found the presence of geotextile has negative impact on nitrate-nitrogen removal, with lower pH resulting in higher nitrate-nitrogen concentrations which aggress the previous laboratory findings.

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Glossary

Absorption refers to the taking up of one substance into the body of another.

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

Attenuation is the reduction of peak stormwater flow.

Base or Base Course is a material of a designed thickness placed under the surface wearing course of paving units and its bedding course.

Bedding Course is a layer of coarse crushed and washed stone screeded smooth as bedding for the pavers.

Best Management Practice (BMP) is a structural (or nonstructural) measure designed to infiltrate, temporarily store, or treat stormwater runoff in order to reduce pollution and/or flooding. Also called a stormwater control measure or SCM.

Block paver is a thin, flat stone designed for use in paving projects such as walkways, patios, and driveways.

Catchment is the area from which any rainfall will flow into a watercourse or wetland.

Design period is the length of time an asset is expected to be safely usable, or the depreciation period for accounting purposes.

Design storm is an idealized storm used for design purposes. It is defined by parameters such as intensity, depth, aerial spread and duration of the rainfall over the catchment area.

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

Filtration here means the filtering of stormwater pollutants by trapping them on vegetative species, in the soil matrix or on geotextiles.

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

Infiltration in the hydrological sense is the downward movement of water into soil.

Infiltrometer is a device used to measure soil permeability.

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

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

Stormwater is surface water resulting from natural precipitation and/or accumulation.

Acronyms and abbreviations

ASCE	American Society of Civil Engineers
ASSHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials International
AUS	Australia
BOD	Biochemical Oxygen Demand
CBP	Concrete Block Paver
Cd	Cadmium
CGP	Concrete Grid Pavers
CoCT	City of Cape Town
COD	Chemical Oxygen Demand
Cu	Copper
DWA	Department of Water and Sanitation
DWAF	Department of Water Affairs and Forestry
EBE	Engineering and the Built Environment (Department of Civil Engineering)
EC	Electrical Conductivity
E.Coli	Escherichia coli
EMC	Event Mean Concentration
EPA	Environmental Protection Agency
Fe	Iron
GSI	Green Stormwater Infrastructure
HDPE	High-Density Polyethylene
HMA	Hot Mix Asphalt
ID	Inner Diameter
IUWM	Integrated Urban Water Management

LID	Low Impact Development
Mn	Manganese
MPBs	Modular Paving Blocks
NCDENR	North Carolina Department of Environment and Natural Resources
NEB	New Engineering Building
NH_3	Ammonia Nitrogen
NO_2^-	Nitrite
NO_3^-	Nitrate
NRCS	The Natura Resources Conservation Service
NZ	New Zealand
OD	Outer Diameter
PA	Porous Asphalt
Pb	Lead
PC	Pervious Concrete
PFC	Permeable Friction Course
PGP	Plastic Grid Pavers
PICP	Permeable Interlocking Concrete Pavers
PO_4^{3-}	Orthophosphate
PP	Permeable Pavement
PPS	Permeable Concrete Block Paving
SCM	Stormwater Control Measures
SIR	Surface Infiltration Rate
SS	Suspended Solids
SuDS	Sustainable Drainage Systems
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen

TP	Total Phosphate
TDS	Total Dissolved solids
TSS	Total Suspended solids
UCT	University of Cape Town
UK	United Kingdom
USA	United States of America
WMA	Warm Mix Asphalt
WSUD	Water Sensitive Urban Design
Zn	Zinc

Symbols

CFU/100mL	Colony forming units per one hundred millilitres
cm	Centimeters
g	Grams
g/mol	Grams per molar mass
kg	Kilograms
ℓ	Litres
ℓ/day	Litres per day
ℓ/min	Litres per minute
ℓ/s	Litres per second
m	Metres
mg	Milligrams
mg/ℓ	Milligrams per liter
min	Minutes
mm	Millimeters
mm/h	Millimeters per hour
m/s	Metres per second
m^2	Square meters
s	Seconds
Ø	Diameter
µS/cm	Micro siemens per centimeter

1. Introduction

1.1 Background and motivation

Rapid urbanization in the 21st century has resulted in many traditionally undeveloped lands becoming impervious owing to the construction of impermeable surfaces such as roads, parking lots, driveways, rooftops, and buildings. This has led to increased runoff volumes, peak flow, pollutant loadings as well as reduced time to peak and groundwater recharge (NRCS, 1986; Finkenbine *et al*., 2000). This, in turn, has resulted in long-term damage to the environment through the erosion of watercourses and deterioration in water quality. Groundwater tables have been dropping in some areas.

The traditional approach to an urban drainage system is to convey stormwater runoff from the pipe networks to the nearest receiving water bodies as quickly as possible (Armitage *et al*., 2013). This conventional way of stormwater management harms both the quality and quantity of stormwater runoff. The pollutants in stormwater such as heavy metals, hydrocarbons from motor vehicles, suspended solids, and nutrients such as nitrogen and phosphorus lead to degraded urban water systems (Maheshwari *et al*., 2016). In many countries, including South Africa, a more sustainable approach for stormwater management termed Sustainable Drainage Systems (SuDS) − called Low Impact Development (LID) in the USA – has emerged (Armitage *et al*., 2013). As one of the source controls in SuDS and LID technologies, permeable pavement systems (PPS) offer a solution to the problem of increased surface runoff and decreased stream water quality by promoting infiltration of stormwater runoff through the wearing course and filtering it through the aggregate layers (Brunetti *et al*., 2016). PPS can also make an effective stormwater harvesting and storage mechanism for fit-for-purpose re-use (Pratt *et al*., 1999; Myers *et al*., 2011).

1.2 Problem Statement

The most common type of PPS in South Africa is Permeable Interlocking Concrete Paving (PICP). The treatment performance of PICP systems appears to depend on various factors such as the layout of the pavers; the size and condition of the stone aggregates; the presence and location of any geotextiles; the type of outlet; and the period between rain events. While some research on the treatment of stormwater by PICP has been published, for example, Tota-maharaj & Scholz (2010) reported that TSS, ammonia-nitrogen and total phosphate removal efficiencies for a permeable pavement were 91%, 84.6%, and 77.5% respectively, and Brattebo & Booth (2003) found that the effluent discharge from PPS contained lower Zn and Cu concentrations than conventional asphalt run-off, not enough is known about the relative performance of different PICP designs. For example, the treatment performance of PICP can be adversely affected by the unwashed aggregates in the PICP structure (Biggs, 2016) and most stormwater practitioners in South Africa currently used unwashed aggregates during the PICP construction in spite of the accepted international recommendation to use washed aggregates. Also, there are different opinions regarding the use of geotextiles in the PPS structure. Studies by the American researchers suggest that the presence of geotextile has an adverse effect on the stormwater treatment due to clogging (Boving *et al*., 2004), while researchers from Coventry University (UK) recommend the use of geotextile for the purposes of water quality improvement in PPS and have not noticed this having any impact on clogging (Newman *et al*., 2002; Nandi *et al*., 2014). There have also been several studies such as Collins *et al*., (2010b) and Drake (2013a) that evaluated the impact of a submerged zone on N removal in permeable pavement systems but there does not appear to be universal agreement on its benefits.

1.3 Research Objectives

This research aimed to investigate the impact of: different types of pavers, the presence or absence of a geotextile, the use of washed and unwashed aggregates and the incorporation of a permanently wet zone in PICP on the treatment of various nutrients (nitrate-nitrogen, nitrite-nitrogen, ammonia-nitrogen, and the orthophosphate-phosphorus) commonly found in stormwater runoff. This was determined through the construction of ten different PICP designs in controlled laboratory-based experiments. Synthetic stormwater with pre-determined nutrient concentrations representative of natural stormwater were sprinkled on to each of the ten designs with a watering can in volumes typical of Cape Town rainfall. The outflow from each PICP was periodically tested for the presence of various pollutants. The results were then compared with studies done elsewhere. A field study in PICP systems was also carried out to address the limitation of results obtained from the controlled laboratory experiment. Ultimately, it is hoped that the new knowledge generated by this – and similar – studies can be incorporated into recommendations for the design of PICP in South Africa.

1.4 Scope and limitations

The scope and limitation of this research are as follows:

- Budgetary constraints limited the number and type of laboratory water quality tests that could be carried out
- The results were based on laboratory models which may not represent reality, however, a fieldwork was conducted to address this limitation.
- Rainfall intensities are not easily replicated in the laboratory environment
- Laboratory synthetic stormwater may not adequately represent stormwater

1.5 Layout of this report

The subsequent chapters of this dissertation include the following:

Chapter 2 provides an overview of the literature relating to the permeable pavement systems, reviewing the types, the hydrological performance, the pollutant removal mechanisms, quality performance, clogging and maintenance issues.

Chapter 3 presents the methodology employed to conduct the research in the laboratory and the fieldwork.

Chapter 4 presents the results and discussion from the laboratory and fieldwork findings including infiltration rate for each cell, base-line pollutant concentration and pollutant removal efficiency for each cell.

Chapter 5 provide a summary of the findings, conclusion and recommendation for future research.

Appendix A provides the sample calculation encountered in the research method. Appendix B provides the infiltration test results. Appendix C provides the data for the clean water test and synthetic stormwater test. Appendix D provides the assessment of ethics in research project form.

2. Literature Review

2.1 Introduction

This literature review provides an overview of urban stormwater runoff. Sustainable Drainage Systems (SuDS) are then discussed as the better and more sustainable way of draining stormwater/surface water compared with conventional methods. Thereafter, a wide range of literature on Permeable Pavement Systems (PPS) are reviewed with particular emphasis given to PICP including aspects such as: hydrological performance, water quality control, incorporation of geotextile, clogging and maintenance.

2.2 Urban stormwater runoff

According to Wong & Brown (2009): '*The commencement of the 21st century marks the period when the proportion of the world's population living in urban environments surpasses that living in the rural environment*'. Rapid urbanisation introduces developments such as roads, buildings, and industry which increase the percentage of impervious area in a region. Impervious surfaces alter the route of natural water flow usually resulting in a decrease of the volume of water that percolates into the ground and an increase in the volume of surface runoff (Center for Watershed Protection, 2003).

Walsh *et al.* (2005) states that the degradation of urban water quality is often associated with surface runoff and increasing impervious area. When rain is collected on roofs, roads, footpaths and other sealed surfaces, it becomes contaminated with metals, oils and other pollutants which with conventional pipe-based drainage systems then flow directly into the waterways. With increasing urbanisation, there is less infiltration and consequently increased volumes of surface runoff. This typically results in stream channel erosion, increased concentration of contaminants compared with the natural state, increased fine sediment in the stream bed and overall degradation of the aquatic habitat (Booth, 1991; Center for Watershed Protection, 2003). Therefore, it is essential to control urban runoff quantity and quality to maintain watercourses. Permeable Pavement Systems (PPS) are one option to increase the surface infiltration, reduce the surface runoff, and consequently decrease the discharge of pollutants in receiving water bodies (Meysam *et al.,* 2016).

Figure 2-1 presents an overview of pathways and sources of nutrients in a typical urban environment, where A shows the urban runoff generated over the impervious surfaces after the precipitation from rain/snowmelt events; B shows the runoff discharged into the streams, rivers and estuaries untreated from the storm drains; and C shows the excessive amount of nutrients in the receiving water bodies resulting in eutrophication and subsequent fish kills (Yang & Lusk, 2018). Numbers one to eight shows the potential nutrient sources in urban stormwater runoff which are: atmospheric deposition; pet waste; improperly functioning septic systems; landscape irrigation; use of chemical fertilizers on lawns; soil and decomposing plant materials; leaking sanitary sewers and microbial sources respectively (Yang & Lusk, 2018).

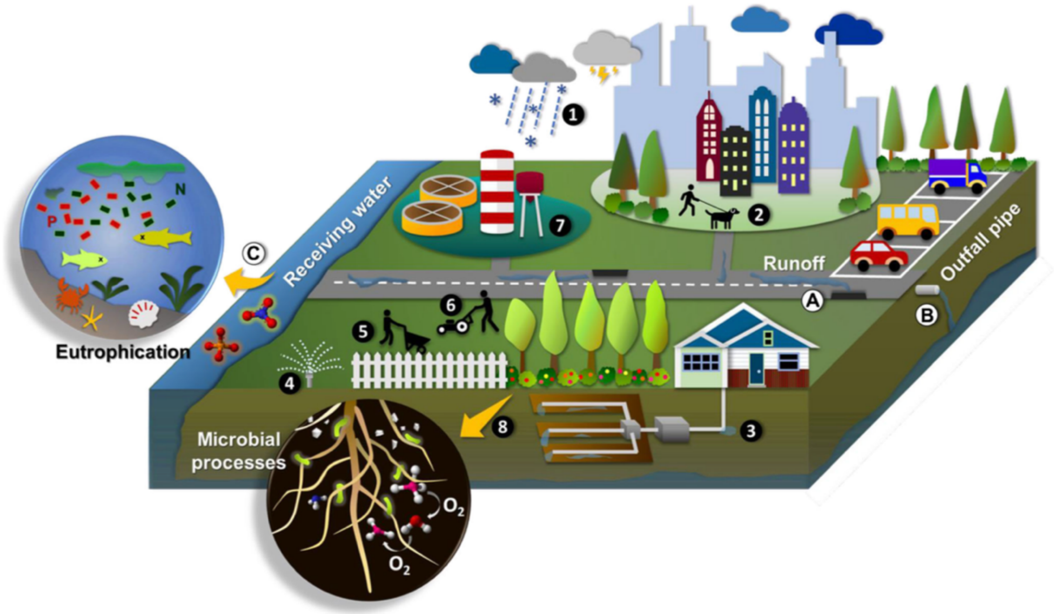


Figure 2-1: Overview of pathways and sources of nutrients in urban environment
(Yang & Lusk, 2018)

2.3 Sustainable Drainage Systems (SuDS)

As land is developed, the 'hardening' of the catchment i.e. covering it with impermeable surfaces such as roofs and roads, generally results in increased quantities of contaminants in the stormwater runoff. According to the *CSIR Guidelines for Human Settlement Planning and Design* (CSIR, 2000) '*Stormwater management is the science of limiting these negative impacts on the environment and enhancing the positive impacts, or catering for the hydraulic needs of development while minimizing the associated negative environmental impacts*'.

Conventional pipe-based stormwater management systems, which mainly focus on the rapid removal of all urban stormwater runoff with the help of channels and pipes, have been shown to have undesirable effects on the urban environments. They ignore the potential for stormwater harvesting as a water resource and the need to preserve or improve the water quality and the associated aspects of biodiversity and amenity (Armitage *et al.*, 2013). Indeed, the conventional approach lowers the water quality of receiving water bodies due to increased sediment yields and related contaminant fluxes, which is unsustainable (Charlesworth *et al.*, 2003).

Sustainable Drainage System (SuDS) technologies are an alternative way to drain stormwater/surface water in a manner that is more sustainable than conventional solutions. The stormwater runoff is treated by Stormwater Control Measures (SCMs) such as: wet ponds, bioretention areas, permeable pavements, rain gardens, and dry detention basins (Selvakumar *et* *al*., 2018). This approach is also known as Water Sensitive Urban Design (WSUD) in Australia and Low Impact Development (LID) or Green Stormwater Infrastructure (GSI) in the United States. It is an approach to urban planning and design that aims to minimize the hydrological impacts of urban development on the surrounding environment (Fletcher *et al.*, 2015). It embraces the concept of integrated land and water management and in particular integrated urban water management (Pezzaniti *et al*., 2009) to mitigate the adverse effects of urban stormwater runoff and finding solutions to integrated water cycle management through flood control, flow management, water quality improvements and opportunities to harvest stormwater to supplement water supply for non-potable uses (Armitage *et al.*, 2013).

SuDS attempt to mimic the natural hydrological cycle process by using the natural processes of infiltration, storage, detention, retention, evapotranspiration, conveyance and treatment of stormwater in the green infrastructure of the urban landscape (Poleto & Tassi, 2012). The key objectives of SuDS approach can be described in forms of hierarchy as shown in Figure 2-2, which starts from the stormwater runoff quantity, and quality and ends with the associated amenity and biodiversity, where each level shows an improved and more sustainable drainage system (Armitage *et al*., 2013).

SuDS allows the stormwater to be managed through a series of SCMs that are ideally arranged in a treatment train. Each options' advantages and limitations should be identified during the planning and design phases to ensure the best options for any particular site (Armitage *et al*., 2013). Four key intervention points in the treatment train may be identified, viz: 'Good housekeeping', 'Source', 'Local' and 'Regional' – each being associated with different SCMs (Table 2-1).

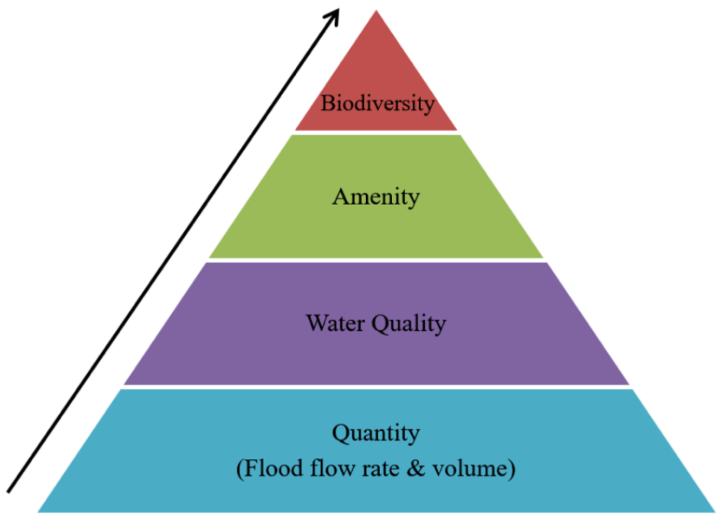


Figure 2-2: The stormwater design hierarchy
(Armitage *et al*., 2013)

Table 2-1: SuDS options for each intervention points (Armitage *et al*., 2013)

Intervention Points	Typical SuDS options
Good housekeeping	Minimize the release of pollutants (e.g. street sweeping, trash collection and leaf collection in autumn)
Source Controls	Permeable Pavement
	Green Roofs
	Rainwater Harvesting
	Soakaways
Local Controls	Swales
	Sand Filters
	Bio-retention areas
	Filter strips
Regional Control	Detention Ponds
	Constructed Wetlands
	Retention ponds

2.4 Permeable Pavement Systems (PPS)

Permeable Pavement Systems (PPS) are one of the source controls in the SuDS suite. They can collect the water run-off, control the rate of discharge to drainage systems, improve groundwater recharge and ultimately reduce pollution. Pavements account for approximately a quarter of impervious area within the urban environments and typically two-thirds of all the rain captured by the impervious surfaces in urban catchments end up on them (Ferguson, 2005; Shackel, 2010). In conventional pavement design, rainwater tends to run across the surface and is then directed into pipes to be removed as quickly as possible. This results in highly polluted water being rapidly conveyed to overloaded drains, streams, and rivers, which are additionally overloaded compared with pre-development state. Furthermore, impervious surfaces prevent infiltration and thus groundwater recharge that can, in extreme situations, cause local groundwater shortages. In contrast, PPS can collect, treat, and infiltrate surface runoff to support groundwater recharge. PPS thus address both flooding and pollution issues whilst additionally supporting traffic loads.

Conventional pavements typically consist of a sub-grade, one or more overlying base courses of compacted pavement material, and an impervious surface seal (Mullaney & Lucke, 2014). PPS are designed to promote the infiltration of stormwater through the paving and structure by filtering the runoff through the paving surface and various different layers of open-graded stones of different sizes (Eisenberg *et al*., 2015). Although PPS can provide a surface suitable for light vehicles or pedestrians, they are not generally suitable for high traffic volumes, heavy loads, or traffic laden with sediments. The main difference between the conventional pavements and PPS is that conventional pavements are constructed to ensure maximum load-carrying capacity while PPS are designed for both hydrological capacity as well as structural capacity and thus can be used as a Low Impact Development (LID) or Sustainable Drainage Systems (SuDS) design for stormwater management (ASCE, 2018). A comparison between the conventional pavement system and the PPS is presented in Table 2-2.

Table 2-2: Comparison between Conventional pavement systems and Permeable Pavement Systems (PPS) (Adpated from Eisenberg *et al*., 2015)

Criteria	Conventional Pavement Systems	Permeable Pavement Systems
Water collection	✗	✓
Potential water treatment	✗	✓
Potential water recycling	✗	✓
Water retention	✗	✓
Surface runoff reduction	✗	✓
Recharge of groundwater	✗	✓
Storm attenuation	✗	✓
Pollutant control	✗	✓
Heavy traffic	✓	✗

2.4.1 Types of PPS

Virginia Department of Conservation and Recreation, (2011) *Stormwater Design Specification No.7 for Permeable Pavements* indicates that there are a variety of available PPS surfaces, including: pervious concrete (PC), porous asphalt (PA), plastic grid pavement systems (PGP), concrete grid pavement systems (CGP) and permeable interlocking concrete pavers (PICP). Although the specific design for different types of permeable pavement vary, all PPS have a similar structure consisting of a surface pavement layer (asphalt, concrete or interlocking pavers) on top of open-graded bedding course. The open-graded bedding course consists of small, open-graded crushed stones which aim to provide a level bed for the concrete pavers, then a 'choker layer' is laid below the bedding course with crushed stone for vehicular traffic with an open-graded subbase reservoir at the bottom for water storage and traffic loads (Weiss *et al*., 2019; ASCE, 2018). A non-woven geotextile fabric is sometimes used in between the reservoir bed and subgrade soil or between the bedding course and subbase layers; however, there are conflicting views regarding the inclusion of a geofabric layer within the permeable pavement systems due to its clogging potential. The use of geotextile in permeable pavement systems will be discussed in detail in Section 2.4.5.

Permeable pavement systems can be designed for full-infiltration, partial infiltration and no infiltration depending on (Eisenberg *et al*., 2015):

- The permeability of the existing subgrade soils;
- The presence of contaminated soils as a result of land use or where there is a potential for an accidental spill of hazardous materials that would prohibit infiltration;
- Proximity to subsurface features such as septic systems and wells;
- Proximity to the exposed slope where lateral breakout of the stormwater on the slope may occur due to the soil conditions; and
- The distance between the permeable pavement and wells for drinking water.

Perforated underdrains are installed in pavement systems designed for partial or no infiltration, and are placed at the bottom of the pavement base/subbase in the reservoir course. No underdrain design is needed for full infiltration permeable pavement systems when the in-situ subgrade has high permeability. A raised or 'upturn elbow' underdrain is sometimes used to increase the water detention capability as well as potentially promote greater infiltration of the systems (Eisenberg *et al.*, 2015). An impermeable liner may be placed at the bottom and sides of the PPS structure to prevent the interchange of water with adjacent and underlying soils (Eisenberg *et al.*, 2015). The use of an underdrain also helps provide a delay in the runoff flow from the road as well as providing some water quality treatment. A typical permeable pavement systems cross-section is shown in Figure 2-3.

The main types of PPS are as follows:

a) Porous asphalt (PA)

Porous asphalt pavements typically consist of a conventional warm mix asphalt (WMA) or hot mix asphalt (HMA) with significantly reduced fines; the reduced fines creating an open-graded mixture that allows water to infiltrate through the interconnected void space which typically ranges from 18% to 25% (Eisenberg *et al.*, 2015). This permeable asphalt surface is underlain by an open-graded aggregate choker course and a reservoir bed. It is important that the aggregate bases are comprised of clean angular stones that are carefully compacted. The compaction of the aggregate subbase of porous asphalt needs to be carefully done in order to provide structural support while still maintaining sufficient infiltration capacity (Eisenberg *et al.*, 2015). In addition, it is important to make sure the mix production temperature, the use of additives, and the selection of the asphalt binder grade are correct otherwise the asphalt binder tends to drain down slowly with sediments and dust from pavement wear to form a clogging layer in the pavement during hot periods (Eisenberg *et al.*, 2015).

b) Pervious Concrete (PC)

Pervious concrete is a mixture of cement, water and open-graded coarse aggregate with little to no sand to produce a very porous medium with 15% to 25% interconnected void space that promotes infiltration while producing a rigid and durable wearing pavement surface. Chemical additives may be combined with the mixture to improve binding and increase strength. It is also important to note that de-icing chemicals or sand should not be used on pervious concrete as they can damage the binding of the concrete and result in disintegration or spalling of the surface, a substantial disincentive to their use in cold climates (Eisenberg *et al.*, 2015).

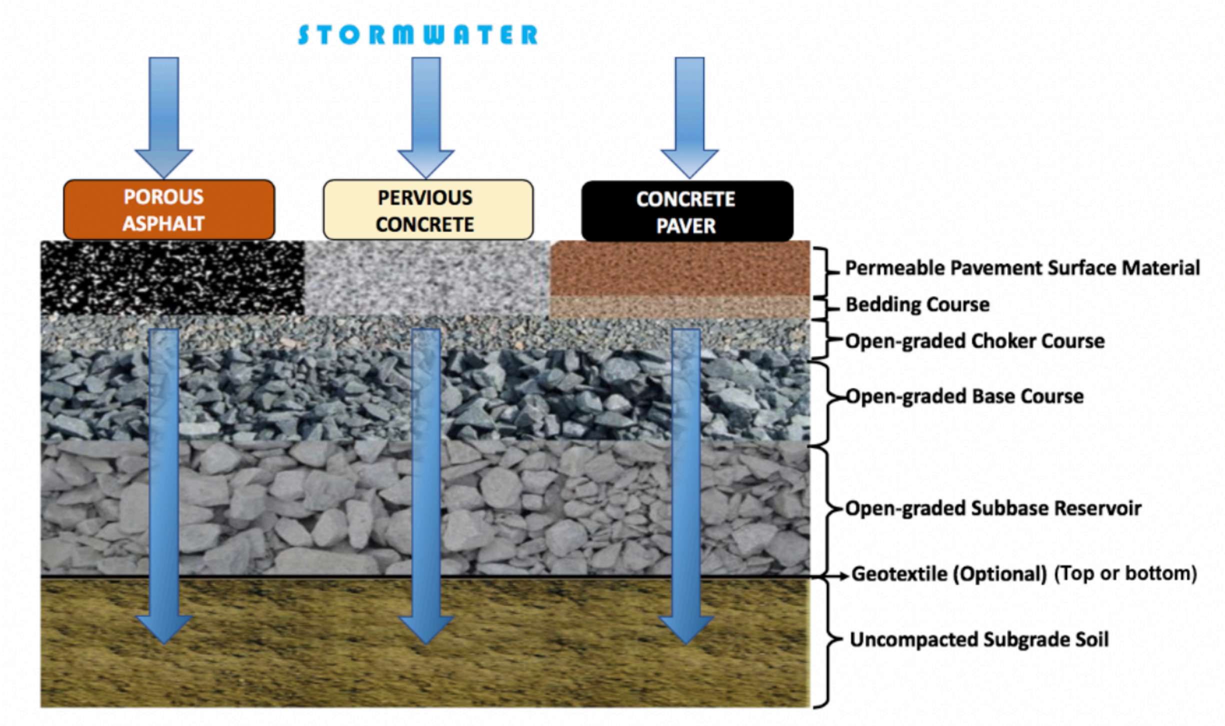


Figure 2-3: Generic permeable pavement cross-section
(Adpated from Eisenberg *et al.*, 2015)

c) Grid Pavement systems

Grid pavement systems normally consist of plastic (PGP) or concrete (CGP) open-cell units with large openings filled with a joint material such as sand or topsoil. This may be grassed. The concrete grid units are typically placed on top of a thin sand bedding layer and dense-graded aggregate layer with open surface area of 20% to 70%. Plastic grid units are typically placed directly upon an open-graded aggregate base and a dense-graded aggregate layer. It is important to note that the grid pavement systems are not intended for areas that receive high daily use; they are mostly designed for light vehicular traffic (Eisenberg *et al.*, 2015).

d) Permeable interlocking concrete pavers (PICP)

Permeable Interlocking Concrete Pavers (PICP) are the most widely used permeable pavement system internationally (Lucke & Beecham, 2011). They are impervious paving blocks with small permeable joints in between accounting for 5% to 15% of the paver surface area and filled with a suitable pea-sized (2-5mm) aggregate (typically ASTM No. 8, 89 or 9). These joints allow surface water to infiltrate into the pavement structure (Mullaney & Lucke, 2014; Eisenberg *et al*., 2015). Below the paving surface is an open-graded bedding layer of a small sized aggregate (2-5 mm in diameter, typically ASTM Nos. 8, 89 or 9) which may be laid on a geofabric (although this is controversial). The geotextile is used to prevent the entrance to fine sediments into the PPS structure and/or provide an environment for bacteria to remove pollutants (Pratt *et al*., 1995; Pratt *et al*., 1999; Rowe *et al*., 2010). Below the bedding layer and geofabric (if present) is a sub-base consisting of open-graded larger aggregate sizes (20-63mm diameter). Apart from its usual role in supporting and distributing vehicle loads, this open-graded subbase acts as a reservoir temporarily detaining runoff before slow release through an underdrain or into permeable underlying soils. It also acts as a pollutant trap. The relatively rapid rate of draining usually keeps the sub-base in an aerobic state suitable for nitrification which is not always desirable as nitrate is difficult to control (Brown & Borst, 2015)

Since PICPs rely on their geometry to provide interlocking and structural strength, they are generally laid in patterns such as herringbone to provide the structural integrity to the pavement surface (Mullaney & Lucke, 2014). Eisenberg *et al*., (2015) found that PICPs do not heave when frozen through many years of experience and monitoring of many PICP projects in Chicago, Minneapolis, and Toronto.

2.4.2 Hydrological performance of PPS

Hunt & Collins (2007) state that there is no significant difference between different PPS designs when it comes to reducing surface runoff except for grid paving systems which has slightly higher surface runoff when the CGP was filled with sand. PPS provide peak flow reductions up to 100% and longer discharging times by enabling rainwater to infiltrate through the surface (Fassman & Blackbourn, 2010; Alsubih *et al.*, 2017). Once in the subgrade, the water is temporarily stored before it is either collected and discharged into a formal stormwater drainage system or simply left to infiltrate through the soil beneath the road structure (Ball & Rankin, 2010). Key elements of the water balance for PPS are presented in Figure 2-4.

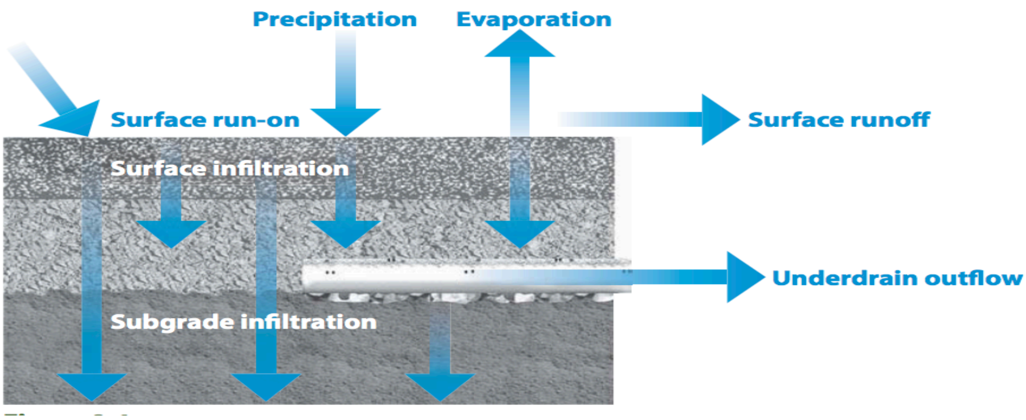


Figure 2-4: Water balance variables for permeable pavement
(©VHB, n.d.)

The Natural Resources Conservation Service curve number (NRCS-CN) (a measure of direct runoff from storm rainfall) (USDA, NRCS, 1986) or runoff coefficient (a ratio of rainfall to runoff) can be used to indicate the functionality of a pervious pavement (Hunt & Collins, 2007; Alsubih, 2016). An impervious surface has a curve number of around 98, but a pervious surface has curve number ranges between 37 to 89 with the curve numbers for PICP ranging between 37 and 45; for CGP ranging between 70 and 89; and for PC ranging between 77 and 89 (under conditions where the surface is free of fine sediments; there is a large storage base and a very permeable in-situ soil) (Ponce & Hawkins, 1996; Bean *et al*., 2007).

Most studies evaluating the potential hydrological benefits of PPS focus on the water balance and the timing and rate of flows (Drake *et al*., 2013a). The hydrologic performance of PPS depends on the condition and age of the pavement, the under-drainage and system design–such as the types of pavers, presence of geotextile, size of basecourses etc. Key inputs include the intensity, duration, magnitude of the storms and the time between storms (Drake *et al*., 2013a). Drake *et al*. (2012a) and Pratt *et al*. (1989) found that PPS generally does not produce any discharge for small rainfall events of less than 5 mm when preceded by dry antecedent conditions. Various studies have evaluated hydrological performance for a range of PPS, and most found ≥70% peak flow reduction relative to an impermeable control (Collins *et al*., 2010; Drake & Bradford, 2012; Roseen *et al.*, 2012). Most of these studies found the volume (runoff) reduction is at least 30% relative to the runoff from impermeable pavements (Pratt *et al*., 1995; Collins *et al.,* 2008; Fassman & Blackbourn, 2007).

Palla *et al.* (2015) studied the hydrological response of PPS when subjected to different rainfall intensities. The discharge coefficient and a time index were used to analyze the hydrological response of four PPS combining two paving types (concrete cell and pervious brick) with two filter layers (recycled glass aggregate and a mix of gravel and coarse sand). The results show that no surface runoff occurred during the tests even at 98 mm/h rainfall intensity. Collins *et al*. (2008) also carried out a comparative study to examine the performance of four types of PPS relative to standard asphalt pavement. The results of this study showed an average runoff volume reduction of 36-67%, and average peak flow reductions of 60-77% which confirm the run-off reduction ability of the PPS. Alsubih et al. (2017) also tested the rainfall / runoff attenuation ability of PPS by using lab experiments to relate the hydrological performance of PPS to rainfall characteristics and soil moisture contents; they found a relationship between the pavement structure's outflow and both rainfall duration and pavement condition. Increased initial pavement wetness and rainfall duration result in a higher outflow. Gilbert & Clausen (2006) compared the stormwater runoff reduction from asphalt, permeable pavers and crushed-stone driveways. They found the reduction of runoff from asphalt to PICP was 72% and to crushed stone was 98%, whilst LeFevre *et al.* (2010) found PICPs can effectively mitigate peak flow by 56% on average. Collins *et al*. (2008) also found both PC and PICP are effective in mitigating storm runoff, and they found peak flow reduction ranging from 60% to 75% in coastal North Carolina. Many studies did not observe surface runoff from PICP surfaces as a consequence of natural storm events (Booth & Leavitt, 1999; Brattebo & Booth, 2003; Pezzaniti *et al*., 2009). Table 2-3 summarises typical research findings on the infiltration rate and surface runoff reduction for different types of PPS with a significant limitation that the duration of all the experiments are less than 2.5 years which is only a fraction of a PPS effective life. There is a need for studies on the long-term hydrological performance of PPS.

2.4.3 PPS water quality improvement

Myers *et al*. (2011) state that the water quality of stormwater harvested and stored using PPS is an important consideration, particularly for fit-for-purpose reuse. Bean *et al*. (2007) and Brattebo & Booth (2003) found that PPS are effective in improving stormwater quality. Removing pollutants from the stormwater reduces the total pollutant mass in the receiving systems (Bean *et al*., 2007).

The performance of PPS in water quality improvement is influenced by many factors which include: the influent pollutant concentration, the materials used in permeable pavement, the presence of geotextiles, the aggregate size, the layer thickness, the surface type, the temperature, the slope of the pavement, the size of the catchment draining to the PPS, the pavement age, and the magnitude of storm (Liu *et al.*, 2019). This section will detail the previous research on PPS's potential for water quality improvement.

2.4.3.1 Typical pollutants in urban stormwater runoff

The typical pollutants in stormwater runoff include nutrients such as phosphates and nitrates, hydrocarbons, Total Suspended Solids (TSS) and heavy metals (Finkenbine *et al.*, 2000; Kayhanian *et al.*, 2019).

Pollutants are introduced into urban stormwater runoff through a range of anthropogenic activities and environmental processes (Drake *et al*., 2013b). Most originate from non-point or diffuse sources such as from road surfaces, industrial sites, housing estates or farmland. The type of pollutants and their concentrations are dependent on land uses, geology, population density, topography and stormwater duration and intensity within the catchment (Mullaney & Lucke, 2014).

Tota-maharaj & Scholz (2010) have summarized the urban runoff pollutants (Table 2-4) indicating typical concentration ranges associated with each pollutant, potential sources, and possible effects (Dierkes *et al*., 1999).

2.4.3.2 PPS's water quality improvement

Many studies have quantitatively assessed the pollutant removal performance of PPS. Li *et al.*, (2017) investigated the effect of six different PPS surface materials on the removal of pollutants from urban runoff and found that the surface material greatly influences the removal efficiency of the pollutants.

Bean *et al*. (2007) investigated the water quality impacts on two PICP sites in eastern North Carolina and found TKN, ammonia, TP, and Zn are significantly (significant difference $p \leq 0.05$ between exfiltrate and runoff concentration) (SAS, 2003) lower in permeable pavement exfiltrate than asphalt runoff. Phosphate, TN, Cu and TSS were not significantly different between asphalt runoff (surface runoff as control) and PICP exfiltrate. However, the nitrate and nitrite concentrations were higher in the PICP exfiltrate than asphalt runoff. They reasoned that this is because the pavement system was designed to be aerobic, and this aerobic condition facilitates the nitrification of ammonia to nitrite and nitrate. Brattebo & Booth (2003) found the effluent discharged from PPS contained lower Zn and Cu concentrations than conventional asphalt run-off. Tota-maharaj & Scholz (2010) reported that TSS, ammonia-nitrogen and total phosphate removal efficiencies for PPS were 91%, 84.6%, and 77.5% respectively. Pratt *et al*., (1995) found that the water quality at the outlet depended on the base course aggregate material used; the concentration of total suspended solids (TSS) was actually higher than that found in surface runoff for all PPS reservoirs (PICP with different sub-base stone type) for several months. This was likely due to the flushing of the base course aggregate materials. Biggs (2016) showed that the use of unwashed aggregates has an adverse impact on the treatment performance of PPS.

The treatment performance of PPS on water quality is also affected by the gravel sizes and the thickness of the aggregate layers. Hatt *et al*., (2007) found a relationship between the pollutant removal and thickness of the gravel layer, whilst Brown *et al.*, (2009) found that gravel layers in PPS could effectively remove sediments with particle sizes greater than 50μm. Fach and Geiger (2005) used different sizes of gravel (5 mm and 45 mm) to determine their performance in pollutant removal, and they found smaller gravel is more effective in removing heavy metals (copper, zinc, and lead).

Table 2-3: Field testing on hydrological performance of different types of PPS

Author	Location	Pavement age	Types of permeable pavement	Findings
Pratt *et al.*, 1995	UK	9 years	PICP	**Infiltration rate**: >1000 mm/h **Runoff reduction**: up to 60%
Brattebo & Booth, 2003	USA	6 years	PGP with sand PGP with gravel PICP CGP with gravel	• All four types of pavements had positive hydrological performance compare to conventional pavement • No runoff from PICP and CGP • PGP produced runoff
Collins *et al.*, 2008	USA	NA	CGP PICP PC Asphalt	**Infiltration rate:** • CGP: 1010 mm/h • PICP: 15,360 mm/h and 2610 mm/h • PC: 49,410 mm/h **Runoff reduction:** • CGP: 77.1% • PICP: 73.5% and 77.1% • PC: 67.1%
Lucke & Beecham, 2011	AUS	8 years	PICP	**Infiltration rate:** • Fully blocked site: 10mm/h • Medium blocked site: 293 mm/h • Unblocked site: 972 mm/h
Fassman & Blackbourn, 2007	NZ	1 year	PICP	**Infiltration rate**: > 1200 mm/h **Runoff reduction**: up to 89% **Lag time**: 3.2 h
Bean *et al.*, 2007	USA	More than 2 years	PICP CGP PC	**Infiltration rate:** • CGP: initially 48 mm/h, then 86 mm/h after maintenance • PICP: 20000 mm/h without fines and 800 mm/h with fines • PC: 40000 mm/h without fines and 130 mm/h with fines
Abbott & Comino-Mateos, 2003	UK	1 years	PICP	**Infiltration rate:** • Ranged between 1100 mm/h and 22900 mm/h with average of 5100 mm/h in 1999 • Ranged between 1030 mm/h and 3880 mm/h with average of 1300 mm/h in 2000
Gilbert & Clausen, 2006	USA	NA	PICP	**Infiltration rate**: 200 mm/h **Runoff reduction**: up to 72%

Table 2-4: Summary of urban runoff pollutants relevant for this study
(Tota-maharaj & Scholz, 2010; Dierkes *et al*., 1999)

Category	**Parameters**	**Typical concentration ranges**	**Possible sources**	**Possible effects**
Sediments	Organic and inorganic suspended solids (SS); turbidity; dissolved solids	SS (100-300 mg/L); total solids (100-3000 mg/L)	Construction sites; urban runoff; agricultural runoff; sewer pipelines; landfills; septic tanks	Turbidity, habitat alternation, recreational and aesthetic loss, contaminant transportation, hydrology, and bank erosion
Nutrients	Nitrates; nitrites; ammonia; organic nitrogen; phosphates; total phosphorus; sulphate;	Ammonia-nitrogen (0.1-10mg/L); nitrate-nitrogen (0.01-10 mg/L); total nitrogen (0.1-50 mg/L); total phosphorus (0,01-5 mg/L); sulphate (0.56-14.4 mg/L)	Urban runoff; agricultural runoff; fertilizers; landfills; septic tanks; atmospheric deposition; soil erosion	Surface waters; algal overgrowth and blooms; ammonia toxicity. Ground water; nitrate toxicity
Heavy metals	Zinc; copper; lead; cadmium	Zinc (5-235 μg/L); copper (1-355 μg/L); lead (5-200 μg/L); cadmium (0-12 μg/L)	Urban runoff; industries; roofs with metal elements; vehicle parts and components; fuel and oils	Toxic effect on receiving water bodies and human health
Pathogens	Total coliforms; fecal coliforms; fecal streptococci; *Escherichia coli*; Enterococcus; viruses	*E. coli* (10^2-10^7 CFU/100 mL); fecal Streptococci (10^2-10^6 CFU/100 mL), fecal coliforms (10^3-10^7 CFU/100 mL)	Urban runoff; agricultural runoff; septic systems; poor sanitary connections; combined sewer overflows;	Intestinal and gastrointestinal infections, ear infections, dysentery, typhoid fever, viral and hepatitis
Organic enrichment	Biochemical oxygen demand (BOD); chemical oxygen demand (COD); total organic carbon; dissolved oxygen	BOD (10-13 mg/L); COD (73-92 mg/L)	Urban runoff; agricultural runoff; landfills; septic tanks; atmospheric deposition; soil erosion	Dissolved oxygen depletion; odours; toxicity levels for fish, and other aquatic life

Kazemi and Hill (2015) investigated the stormwater quality improvements of PPS basecourse aggregates compared with control environments and different water storage residence times. They found pH showed the highest levels after two weeks and EC changes were functions of interactions between aggregate types and residence times. Drake *et al*., (2013b) considered that further research needs to be conducted on evaluating the source, fate, and transport of nutrients in permeable pavement systems.

2.4.4 PPS pollutant removal mechanisms

TSS, phosphate, ammonia, and nitrate are the most common pollutants existing in urban stormwater, if not removed they reduce the quality of downstream water bodies through eutrophication. Tota-Maharaj & Scholz (2010) state that PPS can improve water quality through filtration, interception, interception, nutrient transformation, and microbial removal. According to Li *et al.* (2017), the main mechanism for the removal of these pollutants from runoff in PPS is physical interception and adsorption. This section details the PPS removal mechanisms of TSS, phosphate, ammonia, and nitrate.

2.4.4.1 Total suspended solids (TSS)

TSS is an important pollutant to be removed from stormwater runoff because it contains attached heavy metals which can considerably inhibit plant growth and diversity. TSS can also increase turbidity, affect river biota and reduce the number of aquatic species (Brown *et al.*, 2009). Other pollutants, such as phosphorous and hydrocarbons are also associated with TSS, especially finer particles (Legret & Colandini, 1999; Brown *et al.*, 2009)

TSS removal's primary mechanisms are mechanical filtration through the surface and base layers of the PPS and sedimentation (Drake *et al*., 2013b). Pratt *et al*. (1995) found that most solids accumulate in the top 25 mm of the PPS, whilst the presence of an upper geotextile layer (between the bedding layer and base) can limit the amount of particulate-bound pollutants entering the PP structure by retaining the TSS. Brown *et al.* (2009) found that the TSS removal efficiency for PPS is highly dependent on the size of particles trapped within the pavement surface with TSS removal efficiencies of more than 99% for particles over 75 µm. The TSS removal efficiency decreases markedly with particles finer than 75 µm. In general, excellent TSS removal efficiencies were measured in both the field and the laboratory with removal efficiencies ranges from 90% to 96%. The filtration primarily took place at the geotextile layer.

Many studies have found TSS can be removed at a high level (>80%) by various PPS (Legret & Colandini, 1999; Pagotto *et al*., 2000; Bean *et al*., 2007; Brown *et al*., 2009). Morquecho *et al*. (2005) also found that PPS can reduce TSS and turbidity more than 50%, and Tota-Maharaj and Scholz (2010) reported that TSS removal efficiencies for a PPS of 91%. Huang *et al.* (2016c) found that the use of smaller gravel within the PPS structure provides the additional benefit of removing pollutants through TSS removal, but they tend to clog more easily than with larger diameter gravel. They also found that increasing the thickness of the gravel layer enhances pollutant removal by physical processes (i.e. TSS removal), but it does not benefit pollutant removal by biological processes (e.g. for TN & TP). Tota-Maharaj and Scholz, (2010); Huang *et al.* (2016a) and Huang *et al.* (2012) found TSS removal tends to be independent of climatic condition, and the temperature does not largely influence the process of PPS (PICP) in removing TSS from the storm runoff.

2.4.4.2 Total Phosphorus

Phosphorus exists in water in several forms: organic phosphate (from plant and animal waste), orthophosphate (generally inorganic and dissolved, coming from fertilizers; this is the form commonly measured), total phosphorus (dissolved and particulate) and polyphosphate (from detergents) (EPA, 2006). Orthophosphates are the form that is most immediately biologically available and most of the soluble phosphorus in stormwater is in orthophosphate form (Minnesota Pollution Control Agency, 2018). High phosphorous loads are often delivered during periods of high runoff from storms or irrigation activities. Under oxygenated conditions, phosphate will form chemical complexes with minerals such as iron, manganese and aluminium and deposit on the bottom sediments. If the bottom water in an estuary or pond has no oxygen, the phosphates bound to the sediments will release back into the water. This release can result in the phytoplankton/algae blooms associated with eutrophication.

The Total Phosphorous (TP) removal mechanism in permeable pavement systems is primarily through chemical sorption, filtration, and biological activities. Huang *et al.* (2016a) states that phosphate is likely to be bound to particles less than 250 μm in diameter, and TP is likely to be removed with TSS by sedimentation and filtration, whilst Huang *et al.* (2016c) found strong positive correlations between TP removal and TSS removal in their laboratory study with removal rates increasing with the increase of the layer thickeness. According to Huang *et al.* (2012), when the phosphates come into contact with the aggregates in the pavement structure in the process of infiltration, precipitates of calcium phosphate may be formed and this is the way the phosphate portion of the total phosphorus is reduced.

Many studies have found PICPs are effective in removing TP (Bean *et al*., 2007; Tota-maharaj & Scholz, 2010). Ball & Rankin (2010) found TP removal of more than 70%. Morquecho *et al*. (2005) also found that a PP can reduce TP by more than 50%. Collins *et al*. (2006) found that as the travel time for the pollutants inside the PPS lengthens, PO_4^{3-} removal increases which also implies the time dependency of PO_4^{3-} removal within the PPS. The removal efficiency of phosphate depends on its adsorption capacity by granular material and the amount of time for biogeochemical processes to happen. According to Tota-Maharaj & Scholz (2010), organic phosphorous is likely transformed into inorganic forms by living organisms, and then adsorbed on fine particles or that can be retained by any geotextile within the PPS. Drake *et al*., (2012b) found the effluent phosphate concentration from two PICP sites were significantly lower than the concentration in the runoff, however, she observed the phosphate leaching from the PC which resulted in median phosphate concentrations in PC effluent over four times greater than that in PICP effluents. Li *et al*. (2017) found PPS have little effect on the removal of TP from runoff which may be due to the lack of useful adsorption sites. They also found that the removal efficiency of materials could be increased by creating a higher adsorption capacity, such as adding appropriate iron oxide into the surface of the inside of the materials. Brown & Borst (2015) found PA had a significant phosphate concentration reduction in the effluent compared with the influent sources which could be attributed to possible precipitation with metal cations caused by the high pH, however, they also found phosphate concentration in PICP and PC effluent was significantly larger than that in the influent which indicates phosphate was leaching from these two sites. They indicated that further studies are needed to determine what is the cause of phosphate leaching from the PPS.

2.4.4.3 Total Nitrogen

Nitrogen-containing compounds (nitrite, nitrate, ammonia) are important water pollutants to consider as they can cause eutrophication which impact fisheries and drinking water quality. The inorganic nitrogen includes ammonia, ammonium, nitrite, and nitrate. Ammonia and ammonium are the reduced forms of inorganic nitrogen and their relative proportions are controlled by temperature and pH (DWA, 1996). Nitrogen can be converted into different nitrogen species and gain energy from the process by bacteria. The quantity and form of nitrogen in the water closely relates to the dissolved oxygen levels (EPA, 2006). In aerobic conditions, ammonia is transformed first to nitrite and then to nitrate through oxidation processes – nitrite being a generally short-lived nitrogen species that is found in low oxygen environments. In anoxic conditions, denitrification occurs where bacteria convert nitrate to nitrite and then to nitrogen gas (EPA, 2006). High concentrations of nitrate and ammonia have an adverse impact on the ecosystem as they promote eutrophication (nutrient enrichment) that can, inter alia, simulate toxic *Pfiesteria* strains (Glasgow *et al*., 2001).

Huang *et al.* (2016b) note that TN is removed primarily by biological processes in PPS. Ammonium-nitrogen can be adsorbed to negatively charged sites on the filter material and then be removed with the sediments. Collins *et al.* (2010a) describes the primary nitrogen transformation process in PPS as nitrification and filtration of particulate-bound nitrogen as well as denitrification through an internal anaerobic zone. Tota-Maharaj & Scholz (2010) consider that the nutrient removal process in PPS is mainly due to processes such as nitrification and denitrification as well as biogeochemical degradation, and these processes will occur predominantly in the wet lower sub-base of the PPS. TN is thought to be removed by biological processes that take place in the void space of pavement structures that is largely associated with the growth of biofilm which in turn is highly dependent on temperature (Newman *et al.*, 2002; Tota-maharaj & Scholz, 2010). Huang *et al.* (2012), however, considered that the environment of the pavement structure may not be suitable for bio-film growth and thus PPS may not be very effective in removing TN (Wiesman, 1994). Collins *et al.* (2010a) showed that the anoxic conditions for denitrification and subsequent N removal may not develop in many fast-draining, infiltration-oriented SCMs (such as permeable pavement).

Bean *et al*. (2007) found PICP can remove TN at a moderate level. However, Collins *et al*. (2008) found TN is hardly removed by either PA or PICP. A negative nitrate removal efficiency i.e. increase in nitrates was found by Tota-Maharaj & Scholz (2010) which was explained as the relatively low rate of denitrification and relatively high rate of transformation from ammonia to nitrate.

Collins *et al.* (2010b) and Drake *et al*. (2014) both found the ammonia and TKN effluent concentrations from PICP were significantly lower than the impervious asphalt runoff concentrations, furthermore, they both found that the combined nitrite and nitrate concentration was significantly higher than that in impervious asphalt runoff which might be due to nitrification in PICP. Bean *et al.* (2007) further found that nitrate and nitrite concentration is higher in the PICP exfiltrate than asphalt runoff. They thought that this was because the pavement system was designed to be aerobic, and this aerobic condition facilitates the nitrification of ammonia to nitrite and nitrate. They suggested a secondary stormwater treatment device that performs denitrification should be used in conjunction with the PICP such as riparian buffers (e.g. a vegetated area near stream that can take up the nitrates by plant and then transform the nitrate into nitrogen gas), to help reduce nutrient loadings. Drake (2013a) evaluated the water quality from a partial-infiltration permeable pavement aiming to create an anoxic zone favorable for denitrification, however, the nitrate concentration in the effluent was still larger than in the impervious asphalt runoff. Collins *et al.* (2010b) further found that one PICP section with an inadvertent sump (an underdrain was installed at a higher elevation than designed) discharged significantly larger nitrate and nitrite concentrations than all other PPS tested and was the only PPS with a larger TN concentration than impervious asphalt runoff. Roseen *et al.* (2009) found the average dissolved inorganic nitrogen concentrations (ammonia, nitrate and nitrate) in the effluent from a PA site in New Hampshire were 35% larger than the concentration in impervious asphalt runoff.

Collins *et al.* (2010a) states that the microbial denitrification process is favoured under anoxic conditions and is driven by electron donors such as carbon, iron or sulphur. Kim *et al.* (2003) incorporated a continuously submerged anoxic zone with an over-drain which aimed to promote biological denitrification to remove nitrate-nitrogen (Figure 2-5). They studied different solid-phase electron-donor substrates for denitrification such as newspaper, sawdust, wheat straw, and wood chips, and their results indicated newspaper as the best electron donor and proposed a re-engineered concept of bioretention for nitrate removal.

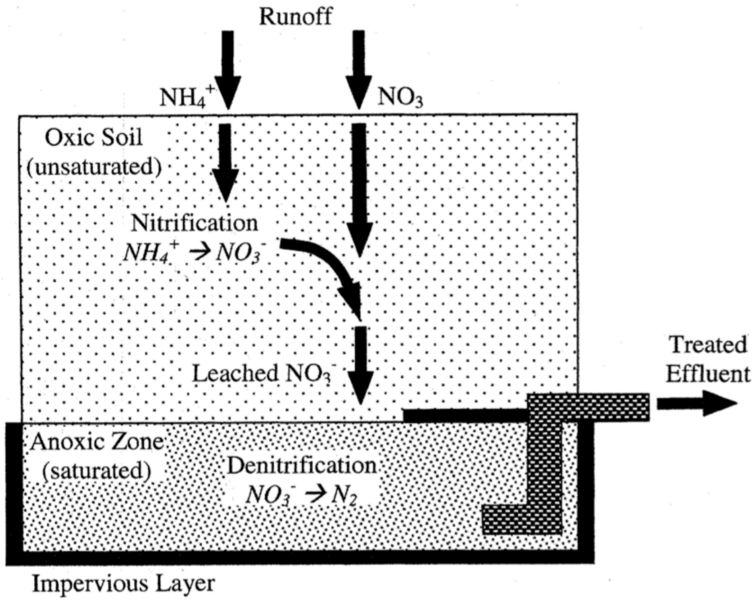


Figure 2-5: Diagram of modified bioretention cell with anoxic zone for denitrification
(Kim *et al*., 2003)

Davis *et al*. (2010) state that the drying and wetting phase has an impact on nitrogen removal. They found that ammonium-nitrogen and nitrate-nitrogen removal did not seem to occur during the wetting phase finding a higher concentration of nitrate in the outflow in the rainfall event following a drying period. They explained this as due to ammonia-nitrogen being adsorbed by soil colloids or soil particles in the filter layer. It is then oxidized to nitrate-nitrogen by the nitrification process during the drying period where it remains in the system until it is flushed out in the next rainfall event. Subramaniam *et al*. (2014) also showed that intermittent wetting and drying plays a significant role in the removal of nitrate-nitrogen from stormwater, and concluded that the removal of nitrate-nitrogen is more active during the drying phase and relatively inactive during the wetting phase of the event. They explained this as due to the complex structured organic material (e.g. soil organic material) being degraded into labile organic carbon during the drying phase of an event cycle; this labile organic carbon is readily consumed by microorganisms which facilitate microbial growth in the system that deplete the dissolved oxygen thereby promoting the growth of anoxic and anaerobic microorganisms which facilitate the nitrate-nitrogen removal process (Jarvis *et al*., 2007).

Collins *et al*., (2010b) and Drake *et al*., (2014) found that the pH in PICP effluent was within or near the optimal range pH between 7.6-8.8 for growth of *Nitrosomonas* and *Nitrobacter* which are the bacteria responsible for nitrifying ammonium to nitrite and then to nitrate (Coyne, 1999). Brown & Borst, (2015) further found that the variability in the nitrogen speciation results across the PA sections corresponded with the pH in the infiltrate and optimal pH range for nitrifying bacteria, with the section with the lowest pH having the highest nitrate concentration, whilst a high pH in PA effluent resulted in incomplete nitrification.

2.4.4.4 Heavy Metals

Dierkes *et al.* (1999) states that the removal rate of heavy metal depends on the state of the heavy metals in the stormwater. Heavy metals in the free element form are mainly trapped on the pavement surface but heavy metals in ionic form are generally trapped in the base course. They found that heavy metals tend to attach themselves to sediment particles between 0.1 and 0.3 μm.

Huang *et al.* (2016a) found heavy metal removal tends to be independent of climatic conditions. Myers *et al*. (2011) measured a reduction in Zn, Cu, and Pb by 94% to 99% in the stormwater runoff after 144 hours in storage in the reservoir from a PICP system with a permeable geotextile under the bedding aggregate. Welker *et al.* (2013) and Ball and Rankin (2010) found that both PA and PC could effectively remove Zn, Cu, and Pb by more than 70%. Booth & Leavitt (1999) found PICP could still effectively remove Cu and Zn after 6 years of service, whilst Gilbert & Clausen (2006) found Zn, Cu, Pb removal between 35 – 78% by PA. However, Bean *et al*. (2007) found PICPs are only effective in removing Zn but not Cu.

2.4.4.5 Microbial Activity

US EPA (2009) states that most of US waters are impaired by sediments, nutrients and various types of toxic chemical loading, and there are more rivers and streams impaired by pathogenic microorganisms than other pollutants. Faecal contamination from humans in urban runoff is a major contributor to the degradation of the urban aquatic systems (Pitt *et al*., 1995; Selvakumar *et al*., 2018). The concentrations of indicator microorganisms (faecal coliform, faecal streptococci, total coliform, enterococci, and *E. coli*) are used to determine the potential for faecal contamination in surface runoff by comparing them with the accepted public health thresholds.

Although many stormwater control measures such as rain gardens, wet ponds, and wetlands have been studied for the removal of microorganism, there have been relatively few studies on the removal ability of PPS for microorganisms. Tota-Maharaj and Scholz (2010) found nearly all microbial pollutants were removed or degraded within each of their PPS with a mean removal efficiency of 98.6% suggesting that PPS can help prevent effect of water-related diseases such as gastroenteritis and cholera. They also found that the temperature did not have a significant impact on biological growth. Selvakumar *et al*. (2018) researched the treatment performance of three different types of permeable pavement (PA, PC, PICP) on three indicator microorganisms (faecal coliform, enterococci, and *E. coli)*. Their results show all three types of pavement have positive removal efficiency on all three indicator organisms, with more than 90% concentration reduction for all three indicator organisms for PA; more than 90% concentration reduction for faecal coliforms and *E. coli* for PC, and about 39% concentration reduction for *E.coli* for PICP. They also found that the temperature and rainfall intensity did not have an observable impact on the concentration of organisms which correspond with the Tota-Maharaj & Scholz (2010) finding.

Table 2.5 summarises the research on the treatment performance on typical pollutants in stormwater for different types of permeable pavement systems.

2.4.5 Geotextiles in PPS design

PPS may include geosynthetic materials such as geotextiles, geomembranes, and geogrids (Eisenberg *et al.*, 2015). According to the NCDENR (2012), the use of geosynthetic materials in PPS should be considered together with the local site soil condition, pavement design and stormwater management. Geotextiles can help to prevent sand from migrating into the base of PPS while providing a good level of pavement structural serviceability (Scholz & Grabowiecki, 2007). However, the ASCE Standard 68-18 for PICP (ASCE, 2018) states that geotextile is typically not placed in between the open-graded aggregates layers as it provides little to no increase in structural capacity and may also cause clogging problems hence the accelerated failure of PICP. On the other hand, geotextile should be placed vertically against the side-walls to separate the permeable pavement from the adjacent soil for all applications that do not use a full-depth concrete curb. As there is conflicting and unreliable results from different researchers regarding the inclusion of a geofabric layer within PPS, the decision to whether incorporate geosynthetic materials in permeable pavement systems should be considered very carefully (Yong *et al*., 2008).

If present, the geotextile layer is usually put at one of two locations within the PPS; it can be placed between the bedding layer and the base, or it can be placed between the sub-base and subgrade layer. The presence of geotextile in PPS can restrict the vertical percolation of sediments to the deeper parts of the permeable pavement system (Boving *et al.*, 2008). However, geotextiles can also encourage microbial activity that facilitates the biological degradation process for organic contamination thus improving the runoff quality (Scholz & Grabowiecki, 2007). Rowe *et al*. (2010) do not recommend the use of a geotextile above the open-graded base material of PPS due to potential of clogging. The use of geotextile at the bottom of the aggregate reservoir may be used upon an evaluation for suitability by a geotechnical engineer (Eisenberg *et al*., 2015).

Table 2-5a: Treatment performance for typical pollutants in stormwater for different types of PPS

Author	**Location**	**Tested Pollutants**	**Types of permeable pavement**	**Findings**
Tota-Maharaj and Scholz (2010)	UK	TSS, PO_4^{3-} NH_3, NO_3^- BOD, turbidity, Total coliforms, *E. coli*, *Faecal Streptococci*	PICP	Total coliforms, *E. coli*, *Faecal Streptococci* removal by 98 to 99%. NH_3 removal efficiencies: 84.6% PO_4^{3-} removal efficiencies: 77.5% NO_3^- removal efficiencies: -77,9% to 43.3% SS, turbidity and BOD removal efficiency: 91%, 82% and 88% respectively.
Brown *et al.* (2009)	Canada	TSS	PICP PA	Both PICP and PA can removal TSS by 90 to 96% TSS removal efficiencies more than 99% for particles over 75 μm
Bean et al. (2007)	USA	TKN, TP, TN NH_3, NO_3^-, Zn	PICP PC CGP	TKN, TP, NH_3 and Zn were significantly lower in the exfiltrate than the asphalt runoff Nitrate concentration was higher in the exfiltrate than the asphalt runoff
Collins *et al.* (2010b)	USA	TKN, pH, TN NH_3, NO_3^-	PICP PC CGP	pH in exfiltrate was higher than pH in asphalt runoff (PPS buffer acidic pH) TKN and NH_3 in the exfiltrate was lower than that in the asphalt runoff Nitrate and nitrite concentration in exfiltrate were higher than that in the asphalt runoff Nitrate removal efficiency from PICP site was between negative 210.3% and negative 331%
Drake *et al.* (2012)	Canada	TKN, TP, TN NH_3, NO_3^-, Zn Cu, Mn, Fe, TSS, oil	PICP PC	Oil, TKN, TP, Zn, SS, Cu, Mn, Fe, NH_3 in exfiltrate were all significantly lower than in the asphalt runoff. Seasonality was more pronounced in runoff than in the exfiltrate
Li *et al.* (2017)	China	TSS, TP, TN NH_3, NO_3^- COD	PA PC Cement brick Ceramic brick Sand base brick Shale brick	TSS removal efficiency: more than 90% With the iron oxide as the electron donor, TN, COD, NO_3^- removal efficiency was 88.2, 35,1 and 17.5 % respectively Surface material had little effect on TP removal The removal efficiency of NH_3 decreased with the increase of the pore volume, from 68% to 2%

Table 2-5b: Treatment performance for typical pollutants in stormwater for different types of PPS

Author	Location	Tested Pollutants	Types of permeable pavement	Findings
Huang *et al.* (2016a)	Canada	TSS, TP, TN Cu, Pb, Zn	PICP PA PC	TSS, TP, Cu, Pb and Zn removal efficiency: more than 70% TN removal rate was <10%, and TN removal was influenced by climatic condition
Eck *et al.* (2012)	USA	TKN, TP NO_3^-, Zn Cu, Pb, TSS	Permeable Friction Course (PFC)	TSS removal efficiency: 91 to 93% TP removal efficiency: 66 to 78% TKN removal efficiency: 25 to 65% NO_3^- removal efficiency: negative 6% to negative 46% Cu removal efficiency: 56 to 69% Zn removal efficiency: 87 to 90% Pb removal efficiency: 90 to 96%
Dierkes *et al.* (1999)	Germany	Zn, Cu, Pb, Cd	PICP	Zn removal efficiency: 97% Cu removal efficiency: 96% Pb removal efficiency: 98% Cd removal efficiency: 98%
Myers *et al.* (2011)	Australia	TN, TKN, NO_x, TP, Zn, Cu, Pb	PICP	Zn and Cu were significantly lower in the dolomite and quartzite reservoirs ($p < 0.05$)
Fassman & Blackbourn (2010)	New Zealand	TSS, Zn, Cu	PICP	TSS removal efficiency: 49% Zn removal efficiency: 85% Cu removal efficiency: 58%
Brattebo & Booth (2003)	USA	Zn, Cu	PGP CGP PICP	Zn removal efficiency: 38.9% to 68.5% with PGP with grass had the lowest removal rate, and PICP had the highest removal rate Cu removal efficiency: 83.3% to 99.9%
Gilbert & Clausen (2006)	USA	TKN, TP, TN NH_3, NO_3^-, Zn Cu, Pb, TSS	PICP	TSS removal efficiency: 66.9% TP removal efficiency: 33.6% TKN removal efficiency: 91.3% NH_3 removal efficiencies: 72.2% NO_3^- removal efficiency: 50% Cu removal efficiency: 64.7% Zn removal efficiency: 71.3% Pb removal efficiency: 66.7%

The University of Abertay has investigated the impact of a geotextile in PPS on the removal efficiency of selected heavy metals, oil and suspended solids (Mullaney *et al*., 2011). The study showed that those test rigs with an upper-level geotextile had higher removal rates than the test rigs without for cadmium, lead, and zinc (between 2% and 6%) after the application of the equivalent of 10 years of metals (the metals were added to the PPS tank in soluble form). The metal removal rates for these metals were insignificant for the first three years of metal application. The presence of geotextile was found to have little impact on the removal of oil or suspended solids. Another study carried out by the University of Edinburgh showed that most of the microbial activity takes place in the vicinity of the geotextile and the presence of a geotextile has the positive effect in keeping nitrate-nitrogen concentration and suspended solids low (Tota-Maharaj & Scholz, 2010). Zhao *et al*. (2018) evaluated the influence of geotextile type and its position in a porous asphalt pavement system on Pb (II) removal efficiency with two types of geotextile (non-woven and woven) positioned separately at upper and lower levels. It was found that the lower level non-woven geotextile improved the Pb (II) removal rate by 20% over an upper-level woven geotextile. They further found the system with geotextile layer generally produces lower Pb (II) in the effluent than the one without. They concluded that the use of non-woven geotextile membrane is preferred as it provides better hydraulic properties and better pollutant removal performance. As previously mentioned in Section 2.4.4.4, Myers *et al*. (2011) measured a reduction in Zn, Cu, and Pb by 94% to 99% in the stormwater runoff after 144 h in storage in the reservoir from a PICP system with a lower-level permeable geotextile under the bedding aggregate.

2.4.6 Clogging and maintenance

2.4.6.1 Clogging

Although PPS have many benefits such as reducing runoff volume and potentially improving water quality, clogging is the biggest enemy of permeable pavement leading to serviceability problems and ultimately failure (Yong *et al*., 2013; Kia *et al*., 2017). The hydraulic performance of PPS is related to surface infiltration capacity, with degrades over time and reduces performance (Sansalone *et al*., 2008).

Clogging mechanisms can be divided into physical clogging and biological clogging. Physical clogging involves the build-up of sediment, debris and various particles on the surface and in the pore structure, whilst biological clogging is caused by plant root penetration, algae and bacteria (Kia *et al*., 2017). Various factors influence clogging including: sediment type, sediment particle size, the pore size of permeable pavement, the presence and type of geotextile, the surrounding land use, the presence of trees and climatic exposure conditions (*ibid*). Schaefer *et al*. (2011) found sand causes significant reduction in the permeability of PPS, with the combination of silt clay and sand causing the highest reduction. Coughlin *et al*. (2012) showed that clay could cause clogging ten times worse than sand, and concluded that the clogging potential is the highest when the particle size is close to the pore size of permeable concrete. Kia *et al*. (2017) note that particles larger than the pore size of the PPS are generally trapped on top of the surface, whilst particle with the finer size are likely to trap within the PPS or carry through to the bottom of the pavement. The presence of the geotextile layer between the aggregate layers helps to retain the fines, but it also increases the clogging risk and reduces the infiltration rates as solids are accumulated on top of the geotextile. It was also found that when PPS are exposed to variable flow and drying periods, the clogging is slowed down compared to that when the PPS is exposed to continuous rainfall (Kia *et al*., 2017). Most clogging occurs close to the pavement surface (Winston *et al.*, 2016); Gerrits & James (2002) and Bean *et al*. (2007) found that removing the upper 2.5 cm of fill material from the pavement surface can result in significant increases in the surface infiltration rate.

The surface infiltration rate (SIR) on a permeable pavement system can give an indication of the extent of clogging in the PPS and whether there is a need for maintenance.

2.4.6.2 Maintenance

There are various maintenance procedures for PPS such as pressure washing, street sweeping and vacuuming. Drake & Bradford (2012) found none of the maintenance measures are 100% effective. Eisenberg *et al*. (2015) suggested a regenerative air vacuum machine for regular cleaning, with major vacuuming only when the clogging is severe. Winston *et al.* (2016) evaluated eight different small-scale and full-scale maintenance techniques including: regenerative-air street sweeping, vacuum sweeping, hand-held vacuuming, mechanical street sweeping, high pressure washing and milling of porous asphalt at ten different PPS sites in the USA and Sweden to see which maintenance technique had the best infiltration recoverability. They found that a street sweeper with suction works better than mechanical sweeping for PICP, whilst industrial hand-held vacuum cleaning, pressure washing, and milling were the most successful for PA maintenance. They further found that milling PA to a depth of 2.5 cm was the most successful maintenance technique for this PPS, it nearly restored the surface infiltration rate (SIR) in a 21-year old PA site to a like-new condition.

2.4.7 PPS for fit-for-purpose use

Nnadi *et al*. (2014) carried out a comparative study to assess the performance of geotextile incorporated PPS as a potential source of irrigation water on two different types of plants. The development, growth, heavy metal content, pH, sodium adsorption ratio, as well as EC of the organs of plants irrigated from treated test rigs (cumulative oil loading from lubricating oil and nutrient addition from slow-release fertilizer) were compared to that of plants irrigated with untreated test rigs (control test models) and plants treated with de-ionized water. The results found that plants irrigated by the water that had been passed through PPS grew better than plants irrigated by untreated or de-ionized water showing the potential of PPS for use in collecting and treating water for irrigation purposes.

2.5 Literature review summary

PPS are one of the source controls in SuDS technology which can collect, treat and recycle water and therefore lead to surface runoff reduction, recharge of groundwater, storm attenuation and pollutant control. While there have been a number of international studies investigating the treatment performance of the PICP, not enough is known about the relative performance of different PICP designs. In addition, there is no universal agreement on the use of geotextile and the impact of a submerged zone on N removal in PICP. This study, therefore, aimed to investigate the relationship between nutrient removal and different PICP design in an attempt to address the literature 'gap'. The next chapter provides a detailed description of the research carried out in this study to address this research aim.

3. Research Method

This section details the method used to determine the treatment efficacy of ten different permeable interlocking concrete pavement (PICP) systems constructed in specially modified test 'bins' in the civil engineering laboratory at the University of Cape Town. First, infiltration tests were carried out to determine the infiltration rate of each of the ten PICP cells. Clean (tap) water was then poured onto the cells to initiate the experiment and determine the initial water quality emanating from each cell. Finally, simulated rainfall using synthetic stormwater was poured on each cell and the effluent regularly analysed for various nutrients to determine the pollutant removal capacity of the ten different PICP systems. A field study to evaluate PICP performance was also carried out at the UCT's New Engineering Building (NEB) permeable parking area for long-term quality and quantity monitoring.

3.1 Overview of the experimental procedure

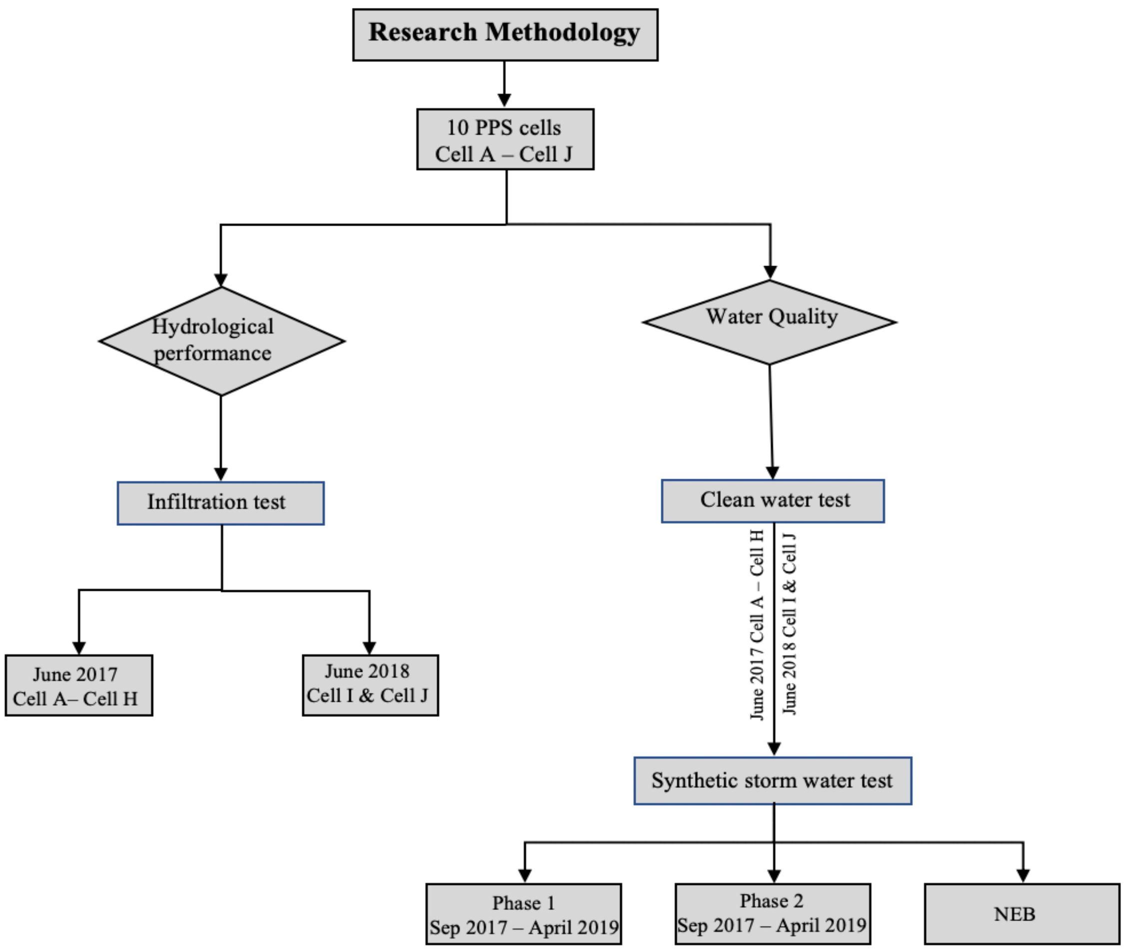


Figure 3-1: Flow chart for the research method

Ten experimental cells housing different PICP test structure were constructed for this work (Table 3-1), eight were constructed by previous students in 2016 and two more were constructed by the author in 2018. In addition, the results were verified through a field study in PICP system equipped for this purpose.

The experiment followed the following steps:

Step 1: An infiltration test was carried out to determine the infiltration rate of each PICP cell with the use of a single ring infiltrometer following the test procedure given by *ASTM C1781: Standard Test Method for surface infiltration rate of permeable unit pavement systems* (ASTM, 2013);

Step 2: A clean water test was then carried out to determine the 'base-line' water quality emanating from each cell prior to the addition of any external pollutants. The 'clean water test' involved the application of clean potable water by watering can to each unit in quantities roughly representing a typical rainfall season in the CoCT but at an accelerated rate. Samples of the water discharging from the bottom of each PPS cell were analyzed in the water quality lab for: TSS, the orthophosphate-phosphorus, ammonia-nitrogen, nitrite, and nitrate-nitrogen. The pH, temperature, and EC were also measured in-situ using hand-held probes;

Step 3: Each PICP cell was subjected to multiple 'seasons' of accelerated rainfall events using pre-prepared synthetic stormwater containing suitable soluble pollutants to test their treatment efficacy. The synthetic stormwater testing was carried out in two distinct phases. In the first phase, three rainfall seasons were simulated in October 2017, September 2018 and April 2019 using water containing the commercial fertilizer 'Growing Orchid' at an appropriate concentration – determined from the literature – as the pollutant. Each season comprised nine distinct 'storm' events applied one per day to the surface of experimental cells with each PPS cell receiving the same volume of water (Biggs, 2016). The pH, temperature and EC of the outflow were determined for each PPS cell for each rainfall event. Samples were taken to the water laboratory on the first, fifth and ninth day where the concentrations of selected pollutants: ammonia-nitrogen, nitrite, nitrate-nitrogen and the orthophosphate-phosphorus, were determined;

Step 4: The second phase of the work took place in August-September 2019. The use of 'Growing Orchid' as the source of stormwater contamination was abandoned as a consequence of problems with inconsistent nitrogen to phosphorus ratios giving rise to inconsistent influent quality – and thus potentially outflow quality (StarkeAyres®, n.d). Synthetic stormwater was thus produced in the laboratory by adding NH_4Cl, $K_2H_2PO_4$, and KNO_3 to tap water in carefully measured quantities in a 500-litre tank. Furthermore, instead of applying stormwater for nine consecutive days without any break – thus ignoring the possible impact of dry periods between rainfall events – a new rainfall regime was purposed with intermittent dry and wet periods to represent the four months of the 'typical' Cape Town rainy season – but in an accelerated 1.5 month period. The pH, temperature and EC of the outflows from each cell were measured daily, whilst samples were tested in the water quality laboratory for ammonia-nitrogen, nitrite-nitrogen, nitrate-nitrogen and the orthophosphate-phosphorus on a weekly basis; and

Step 5: A field study in PICP systems were carried out in the NEB parking area (UCT). Four samples were collected from each of the PPS section's monitoring chambers from 2018 to 2019 after major storm events. The pH, temperature and EC were immediately tested on the collected samples by using the electrical probes, and the samples were then sent to the water quality lab in NEB to analyse the TSS, nitrate-nitrogen, nitrite-nitrogen, ammonia-nitrogen and the orthophosphate-phosphorus concentration.

3.2 Existing PICP test cells

PICP testing has been carried out in the Civil Engineering Laboratory at UCT since 2014. At the commencement of this work, there were eight experimental cells each housing a different PICP test structure. Each cell comprised a polyethylene (HDPE) plastic container of 1200 mm length, 1100 mm width and 400 mm depth (Figure 3-2). Each cell was fitted with a perforated under-drain with the outflow controlled by a valve on the outlet (Figure 3-3). The key for original eight experiment cells is presented in Figure 3-4.

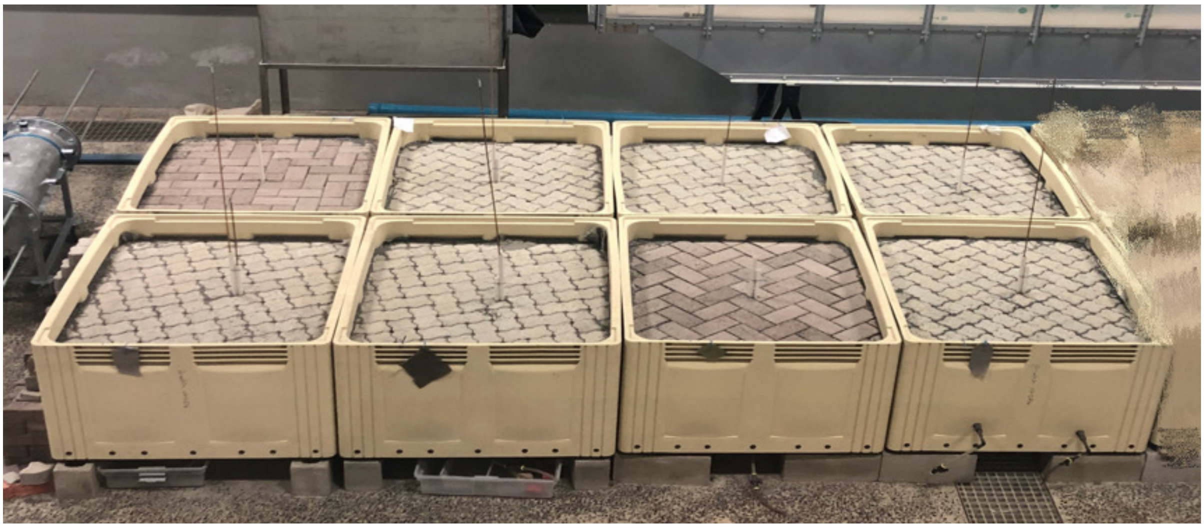
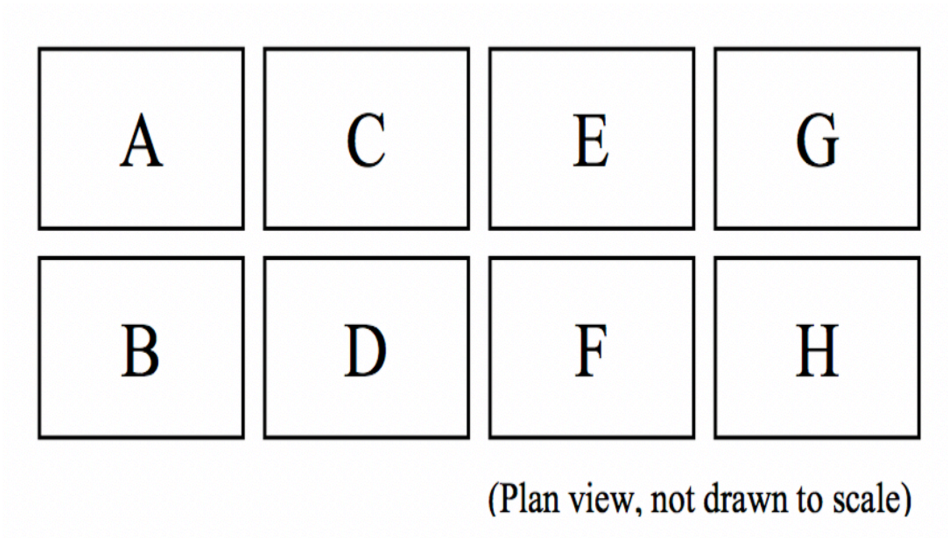


Figure 3-2: PICP experimental cells

The experimental cells generally have a 250 mm sub-base layer of 50-63 mm aggregate at the bottom, upon which is placed a 100 mm base layer of 19-25 mm aggregate, a 50 mm layer of 2-6 mm bedding gravel, then finally various proprietary pavers with 'pea-sized' gravel (2-4 mm quartzite/gritstone) placed in between them to provide a flow-path for the surface water. Some cells have a geotextile between the base and bedding layers (Pavement 2), others do not (Pavement 1). In some cells, the aggregate was 'washed' before installation; others not (more on this later). One cell had a raised outlet – to create a permanent wet space at the bottom of the cell. Figure 3-5 gives the general cross-sections whilst Table 3-1 gives the individual cell specification.

Figure 3-3: Drain pipe at the base of each PICP cell



A – Aquapave, no geotextile, washed stones, base outlet
B – Permealock, Fibertex, unwashed stones, base outlet
C – Permealock, Fibertex, washed stones, base outlet
D – Permealock, Kaytech bidim, washed stones, base outlet
E – Permealock, no geotextile, washed stones, base outlet
F – Aquapave, Inbitex, washed stones, base outlet
G – Permealock, no geotextile, unwashed stones, based outlet
H – Permealock, Fibertex geotextile, unwashed stones, raised outlet

Figure 3-4: General Layout for the original PICP cells
(Brooks, 2016)

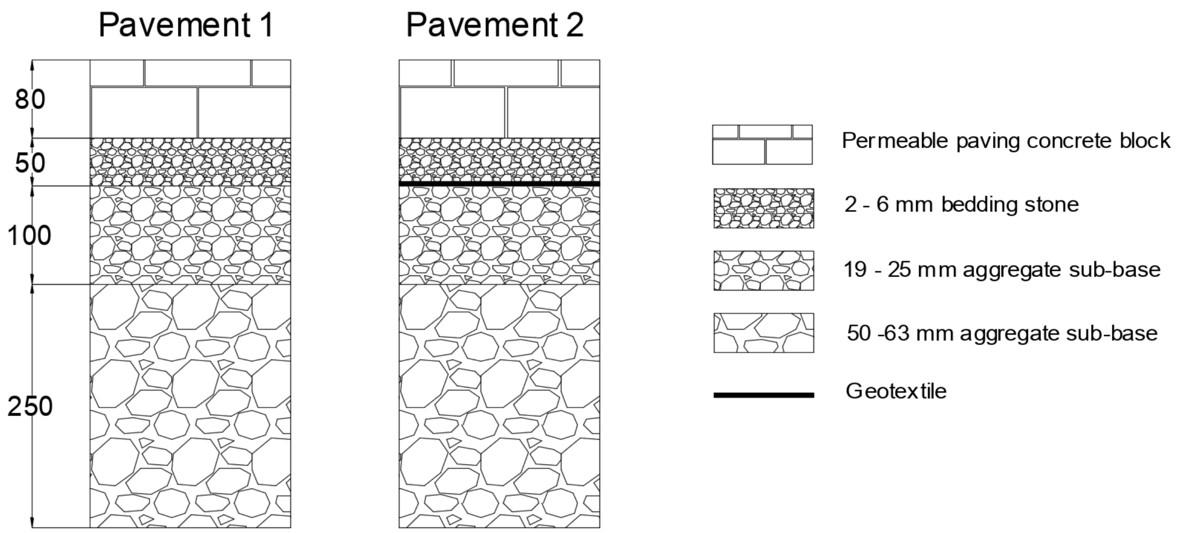


Figure 3-5: Two types of PICP designs based on the presence of geotextile
(Adapted from Brooks, 2016)

3.3 Constructing the new experimental cells

PICP reduces runoff by infiltrating rainfall through specially designed, aggregate-filled joints between the paver units. A local paver supplier wanted to know whether conventional pavers would have the same hydrological performance and nutrient removal ability as custom designed PICP papers if laid out in such a way that gaps are created on the corners which would then be filled with aggregate. This would not only bring down the cost of paving but also open up the possibility of using a wide range of more-decorative paving options. The decision was thus made to construct two additional test cells using this approach and compare their performance with the existing eight cells.

3.3.1 Cleaning the aggregates

Fassman & Blackbourn (2010) found that the aggregate within the PICP can have an adverse impact on the water quality whereby the majority of the pollutants discharging from the underdrains originated from the aggregates and not from surface inputs. This was confirmed by Biggs (2016) who found that the use of unwashed aggregates within the PICP can introduce large quantities of pollutants (TSS, ammonia-nitrogen, the orthophosphate-phosphorus) thus turning PICP from a treatment device to a source of contamination. The fines adhering to the aggregate can also clog the subgrade if not removed prior to installation (ASTM, 2019). Unfortunately, this has proven difficult to achieve in practice – both in South Africa (Wium, personal communication 2019, May 20) and the USA (Winston, personal communication 2019, May 20). For this study, it was deemed essential to ensure the cleanness of the aggregates used in the two new experimental cells.

The first attempt at cleaning the large aggregates was by spreading them out and using a water hose to spray the stones (Figure 3-6 and Figure 3-7).

Figure 3-6: Getting stone aggregate prepared for washing

Figure 3-7: Using water hose to wash the stone aggregate

Care was taken to ensure that each stone was sprayed. The stones were placed on a grid above a drain to ensure that sediment washed from one stone did not contaminate any others. However, it was found that even this – already quite considerable cleaning effort – did not remove all the dirt from the surface of the aggregate as became evident once it had been dried (Figure 3-8). This shows that this method is inadequate and alternative methods would need to be considered if the aggregate was to be truly ‘clean’.

Figure 3-8: Stone aggregate after being hosed with water and then dried

The second method involved brushing the stone aggregates by hand (Figure 3-9). This was successful, but it is also a labour-intensive, time-consuming process which would not be practicable outside of small-scale laboratory experiments.

The third method involved partially filling a container with water and putting the aggregate into this. A combination of brushing, sponging and wobbling the container loosened most of the dirt. (Figure 3-10). The resulting slurry was poured over a geotextile with the majority of the dirt depositing on the geotextile whilst the rest of the dirty water flowing through the nearby grid into the drain underneath. This was repeated two or three times until the water inside the container was visually clear.

The impact of number of flushing cycles on the extent of cleanness of the aggregates can be seen in Figure 3-11, where the left container has been flushed three times and the right only once. The smaller aggregates were cleaned by washing them three times through a sieve (Figure 3-12).

Figure 3-9: Hand washing the stone aggregate

Figure 3-10: Using a broom to brush the aggregate (left) Slurry poured onto the geotextile (right)

Figure 3-11: Comparison between 3rd flush (left) and first flush (right)

Figure 3-12: Sieving the smaller aggregates

3.3.2 PPS Cell preparation

Following cleaning of the stones, two plastic containers of 1200 mm length, 1100 mm width and 400 mm depth were ordered. The under-drain construction used the same design as the existing cells (Figure 3-13). Plastic outlets were inserted in holes drilled in the bottom of the bins and sealed with marine silicone and leak-seal tape to prevent leaking. Once the silicone had set –

after about 24 hours – the 90-degree outlets were connected with a T-piece to take the water from under the bins. A shut-off valve was provided to control the flow of the water. The pipe fittings used in this design is shown in Figure 3-14.

After the completion of the under-drain system for both experimental cells, they were tested for water-tightness by shutting the valves and partly filling them with water.

Each cell was positioned on a concrete footing with two wooden planks inserted between the footing and the bin to provide a 2.5% slope towards the drains to prevent ponding in the bottom of the bins (Figure 3-15).

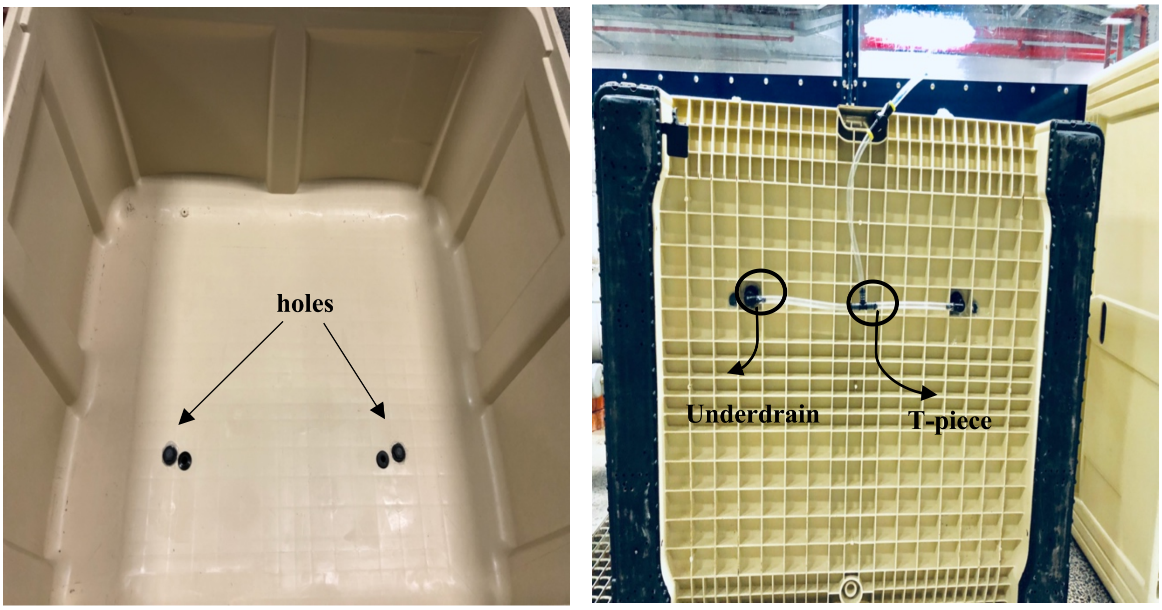


Figure 3-13: Under-drainage system for the PICP cells interior view (left) and bottom view (right)

Figure 3-14: Pipe fittings for under-drain system

Figure 3-15: Jumbo bins positioned on top of the concrete footing

3.3.3 Monitoring Column

Previous studies have found that the PPS structure can behave as an effective in-situ bioreactor, similar to a gully pot (Tota-Maharaj and Scholz, 2010). 600 mm long transparent perspex transparent columns with OD of 150mm and ID of 142mm were thus placed under the pavers in the middle of each of the new PPS structures (Figure 3-16) to allow the use of a ‘GoPro’ type camera in the hope that it may be possible to microbial activity / bacterial growth as well as sedimentation in the different layers.

Figure 3-16: Perspex column in the middle of the bin

3.3.4 Laying the aggregate layers

The different sizes of cleaned aggregate were then laid in the Jumbo bins, beginning with a 250mm layer of 50-63 mm diameter ‘big stones’ on the bottom, followed by a 100 mm layer of the intermediate 19-25 mm diameter aggregate, and finally a 50 mm top layer of the small 2-6 mm diameter bedding gravel above this (Figure 3-17).

Figure 3-17: Placing the aggregate layers in the bins – from left to right: large, intermediate and small

A ‘Fibertex®’ geotextile was then placed in Cell I – but not Cell J – to check the influence of geotextile within the PPS structure. Exposed aggregate pavers provided by one of the local paving companies were laid on top of the stone layers (with and without the geotextile) to a specific pattern that created gaps at the corners to allow the water to infiltrate (Figure 3-18). The pavers next to the bin wall were measured and cut with a concrete cutting machine to ensure that they fitted snugly. The pavers were then carefully levelled using a hammer and spirit level. Finally, pea-sized stones (2-4 mm quartzite/gritstone) were brushed into the gaps between the pavers.

Figure 3-18: Pattern used for the exposed aggregate pavers (Cells I & J)

3.4 Summary of all the experimental cells

A description of each of the ten experimental cells is provided here with the main physical attributes summarised in Table 3-1. As each PICP cell has different design features (types of pavers, presence or absence of a geotextile, the use of washed and unwashed aggregates and the incorporation of a permanently wet zone with the raised outlet), the impact of each design feature could be determined by comparing the PICP cells having a different design feature whilst holding all other design features constant (Table 3-2).

3.4.1 Types of pavers

Three types of pavers were laid in the PICP experimental cells. One is the Aquaflow®, which is the pavers widely used in the Western Cape and manufactured by INCA Concrete Products. The dimensions of the Aquaflow® blocks can be seen in Figure 3-19. The Aquaflow® pavers are 200 x 100 x 80 mm and is specifically designed with a chamfered slot that allows water to permeate through the finished paved surface at a high rate (Hanson-Formpave, 2010).

The second paver is called Permealock®, which is manufactured by a local South African company called C.E.L. Permealock® Pavers are 203 x 102 x 80 mm and are provided with 12 protrusions to separate the pavers for water ingress (Figure 3-20). Both Aquaflow® and Permealock® pavers were specially developed for PICP unlike the third type of the pavers which are standard exposed aggregate pavers with dimension of 220 x 110 x 70 mm (Figure 3-21) simply laid to create gaps for the water to infiltrate through as mentioned in Section 3.3.4.

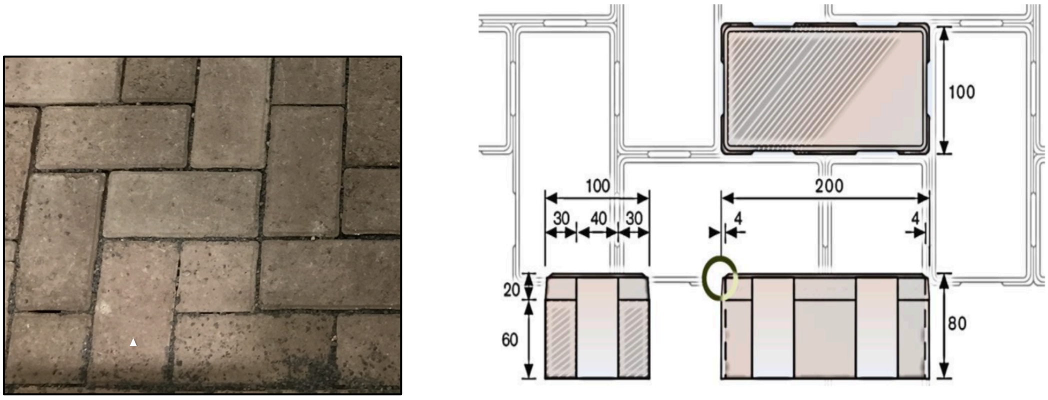


Figure 3-19: Aquaflow® permeable block design (Hanson-Formpave, 2010)

Figure 3-20: Permealock® pavers from C.E.L

Figure 3-21: Exposed aggregate pavers

Table 3-1: PICP experimental cell description

Cell	Pavers	Geotextile	Aggregate Component	Outlet
A	Aquapave®	No Geotextile	Washed	Base outlet
B	Permealock	Fibertex Geotextile	Unwashed	Base outlet
C	Permealock	Fibertex Geotextile	Washed	Base outlet
D	Permealock	Kaytech bidim Geotextile	Washed	Base outlet
E	Permealock	No Geotextile	Washed	Base outlet
F	Aquapave®	Inbitex Geotextile	Washed	Base outlet
G	Permealock	No Geotextile	Unwashed	Based outlet
H	Permealock	Fibertex Geotextile	Unwashed	Raised outlet
I	Exposed pavers	Fibertex Geotextile	washed	Based outlet
J	Exposed pavers	No Geotextile	washed	Based outlet

Table 3-2: Different cells comparison to determine the impact of different criteria

Criteria	Different cells comparison		
Impact of types of pavers	Cell C/Cell E (Permealock pavers) & Cell I/Cell J(Exposed pavers)		
Impact of geotextile	Cell A (no geotextile) & Cell F (Inbitex® geotextile)	Cell E (no geotextile) & Cell C (Fibertex® geotextile) and Cell D (Kaytech bidim® geotextile)	Cell G/Cell J (no geotextile) & Cell B/Cell I (Fibertex® geotextile)
Impact of raised outlet (submerged zone)	Cell B (base outlet) & Cell H (raised outlet)		
Impact of unwashed aggregates	Cell B (unwashed stones) & Cell C (washed stones)		

3.4.2 Type of geotextile

Three types of geotextile were used in the PICP experimental cells: Fibertex® geotextile (non-woven), Kaytech bidim® geotextile (non-woven), and Inbitex geotextile (non-woven) (Figure 3-22). Table 3-3 summarizes the hydraulic properties of all three types which may, in turn, impact the overall infiltration rate through the PICP (Fibertex, 2012; Kaytech, 2015 and Terram, 2012).

Figure 3-22: Three types of Geotextile

(From left to right: Fibertex geotextile, Kaytech Bidim® geotextile, Inbitex geotextile)

Table 3-3: Geotextile hydraulic properties comparison

Geotextile Type	Through flow ℓ/s/m^2	Permeability 10^{-3} m/s
Fibertex	70	2.1
Kaytech bidim	200	4.8
Inbitex	80	2.875

3.5 Infiltration test

Infiltration tests were carried out on all the PICP experimental cells. The infiltration test procedure followed the *ASTM Standards: C1781/C1781M -13 Standard Test Method for surface infiltration rate of permeable unit pavement systems* (ASTM, 2013) and a single ring infiltrometer was used.

3.5.1 The aim of the infiltration test

PICP controls stormwater by allowing it to infiltrate through the paver surface into a stone ‘reservoir’ under the pavers thereby reducing surface runoff volumes and peak discharges (Pratt *et al*., 1995). The infiltration rate of PICP depends on the condition of its surface, most notably the amount of sediment trapped in the openings around the pavers. The aim of these infiltration tests was simply to determine the maximum clean water infiltration rate for each cell prior to any blockage.

3.5.2 Experimental apparatus

A single-ring infiltrometer was used for the infiltration test. The reason for using a single-ring infiltrometer instead of a double-ring infiltrometer is because of the highly permeable characteristic of the laboratory permeable pavement. The possible horizontal migration of water once it enters the media can be neglected due to the high infiltration rate. The double ring infiltrometer is more suitable for field measurements of the infiltration rate of soils where the infiltration rate is relatively low. The apparatus used for the infiltration test is as follows:

- Infiltration Ring (Single ring infiltrometer)
- Balance
- Container
- Stopwatch
- Non-hardening plumbers' putty
- Water

3.5.3 Test procedure

A single-ring infiltrometer consists of a single cylindrical galvanized steel ring with an inner diameter of 300 mm. The inner surface of the ring was marked with two lines at 10 and 15 mm from the bottom (Figure 3-23). The pavement surface was swept of the debris, the ring placed on the pavement surface and non-hardening plumber's putty was applied around the bottom edge of the ring and pressed into the surface around the bottom edge of the ring to create a watertight seal as shown in Figure 3-24.

The pavement was pre-wetted prior to the infiltration test. 18 ℓ tap water was then poured into the ring at a rate sufficient to maintain a reasonably stable depth between the two marked lines. A stopwatch was used to record how long it took to infiltrate all the water. Once each cell had been tested, the plumber's putty was removed from the surface and rings, and the test area swept clean (ASTM, 2013). The data for the tests are to be found in Appendix B.

Figure 3-23: The single-ring infiltrometer (left) and the two lines used to assist with keeping the head constant (right)

Figure 3-24: Plumbers putty used to seal the bottom edge for the infiltrometer

3.6 Clean water base-line testing

Clean tap water was applied to each cell in quantities of 10 liters to establish a base-line pollutant values before the application of synthetic stormwater. Biggs (2016) found that the use of unwashed aggregates can introduce significant quantities of polluted pavement effluents. Since the experimental cells consist of eight cells of washed aggregates and two cells of unwashed aggregates, the discharge collected from the base of the cells could be compared.

Figure 3-25: Pre-wetting stage

Figure 3-26: Infiltration test

3.6.1 Test procedure

A 10 ℓ watering can was used to pour 10 ℓ tap water onto each of the pavement surface. 10 ℓ was found to be the minimum volume that would result in effluent from the previously dry PICP test cells. 500 mℓ plastic sample bottles were used to collect effluent exiting from the PICP cells (Figure 3-27). The collected samples were then analysed individually for pH, temperature, EC, TSS and concentration of selected pollutants (ammonia-nitrogen, the orthophosphate-phosphorus, nitrite-nitrogen and nitrate-nitrogen).

Figure 3-27: Applying water to the surface (left) and collecting the effluent emanating from the base of the cell (right)

3.7 Synthetic stormwater testing

The synthetic stormwater testing aimed to determine the treatment efficacy of the different PICP types. Polluted rainfall events were simulated by pouring synthetic stormwater onto the surface of the pavers in pre-determined amounts. This section describes the determination of the stormwater pollutant concentration for ‘typical’ stormwater in the South Africa context, followed by the determination of an appropriate rainfall regime and lastly method used. The testing took place in two distinct phases. The first phase comprised testing carried out in October 2017, September 2018, and April 2019 and was intended to provide a rapid indication of how each PICP design responded to nutrient loading. The first two rounds were carried out by fourth year civil engineering students (the author being one of these!) – which also limited the time scale of the tests. The second phase (Section 3.7.3) used an improved ‘synthetic stormwater’ and was carried out in August-September 2019. This was also time-limited – although not as severely as in the first phase – but otherwise attempted to be a little more realistic in terms of the simulated ‘rainfall’ regime.

3.7.1 Phase 1: Design for the 'typical' stormwater

Biggs (2016) dissertation was initially used as a baseline for the determination of an appropriate stormwater pollutant concentration in the South African context. Due to the lack of locally available stormwater quality data, the designed synthetic stormwater pollutant concentration was derived from various international studies (US EPA, 1983; Duncan, 1999; Marsalek *et al*., 1993; Debo & Reese, 2003) and the selected pollutant concentration is shown in Table 3-4. The upper bound pollutant values were chosen for the synthetic stormwater.

Table 3-4: Design stormwater quality (Biggs, 2016)

Pollutant	Units	Pollutant concentration for different land uses				Design stormwater
		Residential	Commercial/Industrial	Urban stormwater		
		Debo & Reese (2003)		Duncan (1999)	U.S EPA	
TSS	mg/ℓ	101	69.0	150	100	150
Total Phosphorus	mg/ℓ	0.74	0.57	-	-	0.74
NO_2+NO_3	mg/ℓ	0.38	0.20	0.35	0.33	0.38
Total Nitrogen	mg/ℓ	-	-	2.6	-	2.6

As the focus of this investigation was on the treatment efficacy of PICP for nutrients, ammonia-nitrogen, the orthophosphate-phosphorus, nitrite-nitrogen and nitrate-nitrogen, the ratio of these selected pollutants was calculated to find the most suitable fertilizer that meets the requirement of the designed stormwater quality (Table 3-6). Biggs (2016) had identified a liquid fertilizer called 'Growing Orchids' made by Starke Ayres (Pty) Ltd that met the required ratio – and this was what was what was initially used as the pollutant in the synthetic stormwater.

Table 3-5: Design stormwater ratio versus fertilizer nutrient ratio for Phase 1

Nutrient	Design stormwater		'Growing Orchid' fertilizer	
	Concentration	Ratio	g/kg	ratio
Nitrogen	2.60	6.8	310	6.3
Phosphorus	0.38	1	49	1
Potassium	-	-	91	1.9

Figure 3-28: Growing Orchid soluble fertiliser bag

3.7.2 Synthetic stormwater application

As mentioned in Section 3.7.1, ‘Growing Orchid’ soluble fertilizer was used as the source of nutrients for the synthetic stormwater in the first phase of the study. Following Biggs (2016), two different concentrations were used – 65 g / 100 ℓ and 8 g / 100 ℓ – to facilitate an understanding of how the different PICP cells responded to different concentration of pollutants with respect to treatment.

Biggs (2016) assumed that a minimum of 10 mm rainfall was necessary to get a significant flow through the PICP structures once they were wet. Given the surface areas of the test cells, this equates to the application of 13.2 ℓ of synthetic stormwater per cell. Both the infiltration and clean water tests showed, however, that the use of 10 ℓ per storm, per cell – equating to a 7.5 mm storm depth – generated sufficient effluent for assessment purposes. Given that the testing took place during the worst drought in Cape Town’s history, it seemed more responsible to adopt this lower quantity.

Nine ‘storms’ were simulated on consecutive days with one storm per day. A pollutant concentration of 65 g / 100 ℓ was used for the first four storms; the remaining five storms used a concentration of 8 g /100 ℓ. Influent samples were collected for each experimental cell on Day 1 and Day 5, and effluent samples were collected for each experimental cell daily from Day 1 to Day 9.

The first round of 9 days of synthetic stormwater testing was carried out by the author in October 2017 on the existing 8 experimental cells (Cell A to Cell H), the second round of testing was carried out by Dookhit (2018) – working under the direction of the author in September 2018 (after a year) on the two new experimental cells with the exposed pavers (Cell I and Cell J), whilst the third round of testing was done in March 2019 (after 6 months) on all the 10 experimental cells to ensure that they were all more-or-less in the same state of readiness for Phase 2. Table 3-6 shows the timeline for the synthetic stormwater testing on the PPS experimental cells in the laboratory.

Table 3-6: Timeline for Phase 1 synthetic stormwater application

Date	Cell A-Cell H	Cell I & Cell J
05/10/2017 – 13/10/2017	✓	✗
25/09/2018 – 03/10/2018	✗	✓
07/03/2018 –15/03/2018	✓	✓

The time gap between each complete round of synthetic stormwater testing was determined by student availability, however it could be considered as mimicking the seasonal dry periods that are typical of the region (Cape Town has long, hot, dry summers).

3.7.3 Phase 2: Improved method of synthetic stormwater application

During the three rounds of synthetic stormwater testing from October 2018 to March 2019 (Section 3.7.2), the 'Growing Orchid' fertilizer was used as the added pollutant for the synthetic stormwater. The influent sample testing, however, revealed that the nutrient concentrations in this fertilizer were inconsistent thus potentially distorting the test results. The decision was thus taken to make up a stormwater 'mix' under controlled conditions in the laboratory for Phase 2 of the testing that was carried out in August 2019.

The selected stormwater 'mix' was determined from consideration of typical 'worst-case' published concentrations of ammonia-nitrogen, the orthophosphate-phosphorus and nitrate-nitrogen. The the orthophosphate-phosphorus concentration was chosen as 0.8 mg/ℓ (Caraco, 2000), the nitrate-nitrogen concentration was chosen as 0.6 mg/ℓ (Winter, 2016) and the ammonia-nitrogen concentration was chosen as 2 mg/ℓ (Debo & Reese, 2003) (Table 3-7). The mixture was prepared in the water quality lab prior to application (Appendix A).

Table 3-7: Pollutant concentrations for Phase 2

Nutrient	Concentration mg/ℓ
Ammonia-nitrogen	2
Orthophosphate-phosphorus	0.8
Nitrogen	0.6

3.7.4 Rainfall regime

Previous studies (Davis *et al*., 2010) have shown that the drying and wetting cycle affects the nutrient removal efficiency of stormwater biofilters. An attempt was thus made in Phase 2 to at least partially mimic 'typical' Cape Town rainfall conditions in the laboratory for the tests. Biggs (2016) had collected rainfall data from Cape Town International Airport on the basis that this was a readily accessible daily rainfall database extending for more than 40 years that was reasonably representative of the majority of the city being sourced close to the centre of the metropolis. Biggs (2016) found the mean annual rainfall at this site for 2002 was 522.5 mm which equates to 98% of the mean annual rainfall of 531.4 mm for the years 1960 to 2002 so 2002 was selected for the laboratory rainfall regime. Most rain in Cape Town falls between May and August, the laboratory testing was thus modelled on this period only as constituting the effective 'rainy season'.

Drake *et al*. (2013b) and Pratt *et al*. (1989) found that PICPs do not generally produce any discharge for rainfall events of less than 5 mm when preceded by dry antecedent conditions. The decision was made to focus only on daily rainfall exceeding 5 mm from May-August 2002 as input into the proposed rainfall schedule for the laboratory testing. Table 3-8 presents the rainfall data from May to August in 2002 collected from the Cape Town International Airport rain gauge.

In order to accelerate the testing to a more acceptable time-frame, the decision was made to compress the 4-months of rainy season (123 days) into a third of the time (41 days) by adding the rainfall depths over a three-day period and applying this on the experimental cells once per day. Whenever the three-day rainfall depth was less than 5 mm, it was considered as dry period and no water was sprayed onto the cells. The daily rainfall volumes were then determined by multiplying the three-day depth by the surface area of each cell (1.32 m^2). The final rainfall schedule for the testing is presented in Table 3-9. There were 19 'rainy' days in total.

3.7.5 Preparation of the revised synthetic stormwater

The revised synthetic stormwater mix was made from a mixture of ammonium chloride, di-potassium hydrogen the orthophosphate-phosphorus and potassium nitrate-nitrogen respectively. The sample calculation for the phosphorous is shown in Appendix A.

In Phase 1, the fertilizer was mixed in a watering can immediately prior to be poured onto one of the PICP cells. For Phase 2, the mixing of the chemicals was carried out in a 2 ℓ volumetric flask prior to being added to a pre-determined volume of tap water in a 500 ℓ storage tank.

Table 3-8: Rainfall (mm) at Cape Town International Airport for 2002
(1stWeather.com, 2002)

Day of Month	May	June	July	August
1	0	0	0	4.2
2	1.6	0	0	3.6
3	0	0	0	0.2
4	4.4	0	0	0
5	11.8	10.8	0	0.2
6	1.6	0	0	0
7	0	14.3	2	0
8	0	0	13.8	0
9	0	0.2	0	0
10	0	0	0	0
11	0	0	0	7.5
12	0	1	0	5.6
13	0.2	4.9	0.2	2
14	0	0	12.6	0
15	0	6.2	7.5	0
16	1.4	0	0.5	0
17	0	2	0	0
18	0	3	0	0
19	0	0	0	0
20	0	0	0	0
21	0	0	0	0
22	17.4	1	0.2	4.5
23	1.4	0.4	26	1
24	2.8	0	2	0
25	7.6	0	0	0
26	0	11	8.6	0
27	0	8.8	1.8	0
28	7.6	7.9	18.4	0
29	2.4	4.9	3.6	34
30	0	0	1	2.9
31	11.7	0	0	0
Total	71.9	76.4	98.2	65.7

Table 3-9: August – September 2019 rainfall test schedule

(The numbers in bold indicate the day of the month whilst the numbers in brackets give the rainfall volume (ℓ) applied to each PPS cell. Pollutant test days are indicated by red numbers)

August						
S	**M**	**T**	**W**	**T**	**F**	**S**
				1	**2**	**3**
4	**5** (0)	**6** (23)	**7** (0)	**8** (0)	**9** (0)	**10** (0)
11 (0)	**12** (28)	**13** (10)	**14** (13)	**15** (15)	**16** (14)	**17** (33)
18 (0)	**19** (7)	**20** (10)	**21** (0)	**22** (0)	**23** (14)	**24** (28)
September						
1 (0)	**2** (37)	**3** (38)	**4** (0)	**5** (10)	**6** (0)	**7** (0)
8 (17)	**9** (0)	**10** (0)	**11** (0)	**12** (7)	**13** (0)	**14** (40)

3.7.6 Synthetic stormwater application method

Rain has many characteristics including intensity, volume, drop size, spatial uniformity, velocity and duration (Bateni *et al*., 2018). In the laboratory, it is common to use a rainfall simulator in an attempt to duplicate the characteristics of natural rainfall with the additional advantages that: it can be produced rapidly on demand, the variability is under the control of the experimenter, and data collection is rapid (Askoy *et al*., 2012). On the other hand, Marchioni *et al*., (2016) conducted a laboratory study to analyze the impact of the rainfall intensity on the sediment dynamics on pervious pavements and they found that changes in rainfall intensity do not have a significant impact on discharge in PP systems. The easiest, cheapest, and most accurate – from a volume point of view – is to use a watering can as the rainfall simulator. Therefore, the cells were manually watered with a 10 ℓ watering can. During each simulated rainfall event, care was taken to ensure that the 'rain' was spread as uniformly as possible onto each surface – ensuring that each cell received the same volume. The full procedure for rainfall application was:

i) Fill a 500 ℓ water tank (Figure 3-29) with the requisite amount of tap water for the specific rainfall event being modelled

ii) Prepare 2ℓ of the standard pollutant solution with the concentrated selected soluble pollutants in the water quality lab

iii) Pour the prepared standard solution into the water tank and stir continuously until fully mixed

iv) Determine the exact amount of water required per application using a scale to measure the mass of liquid after subtraction of the weight of the 10 ℓ watering can

v) Distribute the synthetic rain over the test cell using the 10 ℓ watering can

vi) Repeat until each test cell has received the correct amount of rain for the day

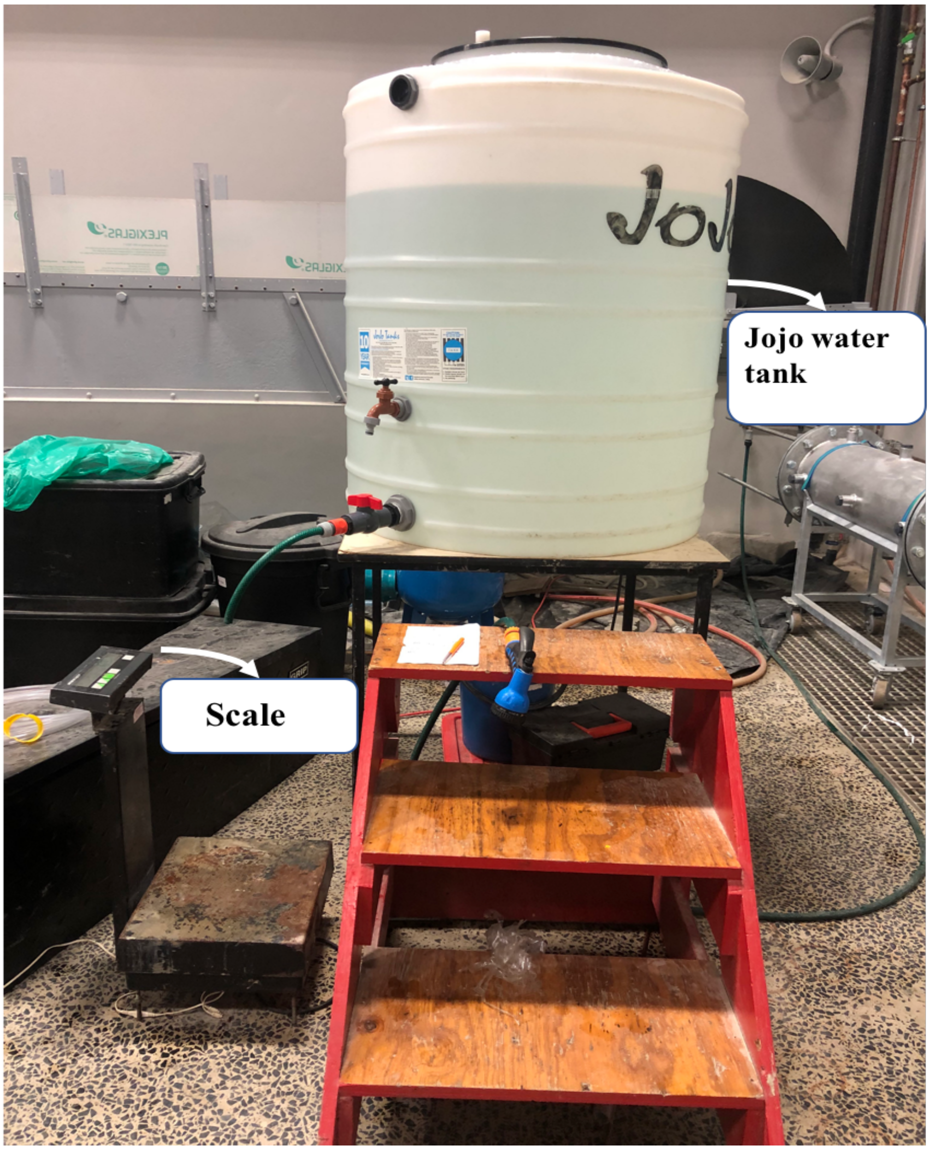


Figure 3-29: 500 ℓ water tank and scale for measuring the mass of the liquid in the 10 ℓ watering can (not shown)

3.8 Experimental laboratory sampling

Manual grab samples were taken to test for pollutant concentrations throughout the lab experiments. For the clean water testing, ten samples of effluent were collected from the bottom of the cell (samples from the old eight PICP cells, Cell A – Cell H, were collected and tested in August 2017 and samples from the two new PICP cells, Cell I & Cell J, were collected and tested in September 2018 for pH, temperature, EC, ammonia-nitrogen, the orthophosphate-phosphorus, nitrite-nitrogen and nitrate-nitrogen (Dookhit, 2018).

3.8.1 pH, temperature and EC

The pH, temperature, and EC were measured by using the OHAUS® hand-held pen meters which was inserted into the samples collected from the model, and the OHAUS® ST20 pH-temperature probe and the OHAUS® ST20 C-B EC-temperature probe were calibrated before use. The readings from the probes was manually recorded.

Figure 3-30: Probes measuring pH and EC

3.8.2 Total suspended solids (TSS)

The test method for measuring TSS follows the USEPA Method 160.2: Total Suspended Solids (TSS) (US EPA, 1999) . The filter paper was first put into the 105°C oven to dry for half an hour before being weighed. 50 mℓ of sample solution was then filtered through the paper using a vacuum filtration machine to speed up the filtration process. Once all the solution had passed through the filter paper, the paper was placed in a crucible and dried at 105°C for more than 12 hours. The dried filter paper was then taken out, cooled in a desiccator and weighed. The difference between the weight of the paper before and after drying is the weight of the TSS. The method is illustrated in Figure 3-31. The filtrate was collected in the plastic container and used for testing the soluble pollutant concentrations (ammonia-nitrogen, the orthophosphate-phosphorus, nitrite-nitrogen and nitrate-nitrogen).

3.8.3 Ammonia-nitrogen, Nitrate-nitrogen, Nitrite-nitrogen and Orthophosphate-phosphorus

The ammonia-nitrogen, nitrate-nitrogen, nitrite-nitrogen, and the orthophosphate-phosphorus tests were all carried out in the Civil Engineering Water Quality Lab. Samples collected from the PPS cells were filtered prior to testing. If the samples were not to be tested immediately, they were stored in a fridge (3°C to 5°C) to minimise bacterial activity and phytoplankton growth. The Thermo Scientific™ Gallery™ Discrete Analyzer was used to analyse the afrorementioned nutrients through an automated photometric (colorimetric and enzymatic) analysis (Figure 3-33) (Thermo Scientific™, n.d).

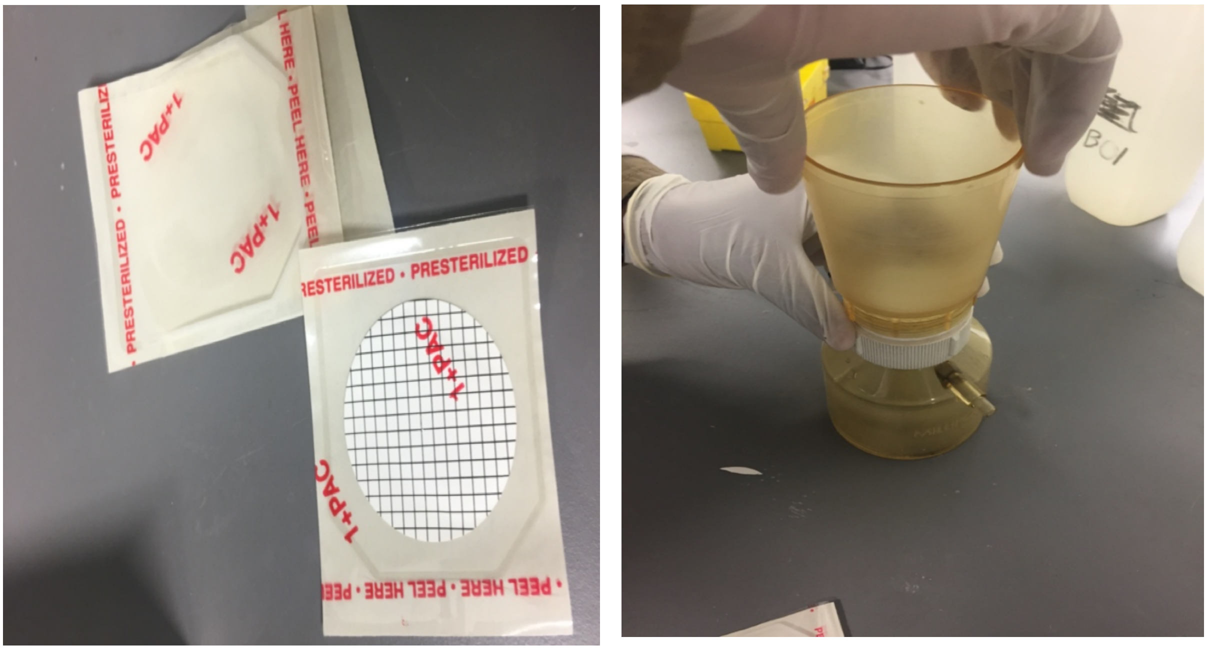


Figure 3-31: TSS measuring technique: Filter paper (left) and Buchner funnel (right)

Figure 3-32: Dry the filter paper in the over at 105 °C (left) and weighing the mass of the filter paper (right)

Figure 3-33: Water quality testing for the selected pollutants: filtered samples (left) and the Thermo Scientific^{TM} Gallery^{TM} Discrete Analyzer (right)

3.8.4 Number of samples tested for the selected pollutants

Over the course of the three rounds of tests in synthetic stormwater: Phase 1, 40 influent and 180 effluent samples were collected and tested for pH, temperature and EC using the OHAUS® hand-held pen meters.

Table 3-10: Number of samples tested for the selected pollutants

Date	Clean water test	Synthetic stormwater test	
		Phase 1	Phase 2
05/10/2017 – 13/10/2017	8	26	0
25/09/2018 – 03/10/2018	2	8	0
07/03/2018 – 15/03/2018	0	32	0
05/08/2019 – 14/09/2019	0	0	55

Table 3-11: Number of samples tested for pH, Temperature and EC

Date	Clean water test	Synthetic stormwater test	
		Phase 1	Phase 2
05/10/2017 – 13/10/2017	8	99	0
25/09/2018 – 03/10/2018	2	27	0
07/03/2018 – 15/03/2018	0	109	0
05/08/2019 – 14/09/2019	0	0	209

For synthetic stormwater Phase 2, 55 samples were collected and tested for ammonia-nitrogen, the orthophosphate-phosphorus, nitrite-nitrogen, and nitrate-nitrogen, and 209 samples were tested for pH, temperature, and EC (Table 3-10 and Table 3-11).

3.9 NEB parking lot

As laboratory investigations are limited, field testing was thus needed to confirm the true treatment performance of permeable pavement systems. This section outlines the tests carried out on the New Engineering Building (NEB) parking lot at the University of Cape Town (UCT).

3.9.1 NEB parking lot site description

The New Engineering Building (NEB) parking lot is located at the upper campus of the University of Cape Town, South Africa. PPS were used with the aim of reducing stormwater runoff coming from the NEB roof area as well as to attenuate peak flows. The pavement layer works used in NEB parking are shown in Figure 3-34.

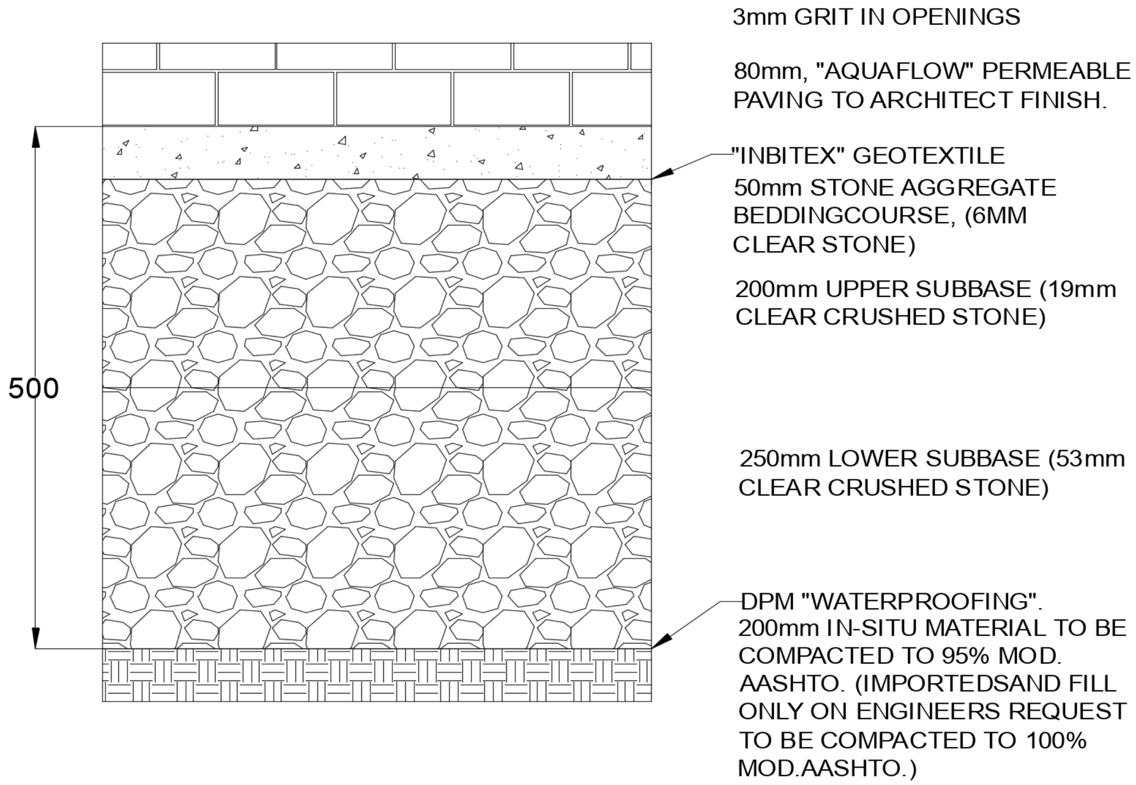


Figure 3-34: NEB permeable pavement layer works
(Adapted from Biggs, 2016)

The NEB parking area was constructed at the end of 2014 and is divided into three separate sections by ground beams as shown in Figure 3-35. The three separate sections were necessary due to the slope of the site and provided an opportunity to form a test site suitable for long-term monitoring of the PICP. The PICP is bordered by two steep embankments, with a garden located on the uphill embankment and held back by the curbs (Schieritz, 2016). The first section (NEB-I) of the pavement includes a non-permeable pavement area that was sealed off to provide surface runoff for comparison with the drainage from the other two permeable pavement areas. The second section (NEB-B) is a normal PPS installation with Inbitex geotextile installed between the bedding material and the sub-grade. The third section (NEB-A) uses the same design as the second section, but without the presence of the geotextile. In addition, four monitoring chambers were installed to allow for the installation of the equipment to monitor the quantity and quality of drainage from each of PPS section.

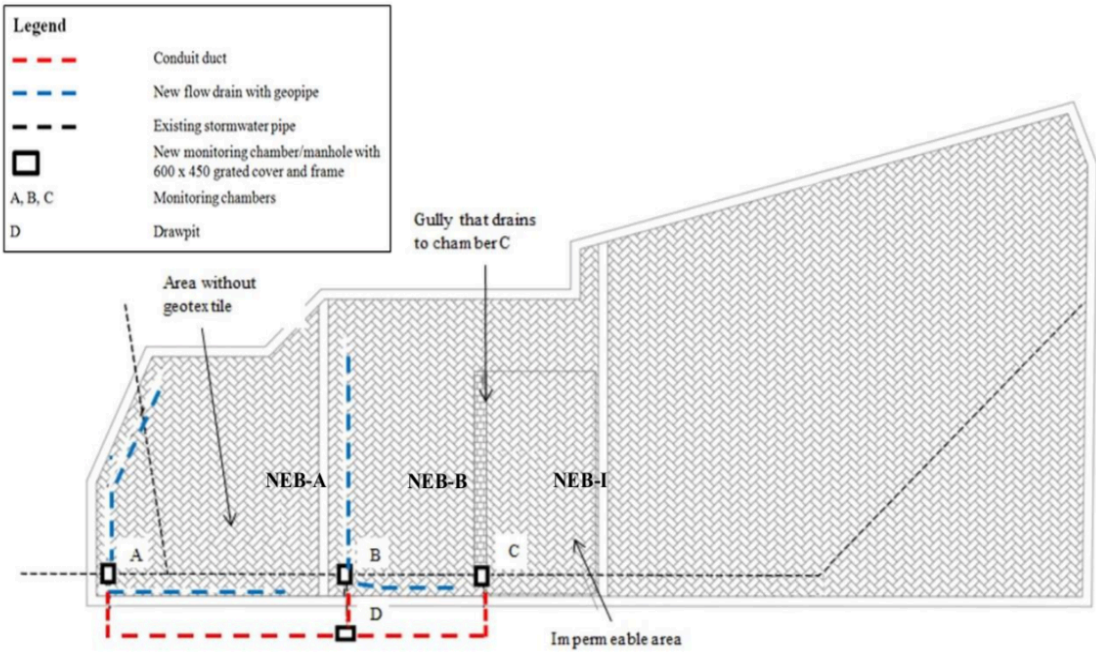


Figure 3-35: NEB site (Biggs, 2016)

3.9.2 Previous research and monitoring measures

Schieritz (2016) set up the monitoring equipment in each monitoring chamber at the NEB parking lot. A 90 degree V-Notch weir box were designed in the monitoring chambers A and B to provide sufficient head height for the peristaltic pumps of the samplers to operate as well as to serve as a flow measurement device (Biggs, 2016). An Isco^{TM} 6712 autosampler with a sequential setup consisting of 24 500ml HDPE bottles was placed in the monitoring chamber B, and was programmed to take samples of 480 ml at an hour intervals, and an ISCO GLS composite sampler which was programmed to take samples of 150ml at 30 minutes interval was placed in the monitoring chamber A. A sequential automatic sampler consisted of self-sealing 500ml PET bottles joined with agricultural piping was used to collect the surface runoff from the NEB-I section.

Schieritz (2016) investigated the treatment efficacy of different permeable pavement sections in 2015, and found the TSS concentration in the effluent from the PPS met the standards required for irrigation and industrial uses, however, the nutrient concentration in the effluent did not meet the desirable nutrient standards for discharge into the aquatic ecosystem.

3.9.3 Research method

To test the treatment efficacy of the NEB PICP in the long-term and compare the impact of geotextile, five samples were collected from each of the PPS section's monitoring chamber from

2018 to 2019 after four major storm events (Table 3-13). The pH, temperature and EC were immediately tested on the collected samples by using the electrical probes, and the samples were then sent to the water quality lab in NEB to analyse the TSS, nitrate-nitrogen, nitrite-nitrogen, ammonia-nitrogen and the orthophosphate-phosphorus concentration.

An ice-cream container was used to collect the surface runoff from NEB-I with the non-permeable pavement area. Figure 3-36 shows the container that was tied with the inlet grate to capture the surface runoff, and Figure 3-37 shows a sampling apparatus with a bottle attached to the end of the stick to collect the exfiltrate from the monitoring chamber in NEB-A and NEB-B section.

Figure 3-36: Installing simple container to collect the surface runoff

Figure 3-37: Using a simple experiment (bottle attached with stick) to collect water from the monitoring chamber

Table 3-12: Date of samples collection

Date of Collection
26th August 2018
30th July 2019
11th August 2019
31st August 2019
15th September 2019

3.10 Summary of the research method

The summary of the above method is as follows:

- There were eight PICP experimental cells housing different test structures at the commencement of this research, with two new PICP experimental cells being added to the experimental set-up for further comparison;
- An infiltration test was performed on all ten PICP cells to determine the infiltration rate of each PICP cell using the *ASTM C1781* standard (The old eight PICP cells were tested in 2017, and the two new PICP cells were tested in 2018) (ASTM, 2013);
- Clean tap water was then applied to each cell in quantities of 20 litres a time to establish a base-line pollutant value. Ten effluent samples (eight samples from 2017 and two samples from 2018) were collected and analysed individually for pH, temperature EC, TSS and concentrations of selected pollutants (ammonia-nitrogen, the orthophosphate-phosphorus, nitrite-nitrogen, and nitrate-nitrogen)
- The impact of different designs of PICP: different types of pavers, the presence or absence of geotextile, the use of washed and unwashed aggregates and the incorporation of a permanently wet zone in PICP on the treatment of various nutrients were investigated by way of the following activities, in two different phases:
    - i) Phase 1: Synthetic stormwater application. Three rainfall 'seasons' were simulated from 2017 to 2019 using tap water mixing with 'Growing Orchid' fertilizer. 66 samples were collected and tested for the selected pollutants (ammonia-nitrogen, the orthophosphate-phosphorus, nitrite-nitrogen, and nitrate-nitrogen), and 235 samples were tested for pH, temperature, and EC.
    - ii) Phase 2: Improved synthetic stormwater application. Synthetic stormwater was produced in the laboratory by adding NH_4Cl, $K_2H_2PO_4$, and KNO_3 to tap water instead of using the fertilizer in Phase 2. A new rainfall regime was used with intermittent dry and wet periods to represent the four months of the 'typical' Cape Town rainy season in an accelerated 1.5 months (41 days). 55 samples were collected and tested for the selected pollutants (ammonia-nitrogen, the

orthophosphate-phosphorus, nitrite-nitrogen, and nitrate-nitrogen), and 209 samples were tested for pH, temperature, and EC.

iii) NEB parking lot: Five samples were collected from each of the PICP section's monitoring chambers at the NEB parking lot from 2018 to 2019 after major storm events. Each sample was tested for the selected pollutants (ammonia-nitrogen, the orthophosphate-phosphorus, nitrite-nitrogen, and nitrate-nitrogen), as well as pH, temperature, and EC.

4. Results and Discussion

This chapter details the results and analysis for the comparative study on the nutrient removal capabilities of the ten PPS experimental cells following the research method detailed in Chapter 3. It is divided into five sections corresponding to: The infiltration test, The clean water test, Phase 1: synthetic stormwater application, Phase 2: improved synthetic stormwater application, and the NEB testing respectively. The purpose of the infiltration test was to determine the maximum clean water rate of each cell prior to any blockage. The purpose of the clean water test was to provide base-line effluent pollutant levels prior to the addition of synthetic stormwater. The purpose of the synthetic stormwater tests was to determine the treatment efficacy of the different PICP types by the application of multiple 'seasons' of accelerated rainfall events using pre-prepared synthetic stormwater containing suitable soluble pollutants. The purpose of the NEB testing was to verify the results from lab experiment through a field study. The results of the testing for the effluent concentrations of TSS, ammonia-nitrogen, the orthophosphate-phosphorus, nitrite-nitrogen and nitrate-nitrogen are presented, and the pollutant reduction determined. Additional information was provided by measurements of pH, temperature and EC.

4.1 Infiltration test results

The method used to estimate the infiltration rate is described in Section 3.5. A summary of the measurements is presented in Appendix B. Table 4-1 summarise the key values for all ten PPS experimental cells.

The infiltration rates for all ten experimental cells were uniformly high – ranging between 9,900 and 17,600 mm/h with Cell F (Aquapave®, Inbitex geotextile, washed stones, base outlet) having the lowest infiltration rate and Cell I (Exposed pavers, Fibertex® geotextile, washed stones, base outlet) the highest. The infiltration rates associated with the different types of pavers are presented in Figure 4-1. The cells with exposed aggregate pavers have the highest average infiltration rate (Cell I and J with average infiltration rate of 16,100 mm/h), followed by the Permealock® pavers (Cell B, C, D, E, F, G and H with average infiltration rate of 13,800 mm/h) and finally the Aquapave® pavers with the lowest (Cell A and F with average infiltration rate of 10,800 mm/h). The most likely reason for this difference is because the exposed aggregate pavers have the biggest openings while the Aquapave® pavers have the smallest. Comparing the infiltration rates between different PICP design suggests that the presence of a geotextile lowers the infiltration rate – although it seems that Kaytech bidim® geotextile allows a higher infiltration rate than the Fibertex® geotextile. This is probably due to the larger pore size and permeability of the Kaytech bidim® geotextile.

Table 4-1:Infiltration Test Results

Experimental Cells	Time elapsed (s)	Weight of infiltrated water (kg)	Infiltration rate (mm/h)
A	78.4	18.02	11,700
B	59.2	18.01	15,500
C	60.3	18.01	15,200
D	57.2	18.01	16,000
E	66.5	18.01	13,800
F	92.4	18.01	9,900
G	88.2	18.01	10,400
H	78.8	18.01	11,600
I	66.5	18.00	17,600
J	63.0	18.00	14,600

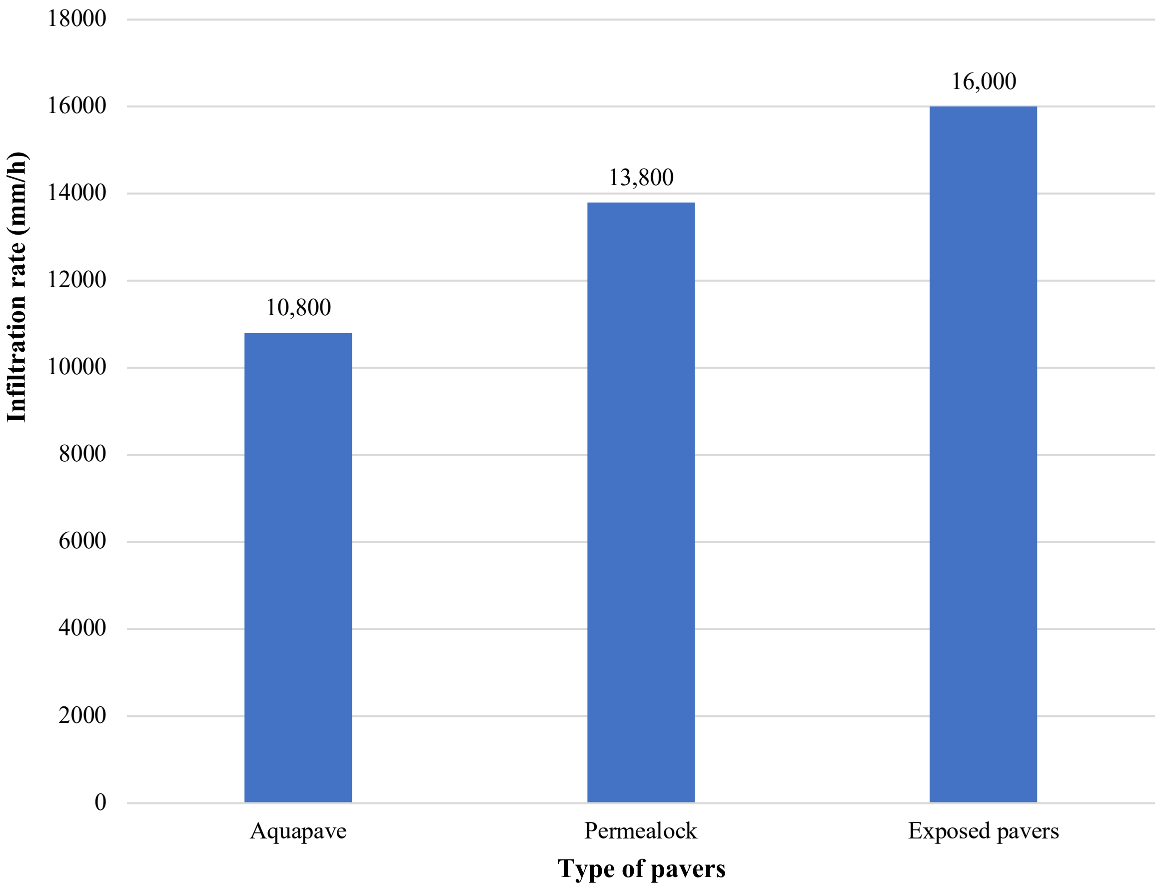


Figure 4-1: Infiltration rate between types of pavers

4.2 Clean water test

The clean water test was to provide base-line pollutant levels before the addition of the synthetic stormwater (Section 3.6). Ten samples (one sample from each PPS cell) were collected and pH, temperature, EC, ammonia-nitrogen, the orthophosphate-phosphorus, nitrite-nitrogen and nitrate-nitrogen were tested for each sample. Biggs (2016) found that the use of unwashed aggregates can introduce significant quantities of polluted pavement effluents, and these results were therefore used to determine whether or not the aggregates from the PICP structure were polluting the water rather than cleaning it. These results were then used to assess the severity of the effluent's pollutant concentration owing to PICP materials and the associated risk to the CoCT riverine system (Biggs, 2016).

Nel *et al.*(2013) derived values for various categories of ecosystem health criteria from the South African Water Quality Guidelines (DWAF, 1996) and the Ecological Reserve Water Quality Benchmarks (Jooste & Rossouw, 2002) (Table 4-2), and this was used as the reference to assess whether the quality of the flushed effluent emanating from the PICP would pose a risk to the ecosystem.

4.2.1 Electrical Conductivity (EC)

The electrical conductivity (EC) is a measurement of the ease with which water conducts electricity and is used as an indicator of the salinity of the water (DWA, 2012). The approximate relationship between Total Dissolved Solids (TDS) and EC is around 6.5:1 – depending on the ions present and the temperature.

Figure 4-2 shows the EC measurements of the single sample collected from each of the 10 experimental cells after the application of the clean tap water. The EC of the 10 PICP cells varied between 261 and 579 μS/cm, whilst the tap water had a EC of 135 μS/cm. It was found that the EC measurements from all the PICP cells were higher than the EC of the tap water, suggesting that the PICP added total dissolved solids presumably from the aggregates. Table 4-3 compares the EC measurements obtained from the clean water test. They indicate that the impact of geotextile on EC is inconclusive; the use of washed stones resulted in a higher EC than the use of unwashed stones, and the use of raised outlet resulted in the highest EC which is probably due to the presence of anaerobic zone introducing more ions such as nitrate-nitrogen and orthophosphate-phosphorus through biological processes. Due to the limited testing data, further investigations need to be conducted to determine the impact of geotextile on EC and how the use of washed aggregates introduced higher EC.

Table 4-2: Ecosystem health criteria: categories

(Adapted from Nel *et al*., 2013)

Variable	Units	Natural	Good	Fair	Poor	Unacceptable	Comments
Temperature*#	°C	Depends on background (Upper boundary = 90th percentile; Lower boundary = 10th percentile); Good ±2°C; Fair ±4°C; Poor > ±4°C					Need to determine typical background water quality – not essential for prioritisation exercise
Total suspended solids*#	mg/l	Depends on background (Not more than 10% higher than background)					Need to determine typical background water quality – not essential for prioritisation exercise
Conductivity (EC)*#	mS/m	Depends on background (not more than 15% different from normal cycles)					Need to determine typical background water quality – not essential for prioritisation exercise
pH*	units	8–6.5	9–8 or 6.5–7.5	10–9 or 5.75–5	>10; <5		Need to determine typical background water quality – not essential for prioritisation exercise
Dissolved oxygen*	mg/l	>8	8–6	6–4	4–2	<2	Also dependent on background DO levels to some extent. No unacceptable range given but if one selects equal bands then 2 mg/l is the next logical band and is applicable to assessing the actual data.
Soluble reactive phosphorus*	mg/l	<0.005	0.005–0.025	0.025–0.125	0.125–0.250	>0.250	Ranges as recommended in the latest water quality benchmarks for the ecological reserve (DWAF 2005)
Total inorganic nitrogen*	mg/l	>0.25	0.25–1	1–4	4–10	>10	
Ammmonia (NH_3-N)*	mg/l	>0.015	0.015–0.058	0.058–0.1	0.1–0.2	>0.2	No unacceptable range given but if one selects equal bands then 0.2 mg/l is the next logical band and is applicable to assessing the actual data
Blue-green algae toxins (microcystins)	µg/l/	<10		10–50	>50		Range as recommended in the World Health Organisation (WHO) guidelines
Algae (Chl-a)*	µg/l/	<10	10–20	20–30	30–40	>40	No unacceptable le 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 1996)

* Ecological reserve water quality benchmarks (Jooste & Rossouw 2002)

® World health Organisation Recreational Guidelines (2003)

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

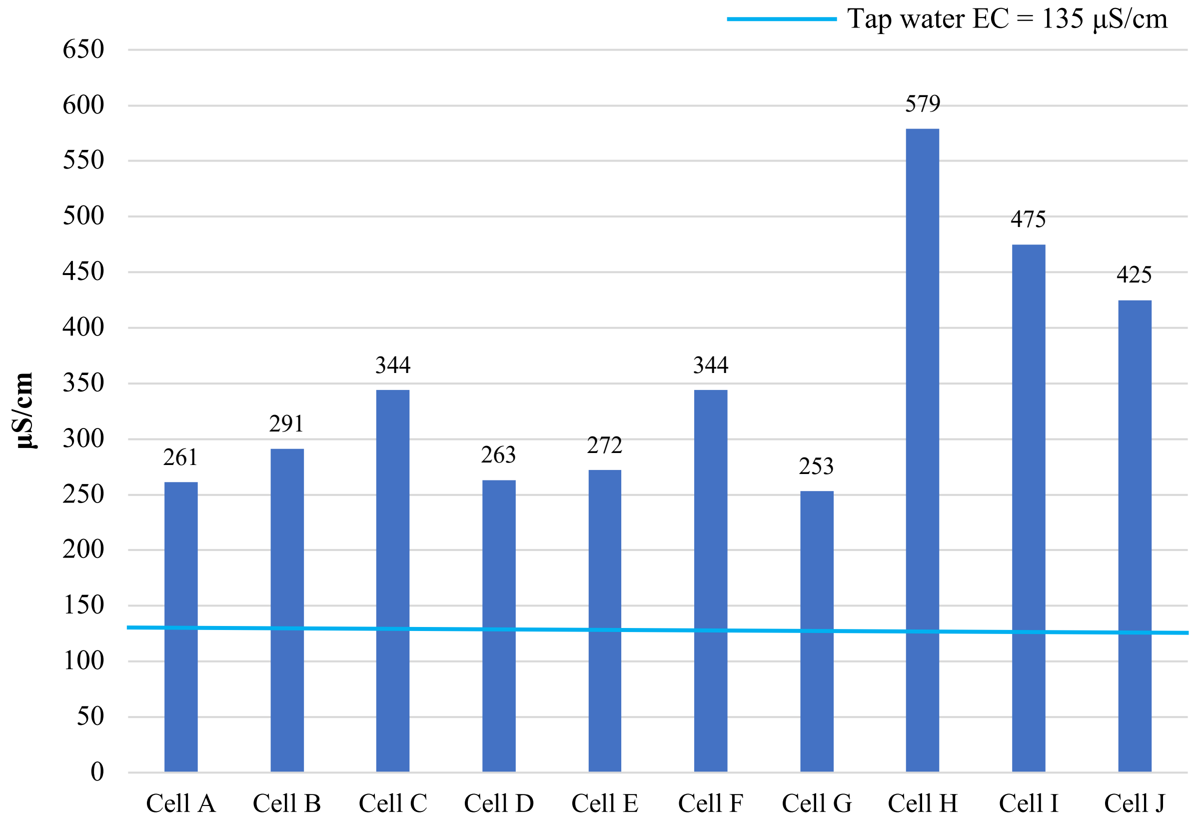


Figure 4-2: EC measured in the clean water test

Table 4-3: Comparison of the EC measurements for the clean water test

Range of EC from Cell A to Cell J	261 to 579 µS/cm			
EC of tap water	135 µS/cm			
Impact of geotextile	Compare A and F (Aquaflow®)	Compare C, D and E (Permealock®)	Compare B and G (Permealock®)	Compare I and J (Exposed pavers)
	EC from Cell F (Inbitex® geotextile) > EC from Cell A (no geotextile)	EC from Cell C (Fibertex® geotextile) > EC from Cell E (no geotextile) > EC from Cell D (Kaytech bidim® geotextile	EC from Cell B (Fibertex® geotextile) > EC from Cell G (no geotextile)	EC from Cell I (Fibertex® geotextile) > EC from Cell J (no geotextile)
	The impact of geotextile on EC was inconclusive			
Impact of raised outlet (submerged zone)	EC from Cell H (raised outlet) > EC from Cell B (base outlet)			
	Presence of submerged zone (raised outlet) resulted in higher EC			
Impact of unwashed aggregates	EC from Cell C (washed stones) >EC from Cell B (unwashed stones)			
	The used of unwashed aggregates resulted in lower EC			

4.2.2 pH

pH is used as an indicator to check the acidity or alkalinity of the water. The pH of water does not generally have direct consequences on the use except at extreme values (DWA, 1996). In the context of PICP, the adverse impact of pH is likely from the solubilisation of toxic heavy metals and the protonation or deprotonation of other ions (DWA, 1996).

Figure 4-3 shows the pH of the single sample collected from each of the 10 experimental cells. It ranges from 7.9 to 8.8, compared with the pH of the tap water of 8.1. The pH of the most PICP cells (except for Cell F (Aquapave®, Inbitex geotextile, washed stones, base outlet) and Cell H (Permealock, Fibertex® geotextile, unwashed stones, raised outlet) was higher than the pH of the tap water. This corresponds to the findings that PPS can buffer acidic pH (Collins *et al.*, 2008). The result shows Cell H with the raised outlet has the lowest pH.

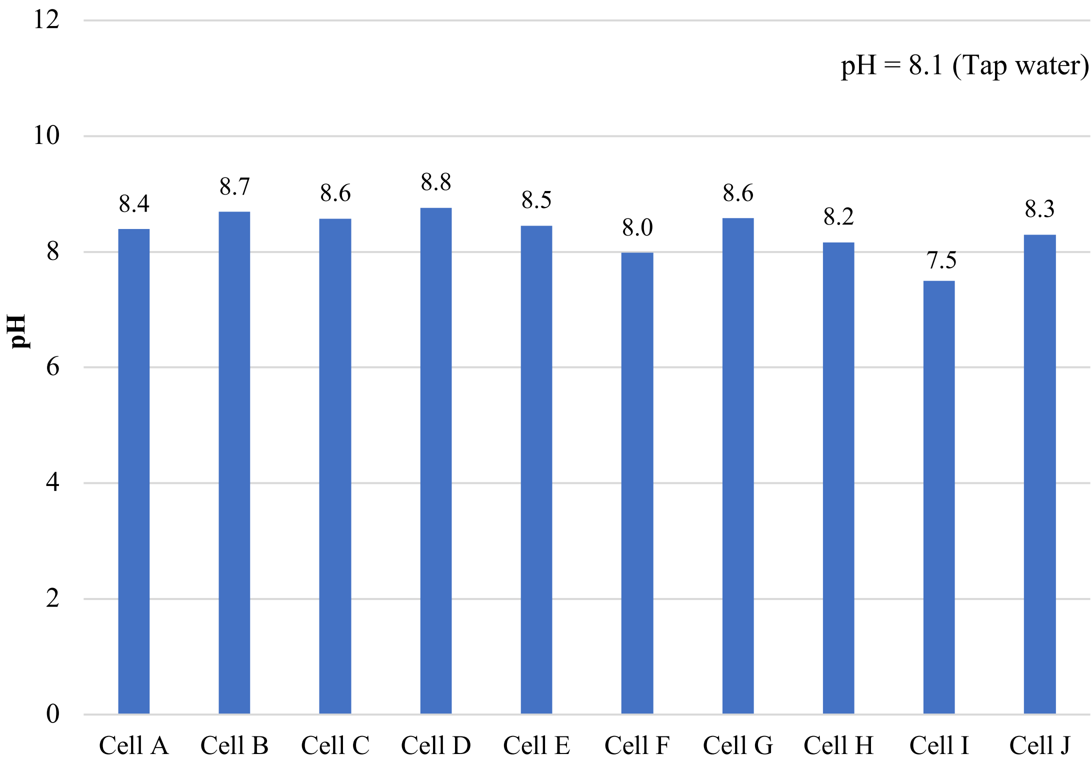


Figure 4-3: pH measured in the clean water test

4.2.3 Ammonia-nitrogen

Ammonia-nitrogen (NH_3) provides an essential link in the nitrogen cycle, and it is the reduced form of inorganic nitrogen derived mostly from aerobic and anaerobic decomposition of organic material (DWA, 1996). The toxicity of ammonia-nitrogen is directly linked to the concentration of the un-ionized form (NH_3), and the toxicity of un-ionized ammonia-nitrogen is affected by water temperature and pH. DWA (1996) states that an increase in either water temperature or pH would result in an increase in toxicity of ammonia-nitrogen to aquatic organisms.

Figure 4-4 shows the ammonia-nitrogen effluent concentrations measured in the single samples collected from each of the 10 experimental cells. The effluent concentrations of ammonia-nitrogen ranges from 0.01 mg/ℓ to 0.26 mg/ℓ, compared with the ammonia-nitrogen concentration of the tap water of 0.01 mg/ℓ. This shows the PICP cells added ammonia-nitrogen to the effluent through the clean water test, presumably from the aggregate. It was found that the cells without a geotextile had higher ammonia-nitrogen effluent concentrations than the cells with geotextile, and the cells with the unwashed aggregates had higher ammonia-nitrogen effluent concentrations than the cells with washed aggregates. However, the number of samples were limited and this needs to be confirmed.

Table 4-2 was used as the reference to assess whether the quality of the ammonia-nitrogen effluent concentrations emanating from the PICP would pose risk to the ecosystem. It was found that the ammonia-nitrogen effluent concentrations from Cell A (Aquapave®, no geotextile, washed stones, base outlet) & Cell G (Permealock®, no geotextile, unwashed stones, base outlet) falls within the category of unacceptable which may due to the absence of geotextile in these two cells. It was also noted that the majority of the cells falls within the category of poor (ammonia-nitrogen concentration between 0.1 – 0.2 mg/ℓ), and this indicates the quality of ammonia-nitrogen effluent concentrations from the PICP would pose a risk to the ecosystem.

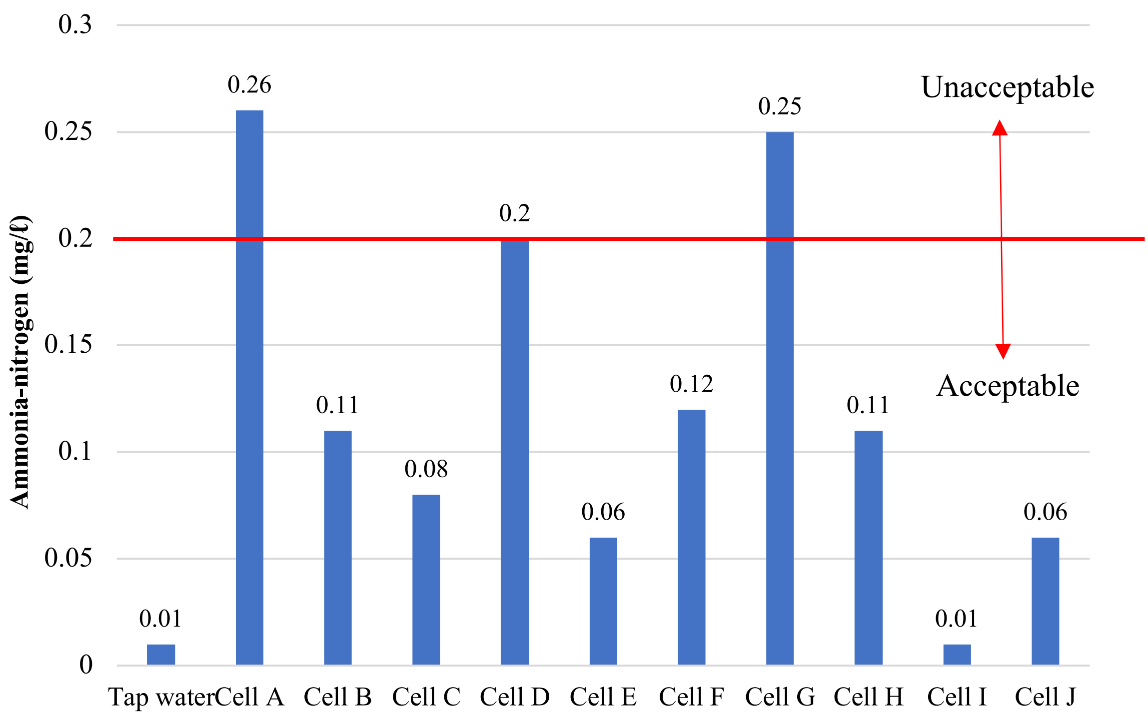


Figure 4-4: Effluent concentrations of ammonia-nitrogen measured in the clean water test

4.2.4 Orthophosphate-phosphorus

Phosphorous concentrations may be presented as orthophosphate-phosphorus, total inorganic phosphate or total dissolved phosphorous. In this research, orthophosphate-phosphorus was measured. Phosphorus is considered to be the principal nutrient causing eutrophication in aquatic ecosystems. It may be present in both point source discharge (domestic and industrial effluents) and non-point sources (surface and subsurface drainage, urban runoff, atmospheric precipitation, and drainage from agricultural land) (DWF, 1996).

Figure 4-5 shows the orthophosphate-phosphorus effluent concentrations from the single sample collected from each of the 10 experimental cells. The effluent concentrations of orthophosphate-phosphorus from all 10 experimental cells ranges from 0.19 mg/ℓ to 1.05 mg/ℓ, whilst the orthophosphate-phosphorus concentration of the tap water is 0 mg/ℓ. This shows the PICP cells added orthophosphate-phosphorus to the effluent, and this added orthophosphate-phosphorus most likely come from the aggregate as orthophosphate-phosphorus adsorbed to the sediments is flushed out. It was found that the Cell H (Permealock, Fibertex® geotextile, unwashed stones, raised outlet)) with the submerged zone had the highest orthophosphate-phosphorus effluent concentration. This can be explained by assuming that P is adsorbed to sediments within the submerged saturated zone and then released under suboxic condition (a condition between oxic condition and anoxic condition). Again, due the limited sample size, further investigation is needed and will be discussed more in detail in Section 4.4.4.

The orthophosphate-phosphorus results were compared with the 'acceptable' stormwater quality values as given by Nel *et al*. (2013) (Table 4-2). It suggests that orthophosphate-phosphorus becomes unacceptable when the concentration exceeds 0.25 mg/ℓ, and orthophosphate-phosphorus effluent concentrations from most of the 10 experimental cells fall within the unacceptable category except for Cell D (Permealock, Kaytech bidim® geotextile, washed stones, base outlet) & Cell I (Exposed pavers, Fibertex® geotextile, washed stones, base outlet).

4.2.5 Nitrite-nitrogen

Nitrite-nitrogen (NO_2^-) is the inorganic intermediate form of the oxidation or organic nitrogen and ammonia-nitrogen (DWA, 1996). It is rapidly oxidized to nitrate-nitrogen by nitrifying bacteria under aerobic conditions, whilst nitrate-nitrogen can be rapidly reduced to nitrite-nitrogen by denitrifying bacteria under anaerobic conditions.

It was found that the nitrite-nitrogen effluent concentrations from the single sample collected from each of the 10 experimental cells were all low, ranging from 0.01 mg/ℓ to 0.02 mg/ℓ. This is probably because most of the nitrite has been oxidized to nitrate which results in very little nitrite.

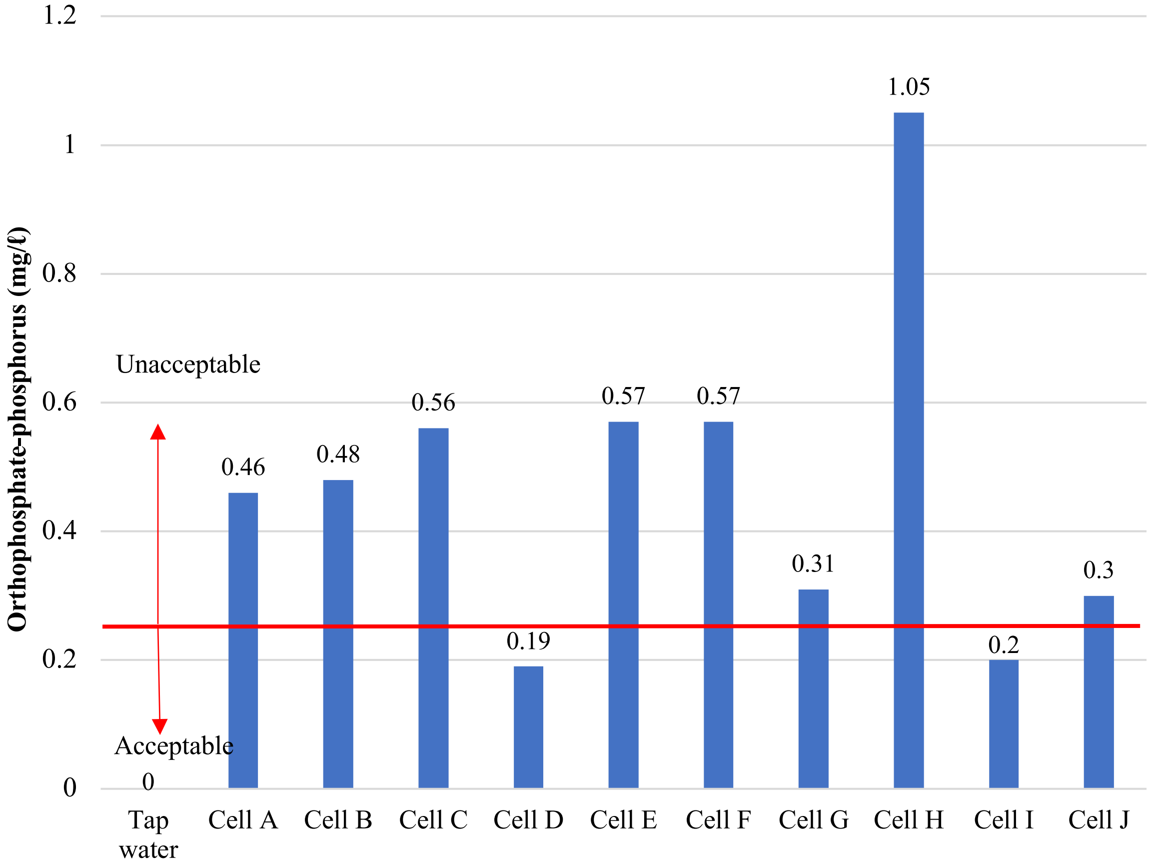


Figure 4-5: Effluent concentrations of orthophosphate-phosphorus measured in the clean water test

4.2.6 Nitrate-nitrogen

Nitrate-nitrogen (NO_3^-) is the end product of the oxidation of organic nitrogen and ammonia-nitrogen. The presence of nitrite-nitrogen and nitrate-nitrogen is generally considered an indication of contamination from human activities in the catchment.

Figure 4-6 shows the nitrate-nitrogen effluent concentrations from the single sample collected from each of the 10 experimental cells. The effluent concentrations of nitrate-nitrogen from all 10 experimental cells ranged from 0.3 mg/ℓ to 34.1 mg/ℓ compared with the nitrate-nitrogen concentration of the tap water of 0 mg/ℓ. This shows that the PICP cells added significant amounts of nitrate-nitrogen to the effluent, presumably from the insufficient washed aggregates as nitrate-nitrogen can be adsorbed onto suspended material. It was found that the Cell H (Permealock, Fibertex® geotextile, unwashed stones, raised outlet) with the submerged zone had the highest nitrate effluent concentration which might be because the submerged zone creates optima conditions for nitrification. Again, due the limited sample size, further investigation is needed; this will be discussed in more detail in Section 4.4.3.

The nitrate-nitrogen results were compared with the 'acceptable' stormwater quality values as defined by Nel *et al*. (2013) (Table 4-2). Nel et al., (2013) states that nitrate-nitrogen becomes unacceptable when the concentration of the total inorganic nitrogen exceeds 10 mg/ℓ, and thus the nitrate-nitrogen effluent concentration from Cell H with the raised outlet falls within the unacceptable category. The nitrate-nitrogen effluent concentrations from the majority of the PICP cells falls within the poor category. This presumably shows that the nitrate-nitrogen from the PICP effluent could pose risk to the ecosystems.

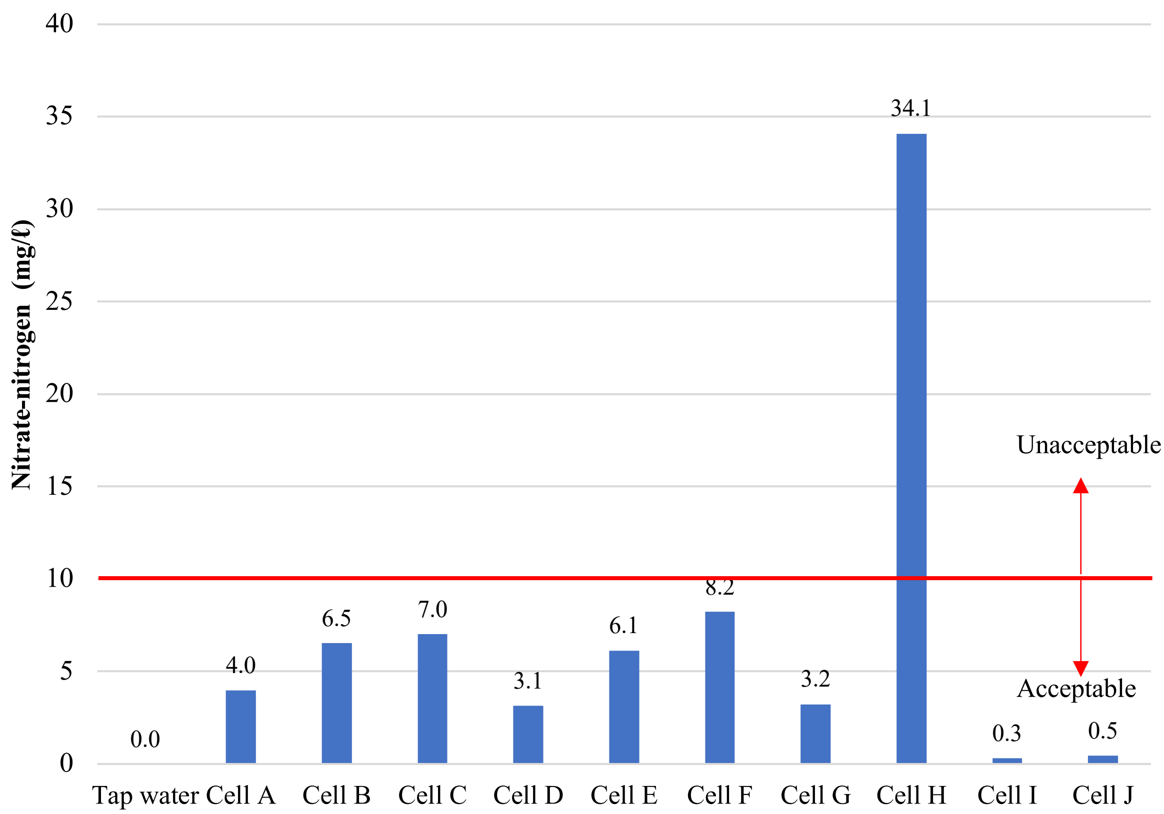


Figure 4-6: Effluent concentrations of nitrate-nitrogen measured in the clean water test

4.2.7 Total Suspended Solids

The presence of Total Suspended Solids (TSS) is a measure of the turbidity of the water and can cause the water due have reduced clarity owing to the light scattering from very small particles in the water (BioWorld, n.d.). TSS can include a wide variety of materials, such as silt, decaying plant and animal matter, industrial wastes and sewage. A high concentration of suspended solids can cause many problems for stream health and aquatic life.

For the 'clean water test', it was assumed that the TSS concentration in the effluent must be directly related to dirt on the aggregates in the PPS structures. Thus, it was expected that cells that used washed aggregates should have low TSS concentrations in the effluent, and those that used unwashed aggregates were likely to have high TSS effluent concentrations. This is only partially supported by the measurements (Figure 4-7) where the TSS concentration in the effluent from Cell G (unwashed aggregate PPS structure) is significantly higher than the other seven cells, but Cell B and Cell H – which also used unwashed aggregates in their base layers – have relatively low effluent concentration of TSS. This may be due to the sediments from these two cells being largely flushed out during the flushing process. It was further noted the TSS effluent concentrations were zero from the two new constructed cells (Cell I & Cell J) which further indicates the importance of the sufficient cleaning of the aggregates since a different method of washing the aggregates was used on the two new cells to ensure that they were clean.

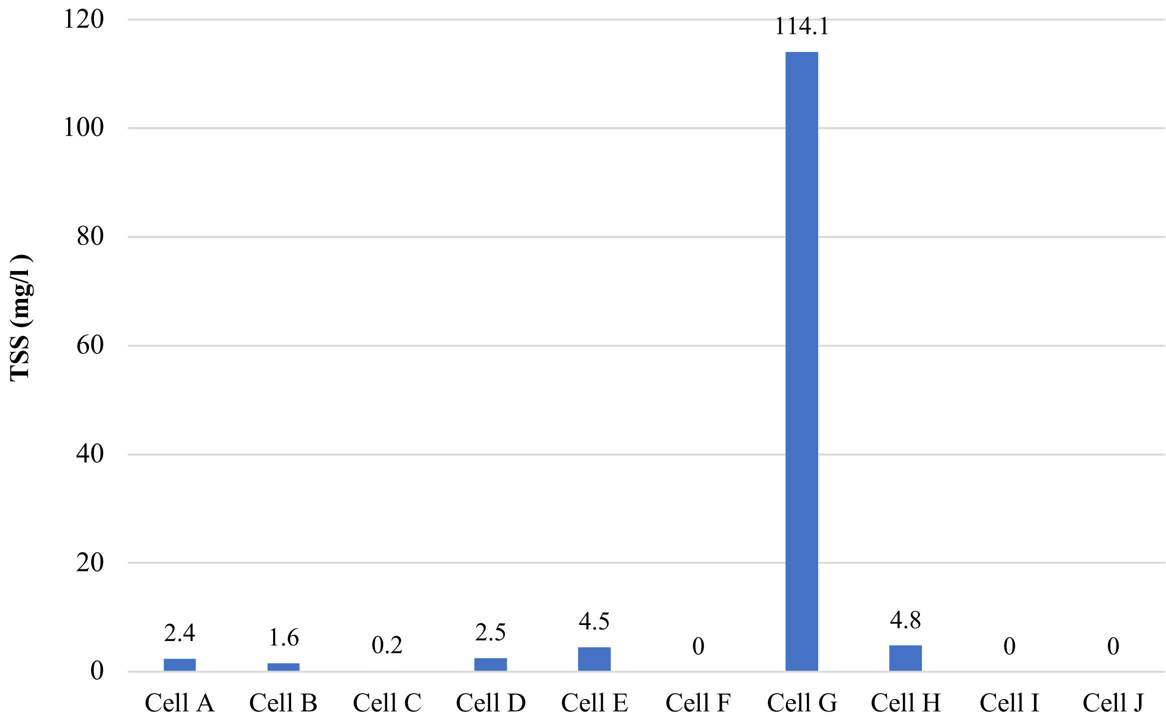


Figure 4-7: TSS effluent concentrations measured in the clean water test

4.3 Phase 1: Synthetic stormwater tests

As mentioned in Section 3.7, in Phase 1 the cells were each twice subjected to nine 10 ℓ discrete 'rainfall events' over consecutive days with the testing taking place in October 2017, September 2019 and April 2019. The soluble fertilizer 'Growing Orchid' was used as the pollutant source – with the first four of the nine storm events using a mixing rate of 65 g / 100 ℓ and the remaining five 8 g / 100 ℓ. The high influent concentration for the first four days was chosen as a potential worst-case scenario for the stormwater quality to show how PICP would respond to such a high concentration of soluble nutrient. Influent samples were collected for each experimental cell on Day 1 and Day 5 when the concentration of the pollutant in the soluble fertilizer was reduced for the remainder of the test. The purpose of collecting the influent samples was to check whether the prepared synthetic stormwater corresponded to the desired concentration. Effluent samples were collected for each experimental cell on a daily basis and were tested for pH, Temperature, and EC daily, whilst ammonia-nitrogen, orthophosphate-phosphorus, nitrite-nitrogen and nitrate-nitrogen were sampled on the 1st, 5th and 9th days. The results from the Phase 1 tests are presented here.

4.3.1 Ammonia-nitrogen

Figure 4-8 shows the mean ammonia-nitrogen effluent concentrations in the form of a box-and-whisker plots for the original eight PICP cells (Cell A-Cell H). One sample was tested from each cell on the 1st, 5th and 9th day during the tests of 2017, and one sample was tested from each cell on the 1st, 5th and 9th day during the tests of 2019.

Figure 4-9 shows the variation in the ammonia-nitrogen effluent concentrations over the testing period from the initial eight different PICP cells (a total of six samples were collected and tested from each PICP cell). For the majority of the PICP cells, the ammonia-nitrogen effluent concentrations fluctuate without a clear trend (decreases on the 5th day and 9th day in 2017). However, this may result from the two different concentrations of nutrient for the synthetic stormwater (concentration decreased on the 5th day and 9th day).

Table 4-4 summarises the ammonia-nitrogen effluent concentrations obtained from Phase 1. It shows that the average removal efficiency for ammonia-nitrogen for all eight cells ranged from 23 to 89%, and the mean ammonia-nitrogen effluent concentrations from Cell A to Cell J ranged from 0.18 to 27.48 mg/ℓ. The influent concentrations were 16.15 mg/ℓ for the first four days and 2 mg/ℓ for the last five days. The impact of different PICP design features (types of pavers, presence or absence of a geotextile, the use of washed and unwashed aggregates and the incorporation of a permanently wet zone with the raised outlet) was determined by comparing the PICP cells having different design feature whilst holding all other design features constant (Table 3-2). The results indicates that the presence of geotextile had a positive impact on the removal efficiency of ammonia-nitrogen for all cells; the presence of submerged zone (raised outlet) increased the ammonia-nitrogen removal efficiency significantly, and the cell with washed aggregates had higher ammonia-nitrogen removal efficiency than the cell with unwashed aggregates.

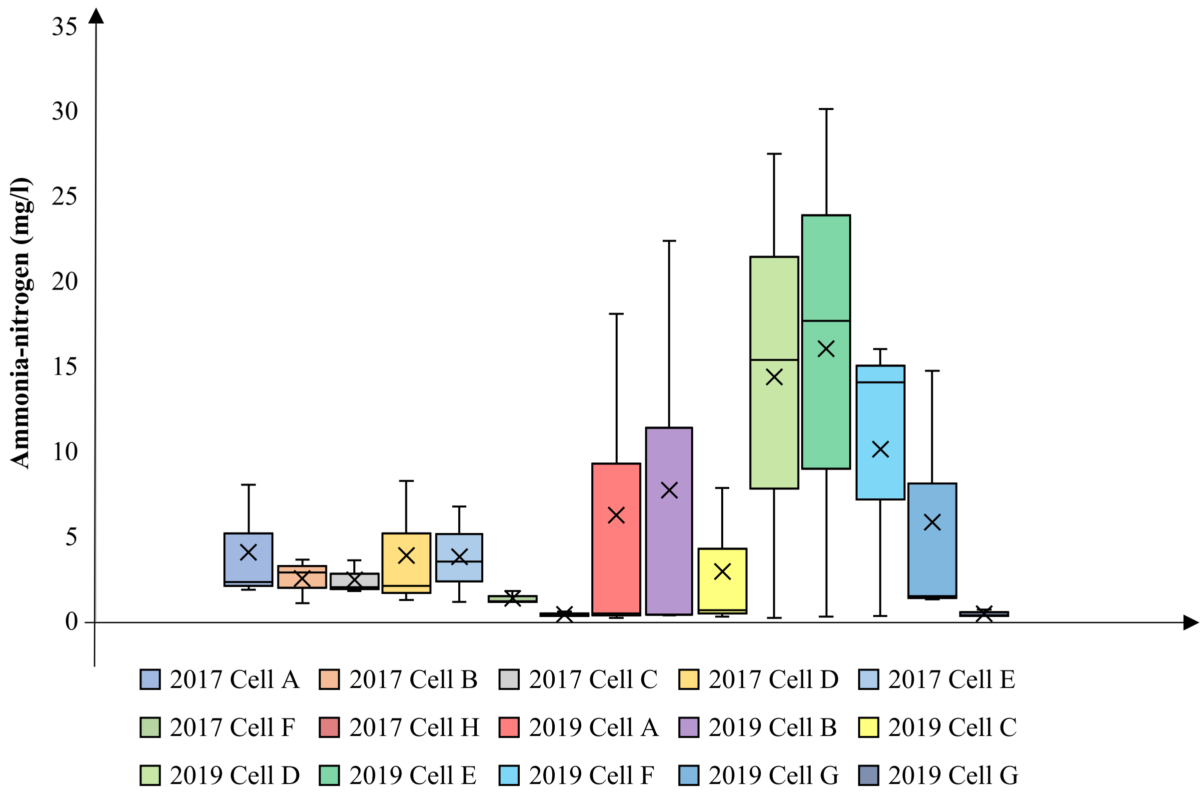


Figure 4-8: Effluent concentrations of ammonia-nitrogen measured from the original eight PICP cells in Phase 1 (August 2017 to April 2019). Sample number = 3; box plots show medians, and 25th and 75th percentiles; whiskers represent the 10th and 90th percentiles; cross markers represent the mean value.

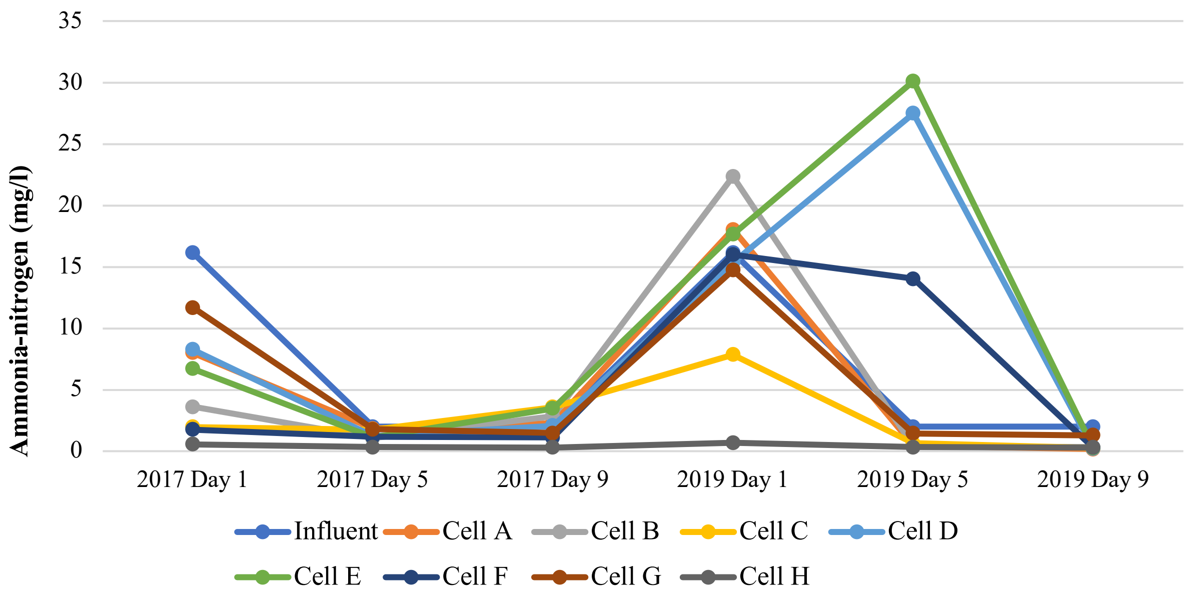


Figure 4-9: Variation in the ammonia-nitrogen effluent concentrations measured from the original eight PICP cells in Phase 1 over time

Table 4-4: Summary of ammonia-nitrogen removed for Phase 1

Range of Ammonia-nitrogen effluent concentrations from Cell A to Cell H	0.18 to 27.48 mg/ℓ		
Range of mean ammonia-nitrogen removal efficiency from Cell A to Cell H	23 to 89%		
Impact of geotextile	Compare A and F (Aquaflow®)	Compare C, D and E (Permealock®)	Compare B and G (Permealock®)
	Ammonia-nitrogen removal efficiency from Cell F (Inbitex® geotextile) > Ammonia-nitrogen removal efficiency from Cell A (no geotextile)	Ammonia-nitrogen removal efficiency from Cell C (Fibertex® geotextile) > Ammonia-nitrogen removal efficiency from Cell D (Kaytech bidim® geotextile > Ammonia removal efficiency from Cell E (no geotextile)	Ammonia-nitrogen removal efficiency from Cell B (Fibertex® geotextile) > Ammonia-nitrogen removal efficiency from Cell G (no geotextile))
	Presence of geotextile had a positive impact on the removal efficiency of ammonia-nitrogen		
Impact of raised outlet (submerged zone)	Ammonia-nitrogen removal efficiency from Cell H (raised outlet) > Ammonia-nitrogen removal efficiency from Cell B (base outlet)		
	Presence of submerged zone (raised outlet) had a positive impact on the removal efficiency of ammonia-nitrogen		
Impact of unwashed aggregates	Ammonia-nitrogen removal efficiency from Cell C (washed stones) > Ammonia-nitrogen removal efficiency from Cell B (unwashed stones)		
	The use of unwashed aggregates introduced more ammonia-nitrogen from the system		

4.3.2 Nitrite-nitrogen & nitrate-nitrogen

Negligible nitrite-nitrogen and nitrate-nitrogen were measured in the collected samples.

4.3.3 Orthophosphate-phosphorus

Figure 4-10 shows the mean orthophosphate-phosphorus effluent concentrations in the form of a box-and-whisker plots for the original eight PICP cells (Cell A-Cell H).

Figure 4-11 shows the orthophosphate-phosphorus effluent concentrations over the testing period from the initial eight different PICP cells (a total of six samples were collected and tested from each PICP cell). For the majority of the PICP cells the orthophosphate-phosphorus effluent concentrations fluctuate without a clear trend.

Table 4-5 summarises the orthophosphate-phosphorus results obtained from the Phase 1. It shows that the average orthophosphate-phosphorus addition for the initial eight cells ranged from 22 to 120 %, and the mean orthophosphate-phosphorus effluent concentrations from Cell A to Cell H ranged from 2.52 to 31.07 mg/ℓ. The influent concentrations were about 25.85 mg/ℓ for the first 4 days and 4.18 mg/ℓ for the last 5 days. It is hard to say whether the presence of geotextile has a positive impact on reducing the orthophosphate-phosphorus. The results show the presence of submerged zone (raised outlet) in the test cell added large amounts of orthophosphate-phosphorus compared with those without. It was further noted that the use of washed aggregates introduced more orthophosphate-phosphorus into the system. Further investigation is needed to find out the reason for this.

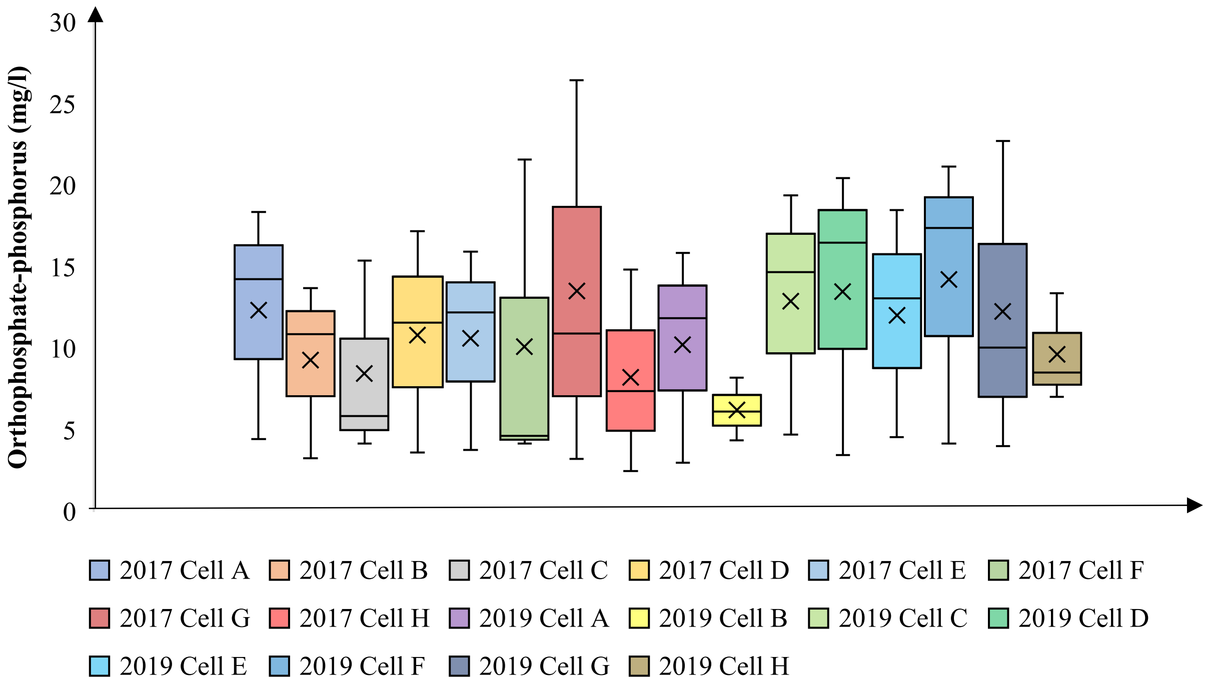


Figure 4-10: Effluent concentrations of orthophosphate-phosphorus measured from the original eight PICP cells in Phase 1 (August 2019 to September 2019). Sample number = 3; box plots show medians and 25th and 75th percentiles; whiskers represent the 10th and 90th percentiles; cross markers represent the mean value.

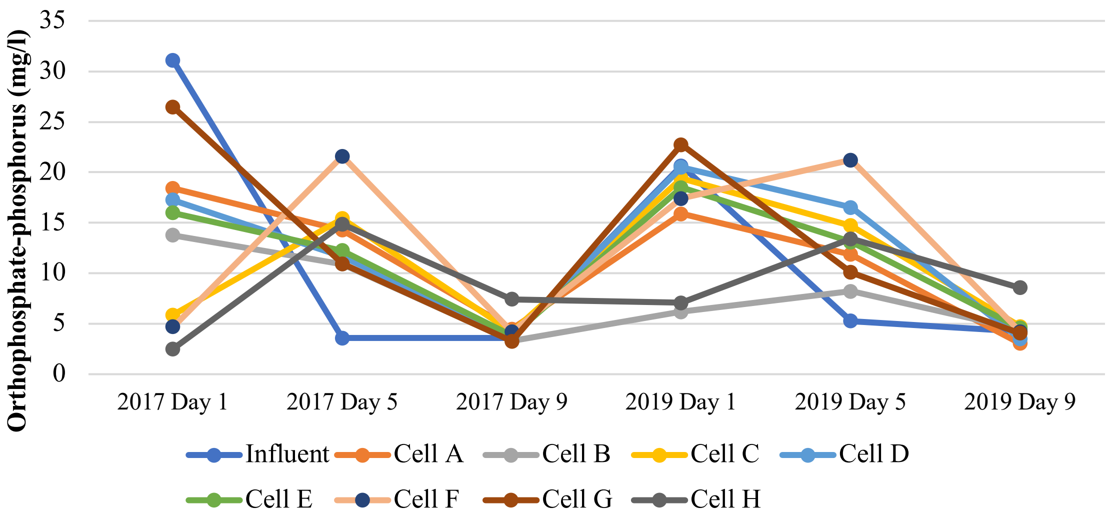


Figure 4-11: Variation in the orthophosphate-phosphorus effluent concentrations measured from the original eight PICP cells in Phase 1 over time

Table 4-5: Summary of orthophosphate-phosphorus produced for Phase 1

Range of orthophosphate-phosphorus effluent concentrations from Cell A to Cell H	2.52 to 31.07 mg/ℓ		
Range of mean orthophosphate-phosphorus addition from Cell A to Cell H	22 to 120%		
Impact of geotextile	Compare A and F (Aquaflow®)	Compare C, D and E (Permealock®)	Compare B and G (Permealock®)
	Orthophosphate-phosphorus added in Cell F (Inbitex® geotextile) > orthophosphate-phosphorus produced in Cell A (no geotextile)	Orthophosphate-phosphorusv added in Cell C (Fibertex® geotextile) > P orthophosphate-phosphorus produced in Cell D > phosphate produced in E (no geotextile)	Orthophosphate-phosphorus added in Cell G (no geotextile) > orthophosphate-phosphorus produced in Cell B (Fibertex® geotextile)
	The impact of geotextile on the orthophosphate-phosphorus concentration was inconclusive		
Impact of raised outlet (submerged zone)	Orthophosphate-phosphorus added in Cell H (raised outlet) > Orthophosphate-phosphorus added in Cell B (base outlet)		
	Presence of submerged zone (raised outlet) resulted in higher orthophosphate-phosphorus addition		
Impact of unwashed aggregates	Orthophosphate-phosphorus added in Cell C (washed stones) > Orthophosphate-phosphorus added in Cell B (unwashed stones)		
	The use of unwashed aggregates resulted in less orthophosphate-phosphorus addition		

4.3.4 Electrical Conductivity (EC)

Figure 4-12 and Figure 4-13 shows how the EC concentrations for the original eight PPS cells changed with time in 2017 and how EC concentrations for all ten PICP cells changed with time in 2019. No clear trend can be seen for the EC concentrations in 2017 (the point marked in red circle may result from a reading error), however, the electrical conductivity show a decreasing trend during 2019. This result may indicate that the PICP system only starts to remove the ions after several wetting & drying cycles. However, further investigation is needed to analyse the long term effect of PICP on the EC concentration to prove this hypothesis.

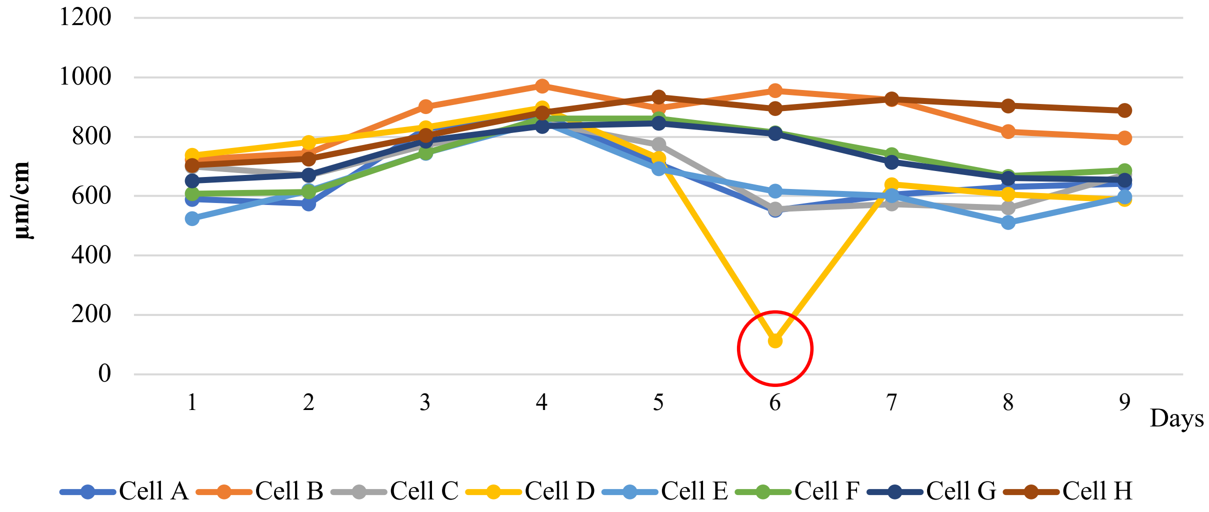


Figure 4-12: Variation in EC measured from the original eight PICP cells in Phase 1 (2017)

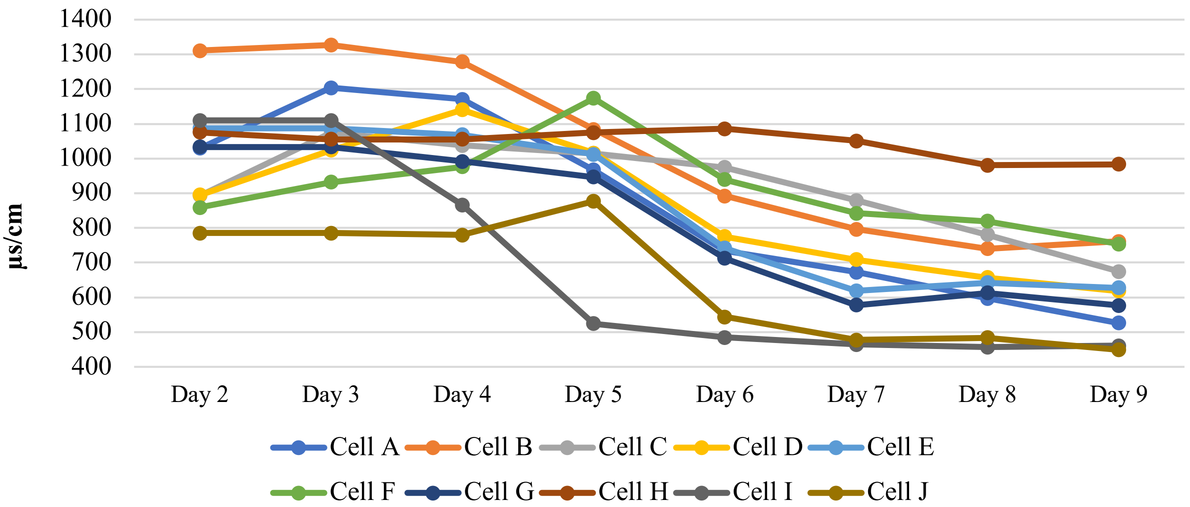


Figure 4-13: Variation in EC measured from all ten PICP cells in Phase 1 (2019)

4.4 Phase 2: Synthetic stormwater tests

During the course of Phase 1, it became apparent the influent pollutant concentrations were not always consistent, furthermore, the use of two different fertilizer concentrations made it difficult to compare influent and effluent pollutant concentrations. As a consequence, in Phase 2, lab-prepared standard solutions were used as the source of pollutants, whilst the rainfall regime was carried out over a more representative 41 days with intermittent dry and wet periods more typical of Cape Town conditions. Five samples were tested from each cell on 6th August, 17th August, 24th August, 5th September and 14th September respectively with roughly a week gap in between each sampling. The results from the Phase 2 tests are presented here.

4.4.1 Ammonia-nitrogen

Figure 4-14 shows the mean ammonia-nitrogen effluent concentrations in the form of box-and-whisker plots for the ten different PICP cells.

Figure 4-15 shows the variation in the ammonia-nitrogen effluent concentrations over time from the ten different PICP cells; the red horizontal line indicates the influent concentration of 2 mg/ℓ. This shows how the ammonia-nitrogen effluent concentrations change during the testing period. The majority of the PICP cells show a decreasing trend in ammonia-nitrogen effluent concentrations over the period. The ammonia-nitrogen effluent concentrations however tended to ‘bounce’ back to higher values during dry periods before dropping again during the wetting periods, which is likely due to biological action being facilitated by wet conditions. However, more data is needed to fully understand the impact of the dry and wet periods on ammonia-nitrogen effluent concentrations in PICP.

Table 4-6 summarises the ammonia-nitrogen results. It shows that the average removal efficiency for ammonia-nitrogen for all ten cells ranged from 27.5 to 78.7%, and the mean ammonia-nitrogen effluent concentrations from Cell A to Cell J ranged from 0.1 to 2.68 mg/ℓ. The results indicate that the presence of geotextile has a positive impact on the removal efficiency of ammonia-nitrogen for all cells; the presence of a submerged zone (raised outlet) increases the ammonia-nitrogen removal efficiency significantly, and that the cell with washed aggregates has higher ammonia-nitrogen removal efficiency than the cell with unwashed aggregates.

4.4.2 Nitrite-nitrogen

Figure 4-16 shows the mean nitrite-nitrogen effluent concentrations in the form of a box-and-whisker plots for the ten different PICP cells.

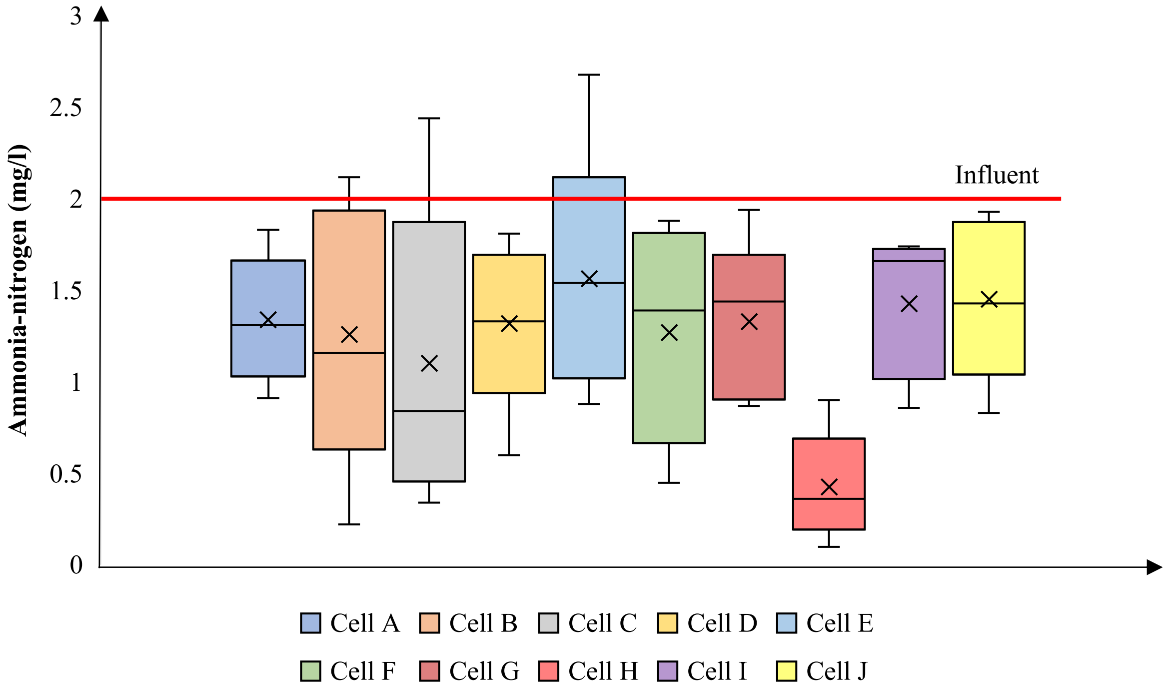


Figure 4-14: Effluent concentrations of ammonia-nitrogen measured in Phase 2 (August 2019 to September 2019). Sample number = 5; box plots show medians and 25th and 75th percentiles; whiskers represent the 10th and 90th percentiles.

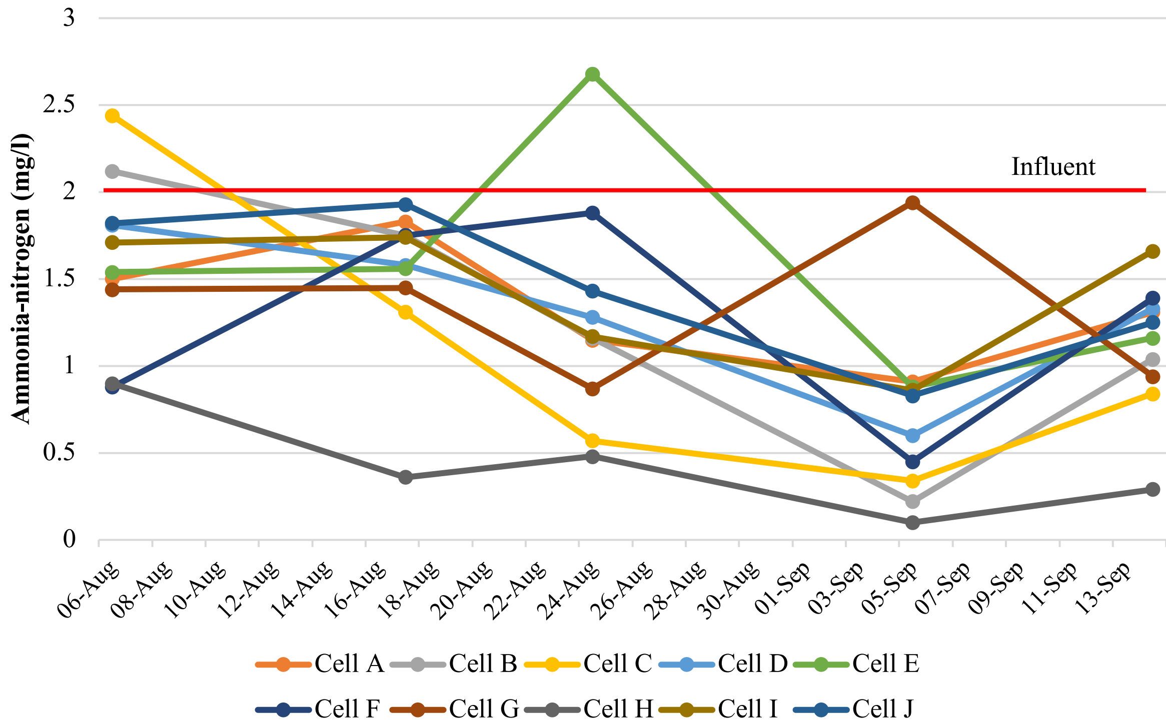


Figure 4-15: Variation in the ammonia-nitrogen effluent concentrations measured in Phase 2 over time

Table 4-6: Summary of ammonia-nitrogen removed for Phase 2

Range of ammonia-nitrogen effluent concentrations from Cell A to Cell J	0.1 to 2.68 mg/ℓ			
Range of mean ammonia-nitrogen removal efficiency from Cell A to Cell J	27.5 to 78.7%			
Mean Influent Ammonia-nitrogen concentration	2 mg/ℓ			
Impact of geotextile	Compare A and F (Aquaflow®)	Compare C, D and E (Permealock®)	Compare B and G (Permealock®)	Compare I and J (Exposed Pavers)
	Ammonia-nitrogen removal efficiency from Cell F (Inbitex® geotextile) > Ammonia-nitrogen removal efficiency from Cell A (no geotextile)	Ammonia-nitrogen removal efficiency from Cell C (Fibertex® geotextile) > Ammonia-nitrogen removal efficiency from Cell D (Kaytech bidim® geotextile > Ammonia removal efficiency from Cell E (no geotextile)	Ammonia-nitrogen removal efficiency from Cell B (Fibertex® geotextile) > Ammonia-nitrogen removal efficiency from Cell G (no geotextile)	Ammonia-nitrogen removal efficiency Cell I (Fibertex® geotextile) > Ammonia-nitrogen removal efficiency from Cell J (no geotextile)
	Presence of geotextile had a positive impact on the removal efficiency of ammonia			
Impact of raised outlet (submerged zone)	Ammonia-nitrogen removal efficiency from Cell H (raised outlet) > Ammonia-nitrogen removal efficiency from Cell B (base outlet)			
	Presence of submerged zone (raised outlet) had a positive impact on the removal efficiency of ammonia			
Impact of unwashed aggregates	Ammonia-nitrogen removal efficiency from Cell C (washed stones) > Ammonia-nitrogen removal efficiency from Cell B (unwashed stones)			
	The use of unwashed aggregates introduced more ammonia-nitrogen into the system			

Figure 4-17 shows the variation in the nitrite-nitrogen effluent concentrations over time from the ten different PICP cells. The influent concentration was 0 mg/ℓ. The nitrite-nitrogen effluent concentrations fluctuate through the entire testing period without any clear trend. The nitrite-nitrogen effluent concentrations from all PICP cells are higher than the influent concentration which indicate that PICP adds nitrite-nitrogen into the system. The added nitrite-nitrogen concentrations may result from the oxidation process through the transforming of ammonia-nitrogen to nitrite-nitrogen and nitrate-nitrogen. In addition, the fluctuation of nitrite-nitrogen effluent concentrations may also relate to the intermittent wet and dry periods, but further investigation is needed to confirm this relationship.

Table 4-7 summarises the nitrite-nitrogen effluent concentrations obtained from the Phase 2 tests. It shows the mean nitrite-nitrogen effluent concentrations measured from Cell A to Cell J ranged from 0 to 0.43 mg/ℓ. The results indicate that the presence of geotextile results in less nitrite-nitrogen addition for most cells except for Cell I; the presence of submerged zone (raised outlet) results in less nitrite-nitrogen addition than the one without, and the use of washed/unwashed aggregates did not appear to have any impact on the nitrite-nitrogen effluent concentrations.

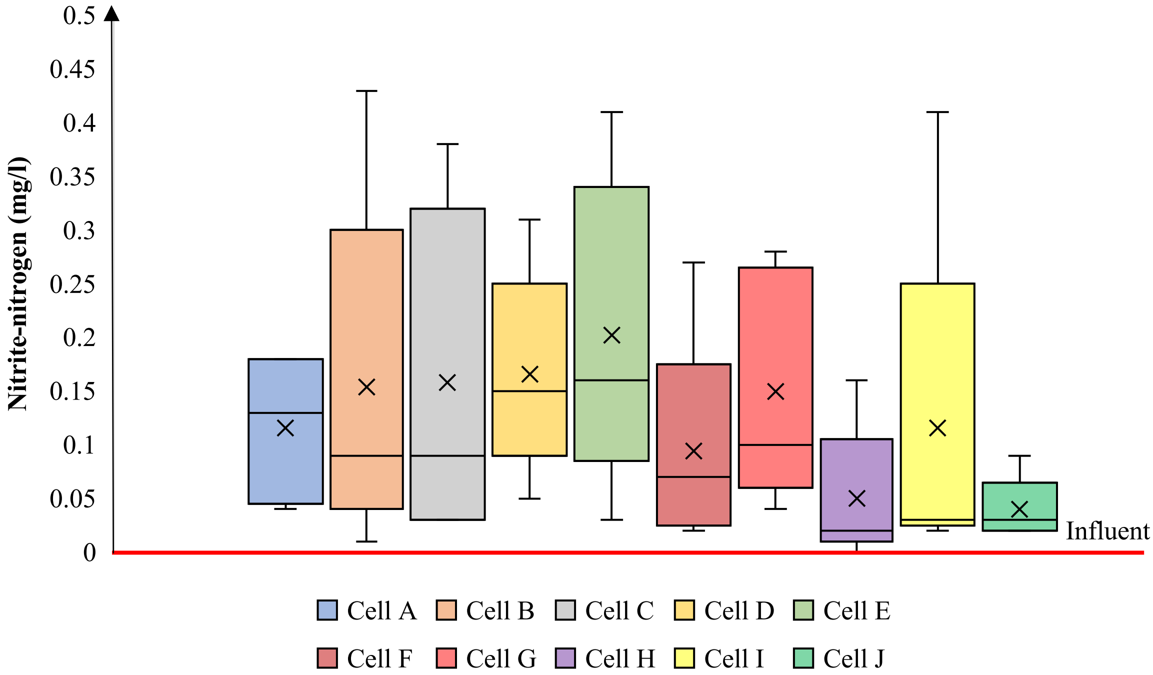


Figure 4-16: Effluent concentrations of nitrite-nitrogen measured in Phase 2 (August 2019 to September 2019). Sample number = 5; box plots show medians and 25th and 75th percentiles; whiskers represent the 10th and 90th percentiles.

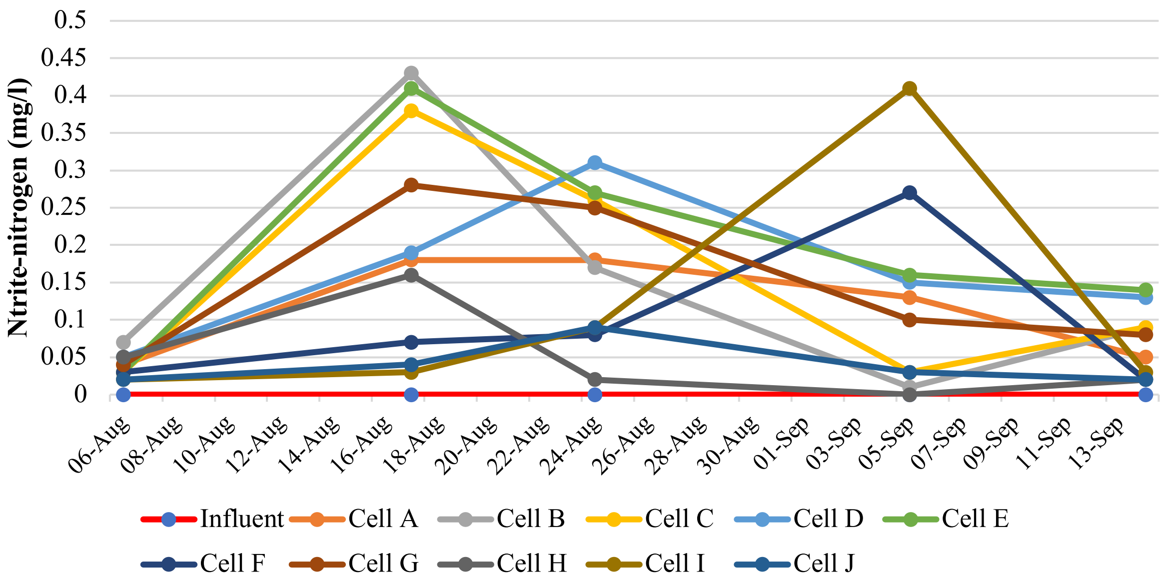


Figure 4-17: Variation in the nitrite-nitrogen effluent concentrations measured in Phase 2 over time

Table 4-7: Summary of nitrite-nitrogen produced for Phase 2

Range of nitrite-nitrogen effluent concentration from Cell A to Cell J	0 to 0.43 mg/ℓ			
Mean Influent nitrite-nitrogen concentration	0 mg/ℓ			
Impact of geotextile	Compare A and F (Aquaflow®)	Compare C, D and E (Permealock®)	Compare B and G (Permealock®)	Compare I and J (Exposed Pavers)
	Nitrite-nitrogen added in Cell A (no geotextile) > Nitrite-nitrogen added in Cell F (Inbitex® geotextile)	Nitrite-nitrogen added in Cell E (no geotextile) > Nitrite produced in Cell D (Kaytech bidim® geotextile > Nitrite-nitrogen added in Cell C (Fibertex® geotextile)	Nitrite-nitrogen added in Cell G (no geotextile) ≈ Nitrite-nitrogen added in Cell B (Fibertex® geotextile)	Nitrite-nitrogen added in Cell I (Fibertex® geotextile) > Nitrite-nitrogen added in Cell J (no geotextile)
	Presence of geotextile resulted in less nitrite-nitrogen addition (except for Cell I)			
Impact of raised outlet (submerged zone)	Nitrite-nitrogen added in Cell B (base outlet) > Nitrite-nitrogen added in Cell H (raised outlet)			
	Presence of submerged zone (raised outlet) resulted in less nitrite-nitrogen addition			
Impact of unwashed aggregates	Nitrite-nitrogen added in Cell B (unwashed stones) ≈ Nitrite-nitrogen added in Cell C (washed stones)			
	The use of unwashed aggregates had no impact on the nitrite-nitrogen effluent concentrations			

4.4.3 Nitrate-nitrogen

Figure 4-18 shows the mean nitrate-nitrogen effluent concentrations in the form of a box-and-whisker plots for the ten different PICP cells.

Figure 4-19 shows the variation in the nitrate-nitrogen effluent concentrations over time for the ten different PICP cells. The influent concentration was 0.6 mg/ℓ. It was found that the nitrate-nitrogen effluent concentrations decrease significantly through the entire testing period, although they were all greater than for the influent.

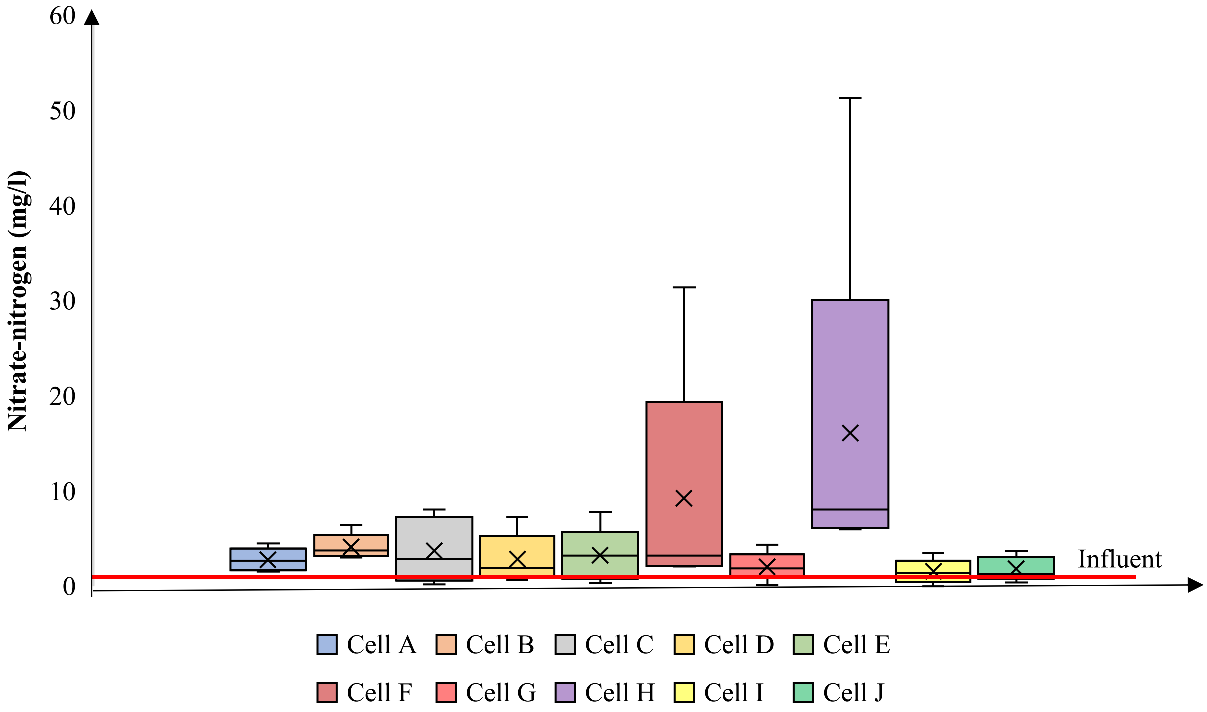


Figure 4-18: Effluent concentrations of nitrate-nitrogen measured in Phase 2 (August 2019 to September 2019). Sample number = 5; box plots show medians and 25th and 75th percentiles; whiskers represent the 10th and 90th percentiles.

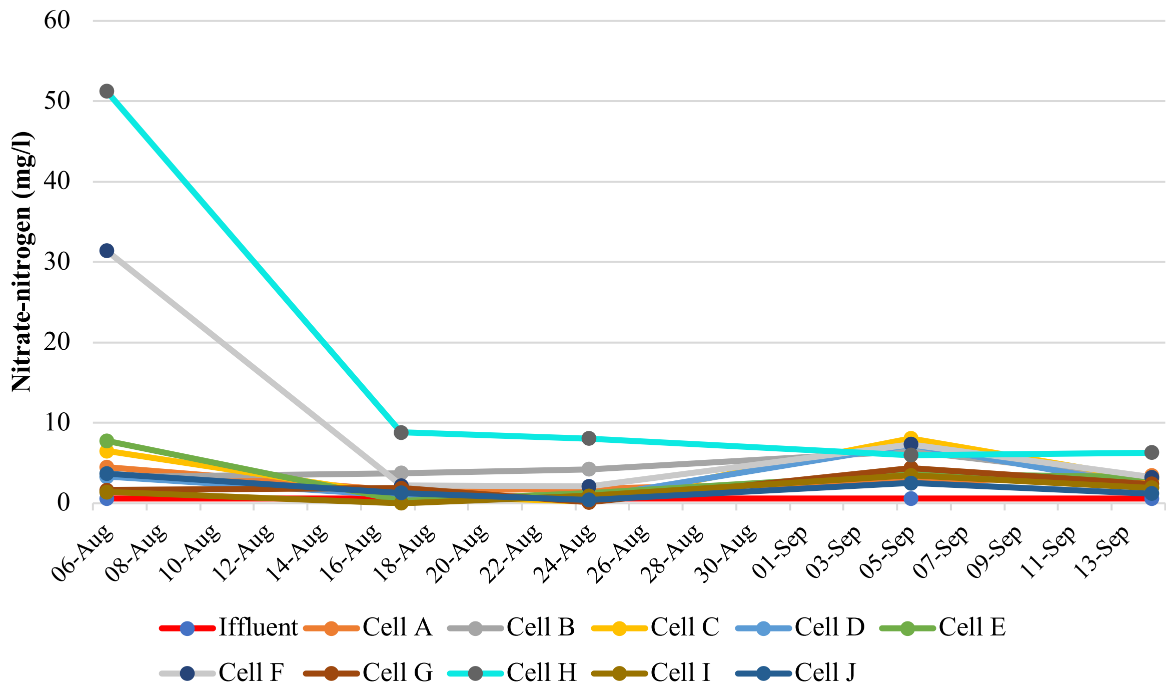


Figure 4-19: Variation in the nitrate-nitrogen effluent concentrations measured in Phase 2 over time

Table 4-8 summarises the nitrate-nitrogen results obtained in Phase 2. It shows that the average nitrate-nitrogen addition for all ten cells ranged from 160% to 2580%, and the mean nitrate-nitrogen effluent concentrations from Cell A to Cell J ranged from 0 to 51.3 mg/ℓ which also indicates the common nitrate addition from PICP. From the results, it shows the presence of geotextile in most cells resulted in higher nitrate-nitrogen addition. The results also shows the presence of a submerged zone (raised outlet) added significant amounts of nitrate-nitrogen compared with the ones without. The extremely high effluent concentration of nitrate-nitrogen in the cell with submerged zone could be attributed to the nitrification process in which ammonia-nitrogen (NH_3) is transformed to nitrate-nitrogen (NO_3^-). This assumption is further supported with the high ammonia-nitrogen removal rate in the same cell. It was further noted that the use of unwashed aggregates introduced more nitrate-nitrogen into the system.

These findings further suggest that the removal of nitrogen is highly dependent on the nitrogen species as well as the oxygen conditions (aerobic, anaerobic or anoxic) within the PICP. Ammonia-nitrogen (NH_3) is transformed into nitrate-nitrogen (NO_3^-) under aerobic conditions via the nitrification process by nitrifying bacteria, or it can be adsorbed to negatively charged sites on the filter material. Denitrification normally takes place under anoxic conditions in the presence of electron donor whereby nitrate-nitrogen is reduced to nitrite-nitrogen (NO_2^-) and N_2 by denitrifying bacteria. The anoxic conditions and the presence of organic carbon as an electron donor are the two essential factors which restrict the process of the denitrification in the treatment systems (Subramaniam *et al.*, 2014; Cheremisinoff, 2002; Von Sperling & De Lemos Chernicharo, 2005)

Table 4-8: Summary of nitrate-nitrogen produced for Phase 2

<table>
<tr><td>Range of nitrate-nitrogen effluent concentration from Cell A to Cell J</td><td colspan="4">0 to 51.3 mg/ℓ</td></tr>
<tr><td>Range of mean nitrate-nitrogen addition from Cell A to Cell J</td><td colspan="4">160% to 2580%</td></tr>
<tr><td>Mean Influent nitrate concentration</td><td colspan="4">0.6 mg/ℓ</td></tr>
<tr><td rowspan="3">Impact of geotextile</td><td>Compare A and F (Aquaflow®)</td><td>Compare C, D and E (Permealock®)</td><td>Compare B and G (Permealock®)</td><td>Compare I and J (Exposed Pavers)</td></tr>
<tr><td>Nitrate-nitrogen added in Cell F (Inbitex® geotextile) > nitrate-nitrogen produced in Cell A (no geotextile)</td><td>Nitrate-nitrogen added in Cell C (Fibertex® geotextile > nitrate produced in Cell E (no geotextile) > nitrate-nitrogen produced in Cell D (Kaytech bidim® geotextile)</td><td>Nitrate-nitrogen added in Cell B (Fibertex® geotextile) > nitrate-nitrogen produced in Cell G (no geotextile)</td><td>Nitrate-nitrogen added in Cell J (no geotextile) > nitrate-nitrogen produced from Cell I (Fibertex® geotextile)</td></tr>
<tr><td colspan="4">Presence of geotextile resulted in higher nitrate addition (except for Cell I)</td></tr>
<tr><td rowspan="2">Impact of raised outlet (submerged zone)</td><td colspan="4">Nitrate-nitrogen added in Cell H (raised outlet) > nitrate-nitrogen added in Cell B (base outlet)</td></tr>
<tr><td colspan="4">Presence of submerged zone (raised outlet) resulted in higher nitrate-nitrogen addition</td></tr>
<tr><td rowspan="2">Impact of unwashed aggregates</td><td colspan="4">Nitrate-nitrogen added in Cell B (unwashed stones) > nitrate-nitrogen added in Cell C (washed stones)</td></tr>
<tr><td colspan="4">The use of unwashed aggregates introduced more nitrate-nitrogen into the system</td></tr>
</table>

4.4.4 Orthophosphate-phosphorus

Figure 4-20 shows the mean orthophosphate-phosphorus effluent concentrations in the form of a box-and-whisker plots for the ten different PICP cells.

Figure 4-21 shows the variation in the orthophosphate-phosphorus effluent concentrations over time from the ten different PICP cells; the red horizontal line indicates the influent concentration of 0.8 mg/ℓ. The majority of the PICP cells show a decreasing trend in orthophosphate-phosphorus effluent concentrations. The orthophosphate-phosphorus effluent concentrations however tend to 'bounce' back to higher effluent concentrations during dry periods between tests before dropping again during the wet periods, which is likely due to biological action being facilitated by wet conditions. However, more data is needed to fully understand the impact of the dry and wet period on orthophosphate-phosphorus effluent concentrations in PICP.

Table 4-9 summarises the orthophosphate-phosphorus results obtained from Phase 2. It shows that the average removal efficiency for orthophosphate-phosphorus for all ten cells ranged from -37 to 11%, and the mean orthophosphate-phosphorus effluent concentrations from Cell A to Cell J ranges from 0.53 to 1.39 mg/ℓ. From the results, it is hard to say whether the presence of geotextile had a positive impact on the removal efficiency of orthophosphate-phosphorus. The results also shows the presence of a submerged zone (raised outlet) added a significant amount of orthophosphate-phosphorus compared to the one without. This could be because orthophosphate-phosphorus is adsorbed to sediments within the submerged saturated zone that could potentially be released under anoxic conditions. Also the low oxygen condition in the submerged zone is likely to cause a mobilisation and export of previous particle-bound phosphate from the filter material (Correll, 1999; Zinger *et al.*, 2013). It was further noted that the use of unwashed aggregates introduced more orthophosphate-phosphorus into the system.

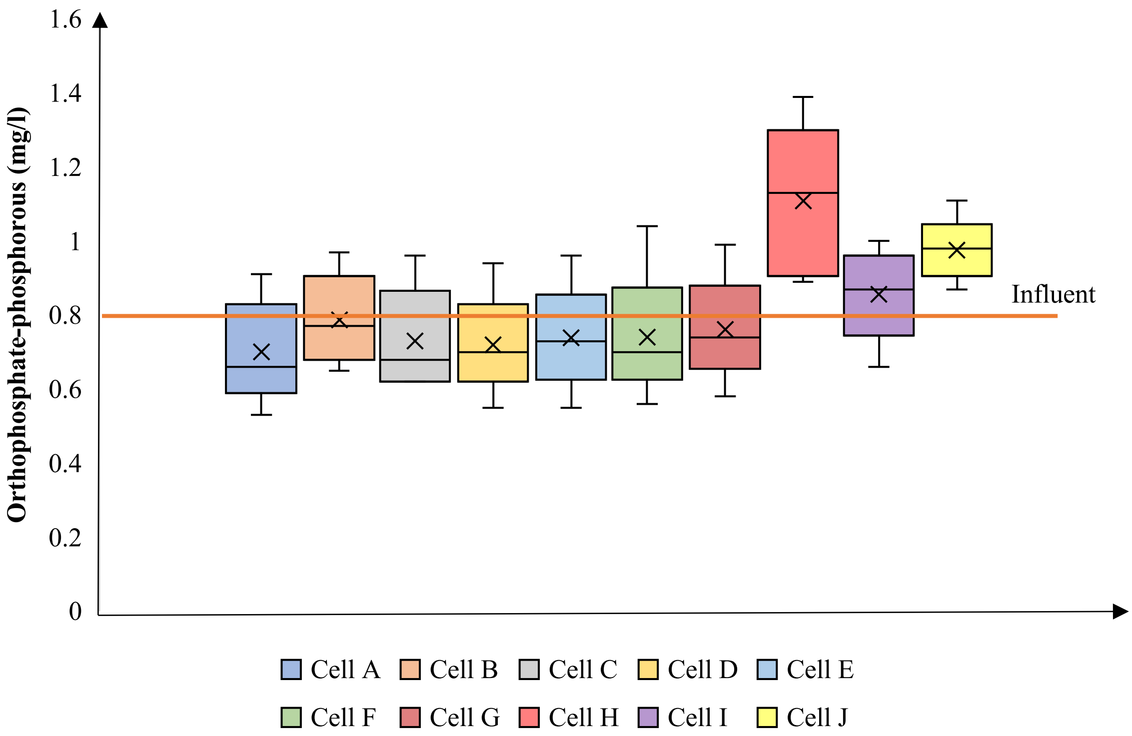


Figure 4-20: Effluent concentrations of orthophosphate-phosphorus measured in Phase 2 (August 2019 to September 2019). Sample number = 5; box plots show medians and 25th and 75th percentiles; whiskers represent the 10th and 90th percentiles.

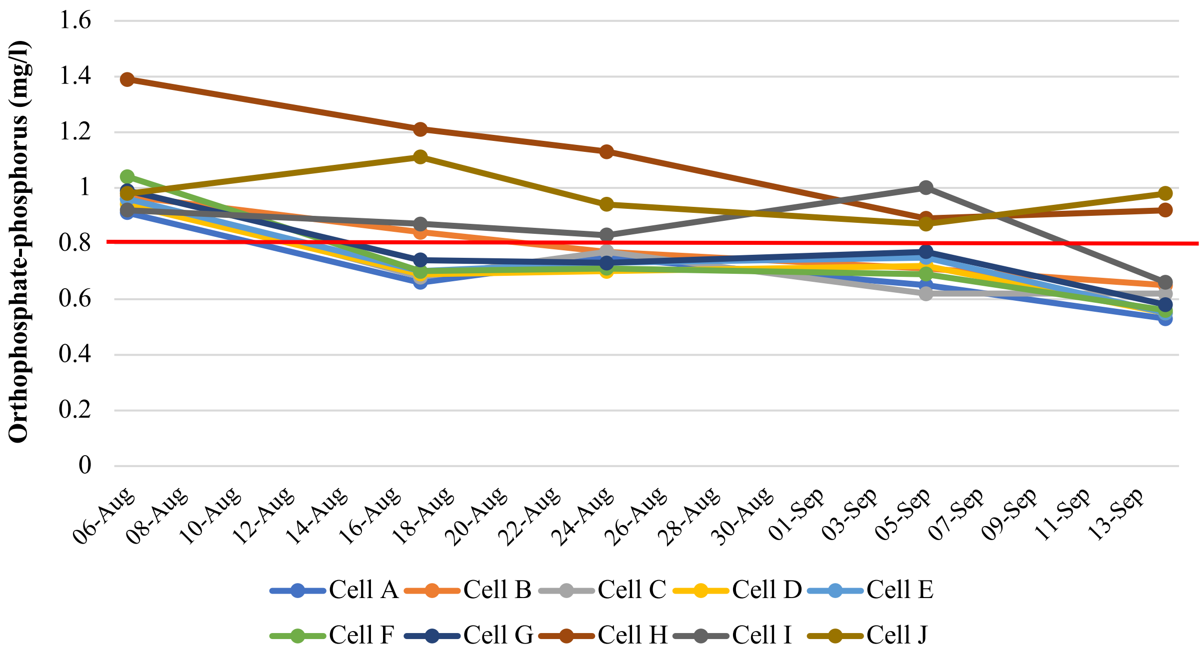


Figure 4-21: Variation in the orthophosphate-phosphorus effluent concentrations measured in Phase 2 over time

Table 4-9: Summary of orthophosphate-phosphorus removed for Phase 2

Range of orthophosphate-phosphorus effluent concentrations from Cell A to Cell J	0.53 to 1.39 mg/ℓ			
Range of mean orthophosphate-phosphorus removal efficiency from Cell A to Cell J	-37 to 11%			
Mean Influent orthophosphate-phosphorus concentration	0.8 mg/ℓ			
Impact of geotextile	Compare A and F (Aquaflow®)	Compare C, D and E (Permealock®)	Compare B and G (Permealock®)	Compare I and J (Exposed Pavers)
	Orthophosphate-phosphorus removal efficiency from Cell A (no geotextile) > orthophosphate-phosphorus removal	Orthophosphate-phosphorus removal efficiency from Cell D (Kaytech bidim® geotextile > orthophosphate-phosphorus removal efficiency from Cell C (Fibertex® geotextile) >	Orthophosphate-phosphorus removal efficiency from Cell G (no geotextile) > orthophosphate-phosphorus removal	Orthophosphate-phosphorus removal efficiency Cell I (Fibertex® geotextile) > orthophosphate-phosphorus removal

	efficiency from Cell F (Inbitex® geotextile)	phosphate removal efficiency from Cell E (no geotextile)	efficiency from Cell B (Fibertex® geotextile)	efficiency from Cell J (no geotextile)
	The impact of geotextile on the removal efficiency of orthophosphate-phosphorus was inconclusive			
Impact of raised outlet (submerged zone)	Orthophosphate-phosphorus removal efficiency from Cell B (base outlet) > Orthophosphate-phosphorus removal efficiency from Cell H (raised outlet)			
	Presence of submerged zone (raised outlet) had a negative impact on the removal efficiency of orthophosphate-phosphorus			
Impact of unwashed aggregates	Orthophosphate-phosphorus removal efficiency from Cell C (washed stones) > Orthophosphate-phosphorus removal efficiency from Cell B (unwashed stones)			
	The use of unwashed aggregates introduced more orthophosphate-phosphorus into the system			

4.4.5 Electrical Conductivity (EC)

The electrical conductivity (EC) of water is related to the total amount of solids dissolved in water by measuring the capacity of water to conduct electrical current. It is temperature dependent; the higher the temperature, the higher the electrical conductivity. An increase of 1 degree Celsius in the water temperature results in the EC of water increasing by 2-3%.

Figure 4-22 shows how EC for the ten PPS cells changed with time. It can be seen that the electrical conductivity drops overall during wet periods, whilst dry periods see a rise in EC. This result might suggest that the bacterial colony within the PICP is only active during the wet periods which reduces the ionic strength and thus a decrease in the EC, then during the dry periods, the bacteria colony goes into 'hibernation' and becomes inactive, resulting in an increase in EC as the ions are accumulating from the added stormwater.

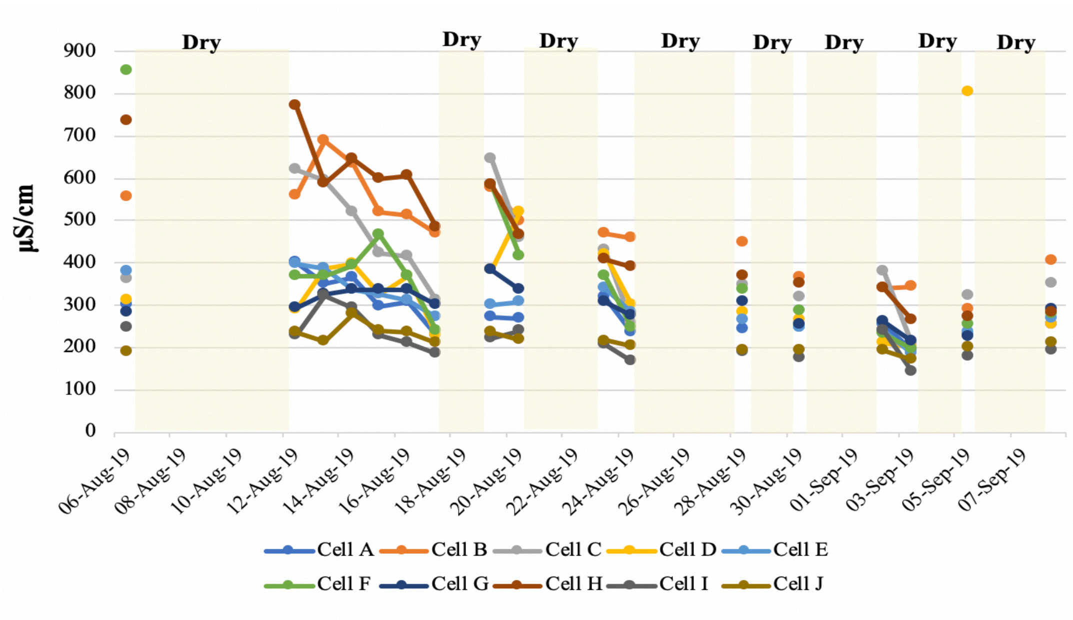


Figure 4-22: EC for all PICP cells change with time

Figure 4-23 shows the mean EC for all PICP cells. The mean EC from Cell A to Cell J ranges from 223 to 478 µS/cm, while the influent had a EC of 126 µS/cm which is shown as the red horizontal line. Significantly, the EC from all PICP cells was higher than the influent which suggests that the aggregates in the PICP introduced more ions to the effluent.

Table 4-10 summarises the EC results. This indicates that the impact of geotextile on EC is inconclusive; the use of unwashed stones resulted in a higher EC than the use of washed stones (possibly due to the introduction of ions adsorbed on the sediments), and the use of raised outlet resulted in similar EC compared with the one without the raised outlet which indicate the submerged zone has no impact on EC.

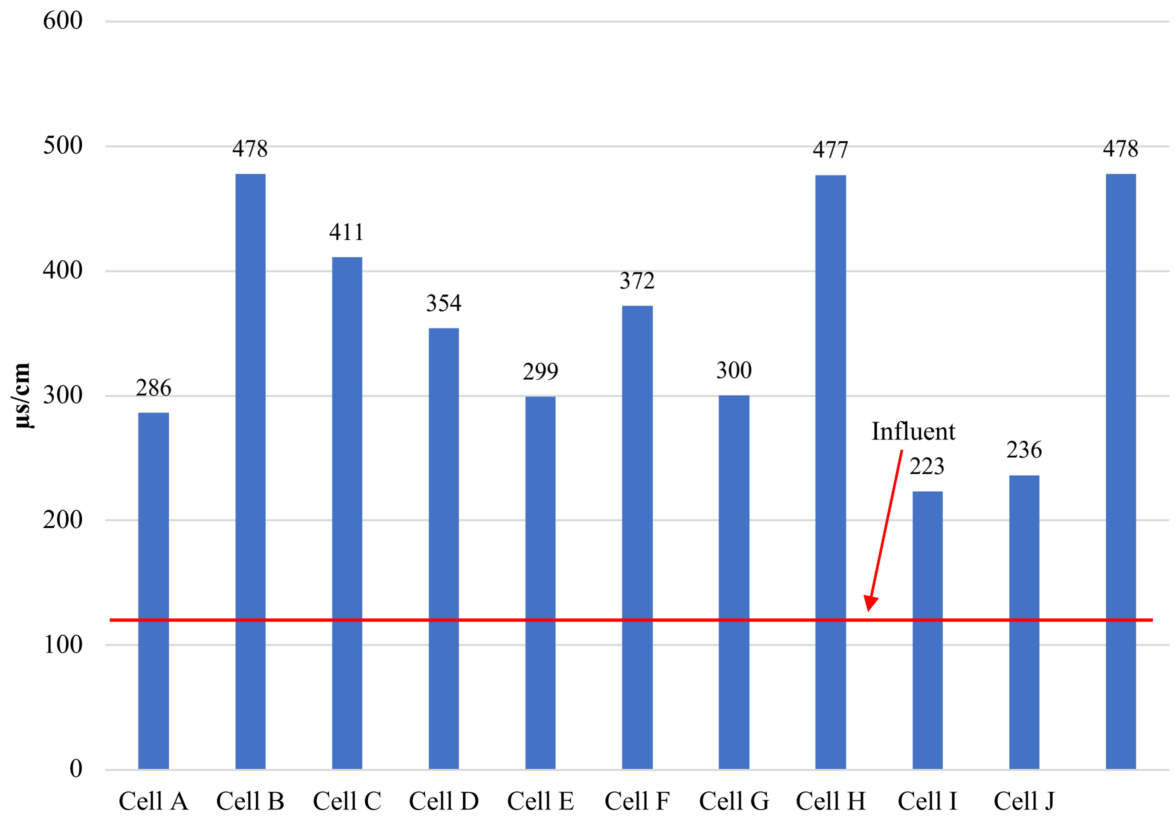


Figure 4-23: Mean EC for all PICP cells

Table 4-10: Summary of EC results for the Phase 2

<table>
<tr><td>Range of EC from Cell A to Cell J</td><td colspan="4">223 to 478 µS/cm</td></tr>
<tr><td>EC of tap water</td><td colspan="4">126 µS/cm</td></tr>
<tr><td rowspan="3">Impact of geotextile</td><td>Compare A and F (Aquaflow®)</td><td>Compare C, D and E (Permealock®)</td><td>Compare B and G (Permealock®)</td><td>Compare I and J (Exposed Pavers)</td></tr>
<tr><td>EC from Cell F (Inbitex® geotextile) > EC from Cell A (no geotextile)</td><td>EC from Cell C (Fibertex® geotextile) > EC from Cell D (Kaytech bidim® geotextile) > EC from Cell E (no geotextile)</td><td>EC from Cell B (Fibertex® geotextile) > EC from Cell G (no geotextile)</td><td>EC from Cell J (no geotextile) > Cell I (Fibertex® geotextile)</td></tr>
<tr><td colspan="4">The impact of geotextile on EC was inconclusive</td></tr>
<tr><td rowspan="2">Impact of raised outlet (submerged zone)</td><td colspan="4">EC from Cell B (base outlet) ≈ EC from Cell H (raised outlet)</td></tr>
<tr><td colspan="4">Presence of submerged zone (raised outlet) had no impact on EC</td></tr>
<tr><td rowspan="2">Impact of unwashed aggregates</td><td colspan="4">EC from Cell B (unwashed stones) > EC from Cell C (washed stones)</td></tr>
<tr><td colspan="4">The use of unwashed aggregates introduced more EC into the system</td></tr>
</table>

4.4.6 pH

Collins *et al*., (2008) states that permeable pavement can buffer acidic rainfall pH, which is likely due to the presence of calcium carbonate and magnesium carbonate in the concrete pavement. In South Africa, most fresh water has a pH between 6 and 8 (DWA, 1996). pH is affected by temperature, the concentration of inorganic and organic ions, and biological activity, however, the change in temperature is not very significant as the pH of fresh water only decreases by 0.1 of a unit for a temperature increase of 20°C (DWA, 1996). The pH affects the availability and toxicity of constituents such as trace metals, non-metallic ions such as ammonium, and essential elements such as selenium.

Figure 4-24 shows the mean pH for all PPS cells during the testing period, and it was found that pH ranges from 7.71 to 8.52. It can also be seen that the all PPS cells except for the two PICP with the exposed aggregate pavers have lower pH than the influent, the types of pavers might be responsible for this lower pH since calcium carbonate / magnesium carbonate in the concrete pavers can buffer pH. High pH may be attributable to the dissolution process of the aggregate constituents such as calcium and magnesium carbonate in limestone (Chou et al., 1989). The dissolution of quartz minerals such as aluminium, potassium and iron fractions has also been reported by Dove and Rimstidt (1994).

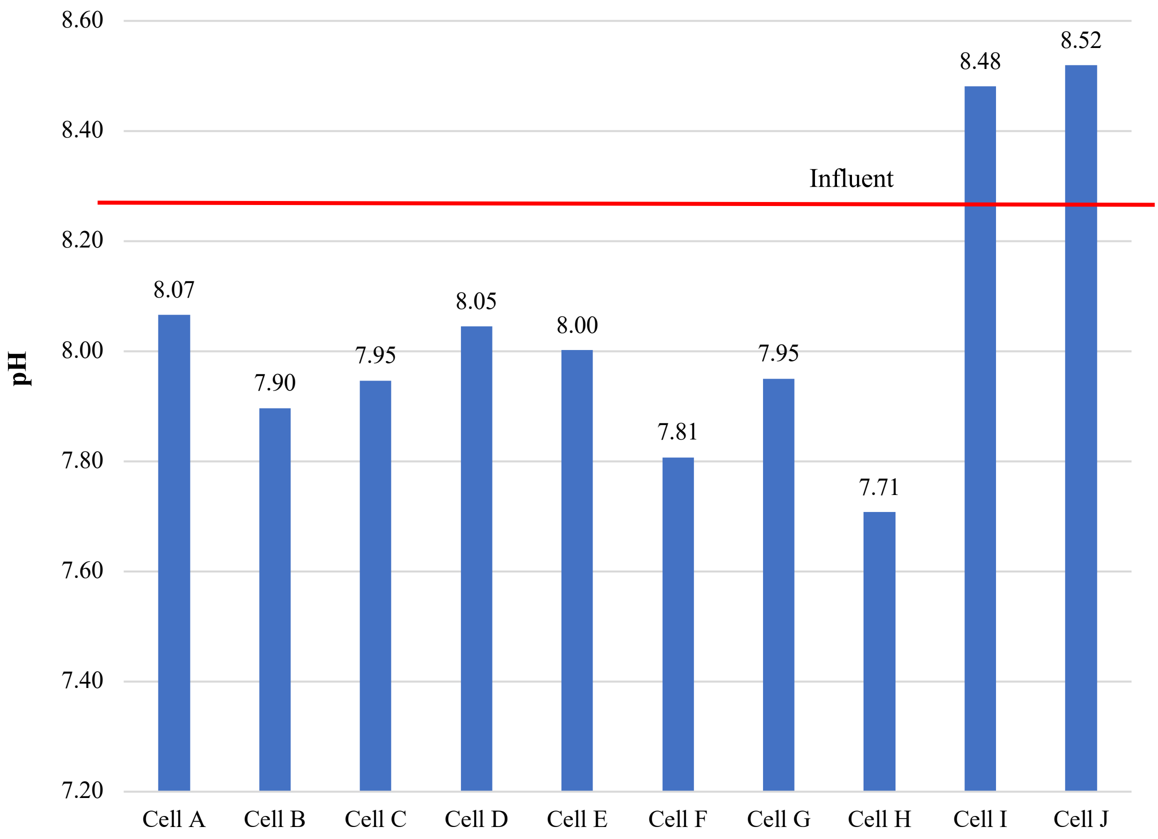


Figure 4-24: Mean pH for each PPS cells

The pH of the cells falls within the range of 7.6-8.8 for growth of *Nitrosomonas* and *Nitrobacter*. The relationship between the pH and nitrate-nitrogen concentration is shown in Figure 4-25. It can be clearly seen that the PPS Cell with the highest pH produced the lowest nitrate-nitrogen concentration in the effluent whilst the PPS cell with the lowest pH produced the highest. This results correspond to the findings from Collins *et al.* (2010b); Drake *et al*. (2014) and Brown & Borst (2015).

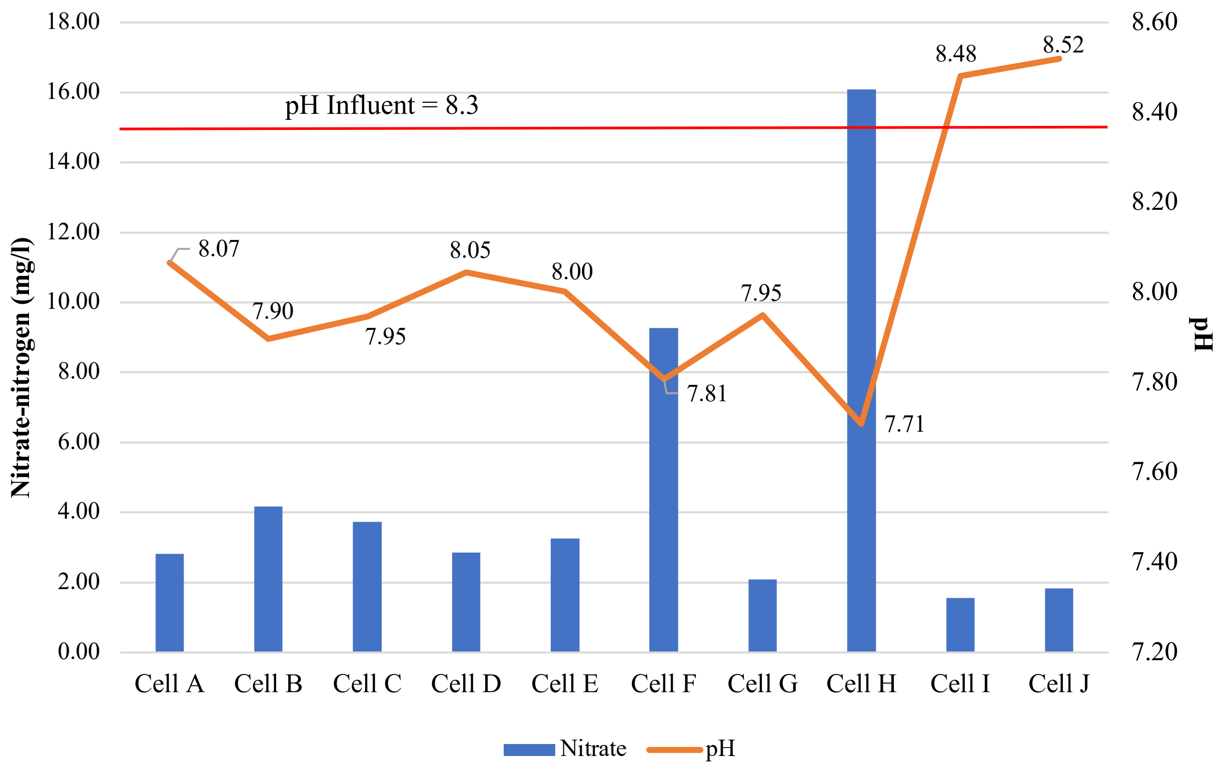


Figure 4-25: Relationship between pH and nitrate-nitrogen concentration

4.5 NEB parking lot

As mentioned in Section 3.8.3, field testing on the water quality of PICP were conducted in the NEB parking lot at UCT. Five samples were collected from each of the PPS section's monitoring chamber from 2018 to 2019 after each of four major storm events (Table 3-10). The pH, temperature and EC were immediately tested on the collected samples by using the electrical probes, and the samples were then sent to the water quality lab in NEB to analyze the TSS, nitrate-nitrogen, nitrite-nitrogen, ammonia-nitrogen and orthophosphate-phosphorus effluent concentration. Plots of pH, EC and TSS, ammonia-nitrogen, nitrite-nitrogen, nitrate-nitrogen and orthophosphate-phosphorus effluent concentrations were generated for each pavement section with the aim of determining the impact of geotextile on the water quality of the exfiltrate emanating from the permeable pavement systems.

4.5.1 TSS

Figure 4-26 shows the TSS effluent concentrations from all three pavement sections (two permeable sections and one impermeable section) on the NEB parking lot. It can be seen that the impermeable NEB-I section with the surface runoff has the highest TSS effluent concentrations possibly emanating from the surrounding trees and litter on the road. NEB-B (without geotextile) and NEB-A (with geotextile) have much lower TSS discharges compared with the influent / surface runoff which further supports other studies that have shown the excellent TSS removal efficiencies from the permeable pavement systems (Legret & Colandini, 1999; Pagotto *et al.*, 2000; Bean *et al.*, 2007; Brown *et al.*, 2009). The PICP with the geotextile discharges lower TSS than the PICP without geotextile as can be seen by comparing the TSS from NEB-A with that from NEB-B. This suggests that the presence of geotextile in the PICP reduces the TSS effluent concentrations by preventing the fine particles flowing downward into the aggregate layers.

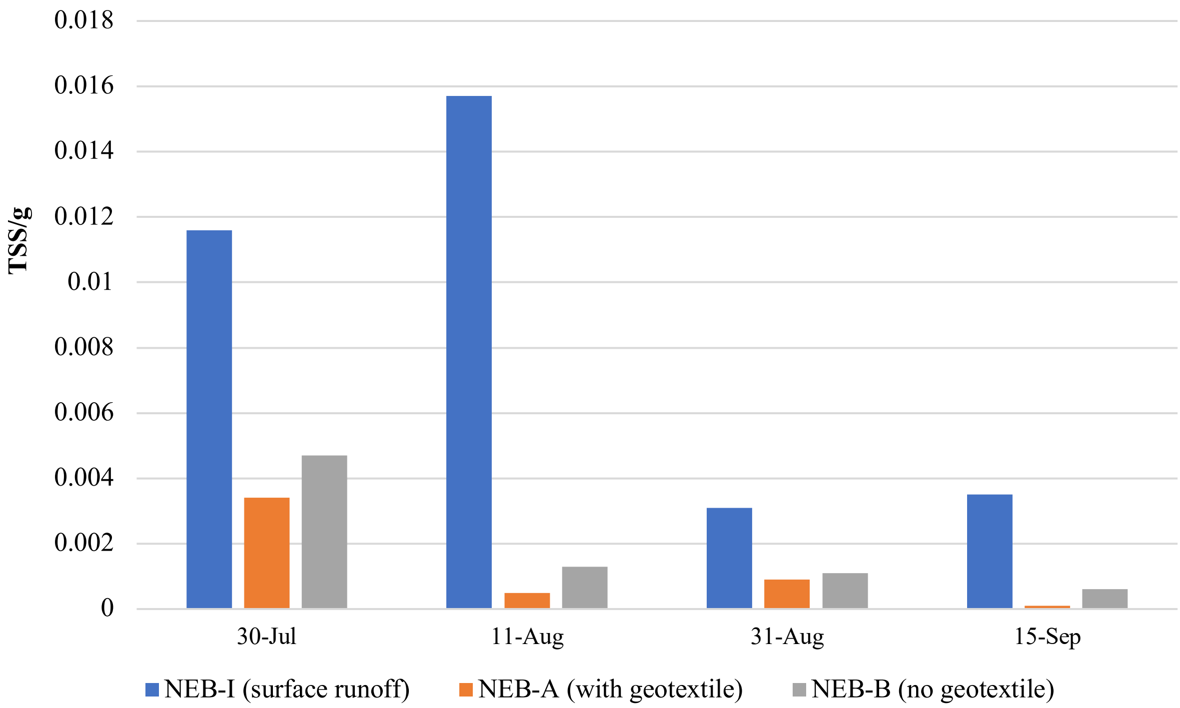


Figure 4-26: TSS effluent concentrations measured from the NEB parking lot

4.5.2 Orthophosphate-phosphorus

Figure 4-27 shows the orthophosphate-phosphorus effluent concentrations from all three pavement sections on the NEB parking lot. From the graph, there is insufficient information to determine whether there is a trend in the orthophosphate-phosphorus effluent concentrations over time.

Figure 4-28 shows the mean effluent concentrations of orthophosphate-phosphorus from all three pavement sections, and it shows that the surface runoff has the highest mean orthophosphate-phosphorus effluent concentration which indicates that PICP has a orthophosphate-phosphorus removal ability. By comparing the effluent concentration of orthophosphate-phosphorus discharged by NEB-A (with geotextile) and NEB-B (without geotextile), it was found that they have similar orthophosphate-phosphorus effluent concentrations with NEB-A (with geotextile) being slightly lower than NEB-B (without geotextile) (50.9% versus 49.1%). It is hard to say on whether the presence of a geotextile has an impact on the orthophosphate-phosphorus removal.

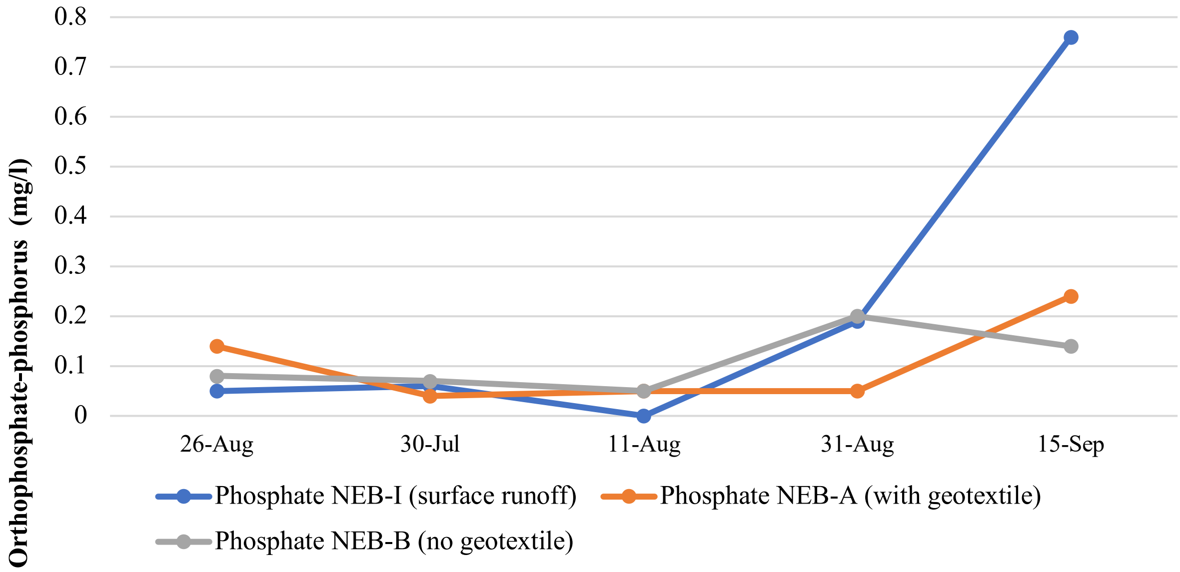


Figure 4-27: Effluent concentrations of orthophosphate-phosphorus measured from the NEB parking lot

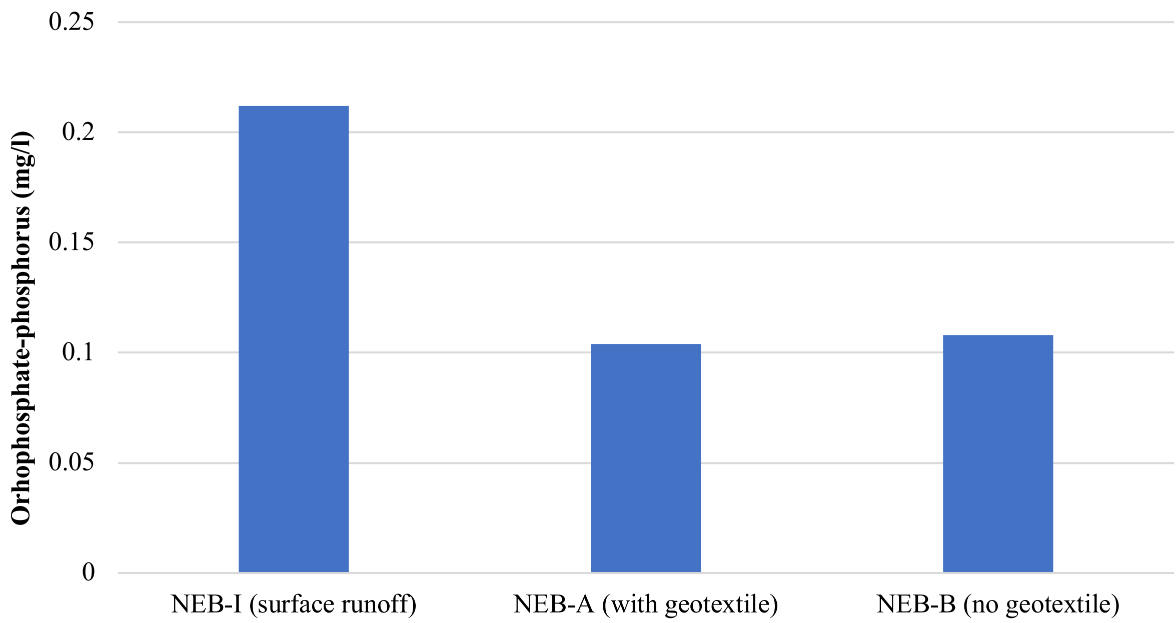


Figure 4-28:Mean orthophosphate-phosphorus effluent concentrations measured from the NEB parking lot

4.5.3 Ammonia-nitrogen

Figure 4-29 shows the ammonia-nitrogen effluent concentrations from all three pavement sections on the NEB parking lot. From the graph, there is insufficient information to see if there is trend of ammonia-nitrogen effluent concentrations change with time.

Figure 4-30 shows the mean effluent concentrations of ammonia-nitrogen from all three pavement sections, and it shows that the surface runoff has the highest ammonia-nitrogen effluent concentration which indicates that PICP has ammonia-nitrogen removal ability. By comparing the effluent concentration of ammonia-nitrogen between NEB-A (with geotextile) and NEB-B (without geotextile), it was found NEB-A with a geotextile discharged less ammonia-nitrogen than NEB-B without a geotextile (62.1% versus 37.9%).. This suggests the presence of geotextile has a positive impact on the ammonia-nitrogen removal.

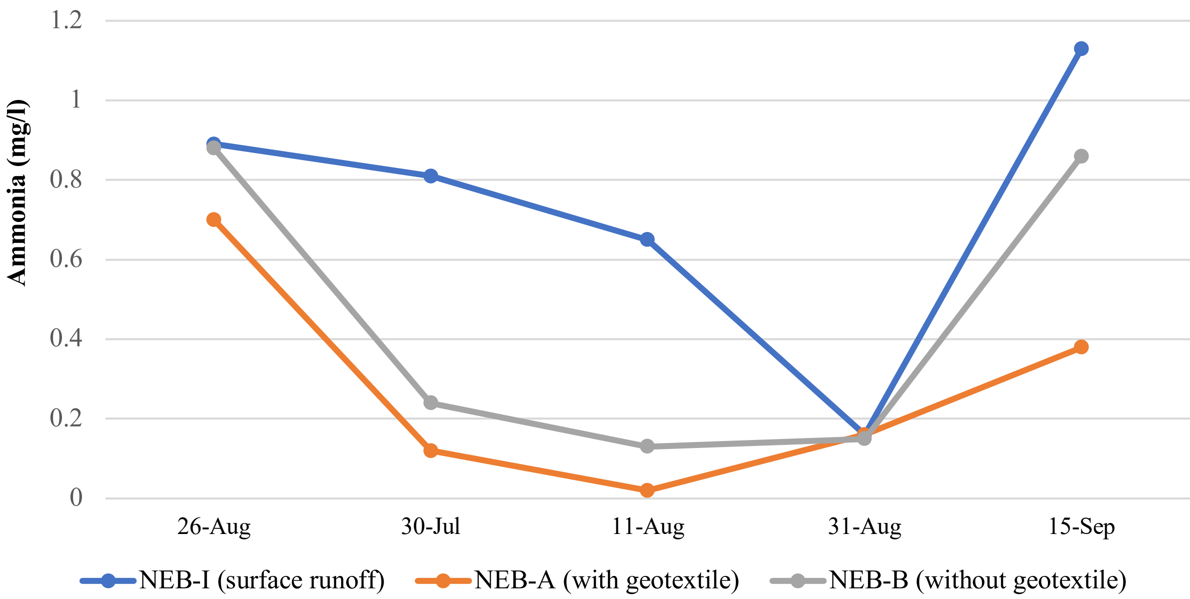


Figure 4-29: Effluent concentrations of ammonia-nitrogen measured from the NEB parking lot

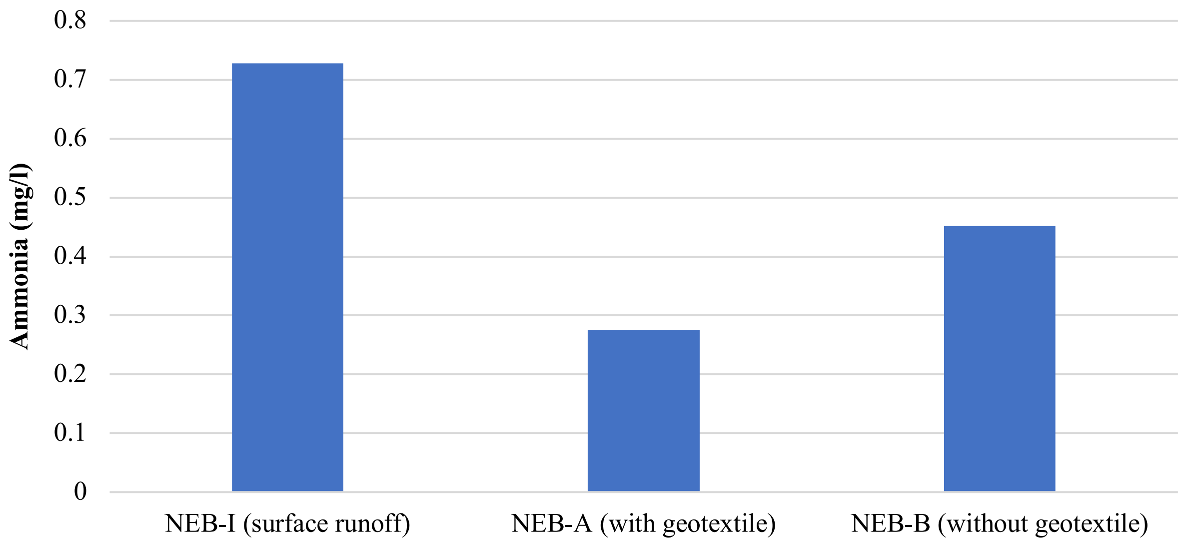


Figure 4-30:Mean ammonia-nitrogen effluent concentrations measured from the NEB parking lot

4.5.4 Nitrate-nitrogen

Figure 4-31 shows the nitrate-nitrogen effluent concentration from all three pavement sections on the NEB parking lot. From the graph, there is insufficient information to see if there is trend of nitrate-nitrogen effluent concentrations change with time.

Figure 4-32 shows the mean effluent concentrations of nitrate-nitrogen from all three pavement sections, and it shows that the NEB-A section with geotextile has the highest nitrate-nitrogen effluent concentration, and the NEB-B section without geotextile has the lowest nitrate-nitrogen effluent concentration. This suggests the presence of geotextile results in higher nitrate-nitrogen which corresponding to the result from Section 4.4.3. It also shows that PICP is not ideal for nitrate-nitrogen removal.

The range of pH is between 7.65 – 8.32 which falls within the range of 7.6-8.8 for growth of Nitrosomonas and Nitrobacter which are the bacteria responsible for nitrifying ammonium to nitrite-nitrogen and then to nitrate-nitrogen. Figure 4-33 shows the relationship between the pH and nitrate-nitrogen effluent concentrations, and it shows that the PICP (NEB-A) (with geotextile) with the highest pH corresponds to the lowest nitrate-nitrogen effluent concentration, and the PICP (NEB-B) (without geotextile) with lowest pH corresponding to the highest nitrate-nitrogen effluent concentration. This finding also correspond to the result from Section 4.4.6.

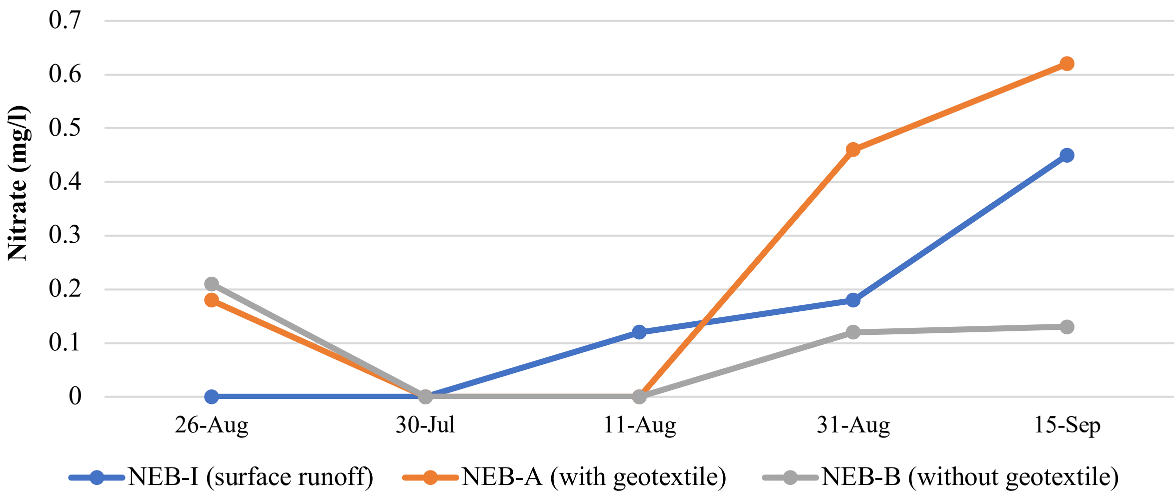


Figure 4-31: Effluent concentrations of nitrate-nitrogen measured from the NEB parking lot

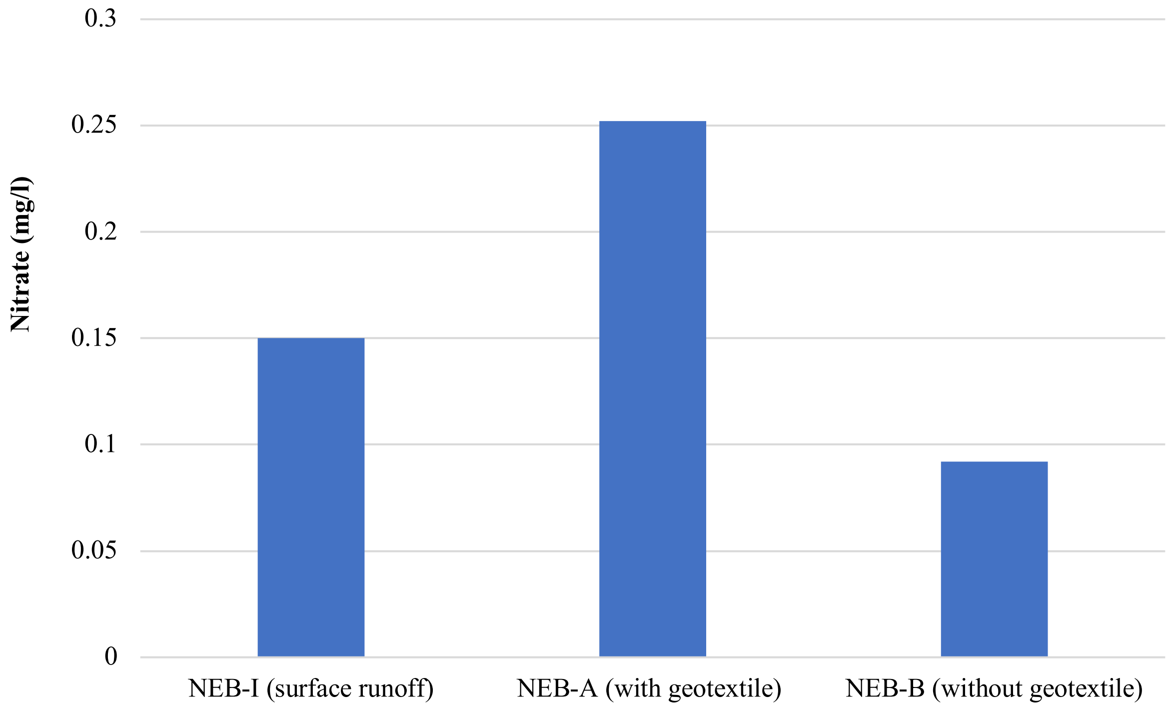


Figure 4-32: Mean nitrate-nitrogen effluent concentrations measured from the NEB parking lot

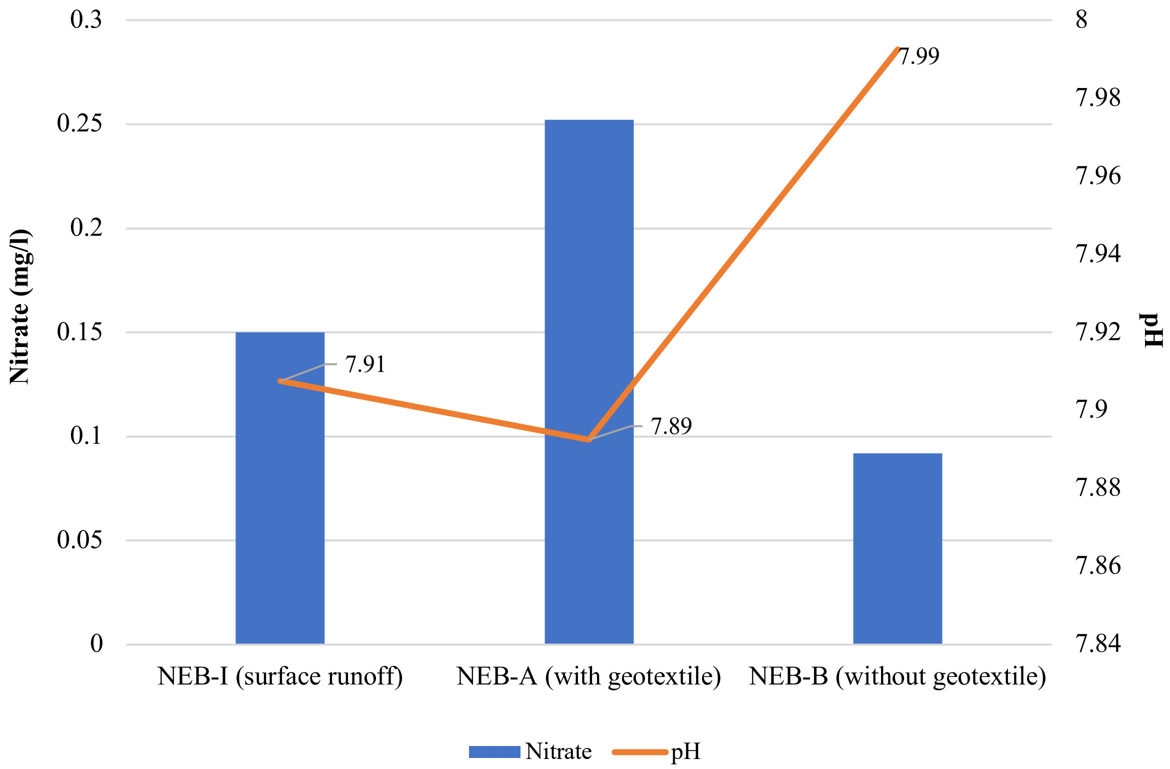


Figure 4-33: Relationship between pH and nitrate-nitrogen effluent concentrations

4.6 Summary

The summary of the above findings is:

- The infiltration rates for all ten PICP cells were uniformly high – ranging between 9,900 and 17,600 mm/h. The results show that the types of pavers and the presence of geotextile are the two factors that influence the infiltration rate. Larger openings between the pavers result in higher infiltration rates, and the presence of geotextile in the PICP lowers the infiltration rate.
- The clean water test was to provide base-line pollutant levels before the addition of the synthetic stormwater. Ten samples were collected in the clean water test and the pH, temperature, EC, ammonia-nitrogen, orthophosphate-phosphorus, nitrite-nitrogen and nitrate-nitrogen were tested for each sample. The result shows all ten PICP cells introduced pollutants (higher ammonia-nitrogen, orthophosphate-phosphorus, nitrite-nitrogen and nitrate-nitrogen effluent concentrations) to the system, and these added pollutants was assumed to come from the aggregate layers in the PICP system. This finding further supports the importance of sufficiently clean aggregates so as to minimize the added pollutant concentration from the PICP itself.

- The quality of the discharged effluent from all ten PICP cells in the clean water test was assessed to determine the severity of the effluent's pollutant concentration to the CoCT riverine system. The results show the ammonia-nitrogen effluent concentration from PICP would not pose a risk to the ecosystem, however the orthophosphate-phosphorus and nitrate-nitrogen effluent concentrations fall within the unacceptable category in the Ecosystem Health criteria. This indicates a second treatment system is probably needed after the PICP to prevent polluted water discharged into the riverine system and ecosystem degradation.
- Synthetic stormwater testing was done to determine the pollutant (ammonia-nitrogen, orthophosphate-phosphorus, nitrite-nitrogen and nitrate-nitrogen) removal ability of different PICP design. The results from Phase 1 show PICP can remove ammonia-nitrogen efficiently (23% to 89%), however, all ten PICP cells added orthophosphate-phosphorus (22% to 120%) which may due to dirty aggregates. It was found the presence of geotextile resulted in higher ammonia-nitrogen removal efficiencies compared with the ones without, and the cells with washed aggregates had higher ammonia-nitrogen removal than ones with unwashed aggregates. It was further found the cell with a raised outlet (creating a 'sump' in the underlying stone aggregate) had the highest ammonia-nitrogen removal.
- The results from Phase 2 were similar to Phase 1. It was found PICP can efficiently remove ammonia-nitrogen (25% to 79%), however, the removal of orthophosphate-phosphorus from the PICP is not significant (-37% to 11%). It was further found all ten PICP cells added significant quantities of nitrate-nitrogen and nitrite-nitrogen which may due to the nitrification process of ammonia-nitrogen to nitrate-nitrogen; The presence of geotextile was also found to have positive impact on ammonia-nitrogen removal compared with the ones without, and the cells with unwashed aggregates introduced more ammonia and orthophosphate-phosphorus effluent concentrations to the system. It was also found the cell with a raised outlet had the highest ammonia-nitrogen removal however the cell has the highest nitrate-nitrogen effluent concentration, suggesting better nitrification transforming ammonia-nitrogen into nitrate-nitrogen.
- It was found when pH is within the optimum range of 7.6 to 8.8 for growth of nitrifying bacteria, lower pH results in higher nitrate-nitrogen concentration.
- The electrical conductivity was found to be strongly dependant on the length of the period between rainfall 'seasons'; it decreases during the wet periods and increases during the dry period. This finding could be related to the presence of bacterial colonies within the PICP systems that become active during wet periods and inactive during dry periods.
- The field testing results from NEB parking show the PICP are efficiently removing TSS, ammonia-nitrogen and orthophosphate-phosphorus. The PICP with geotextile was found to have positive impact on TSS, ammonia-nitrogen and orthophosphate-phosphorus removal than the one without. It was also found the presence of geotextile has negative

impact on nitrate-nitrogen removal, with lower pH resulting in higher nitrate-nitrogen concentrations which agrees the findings from Phase 2: Synthetic stormwater test.

5. Conclusions and Recommendations

This chapter details the conclusions drawn from the study, discusses some methodological and operational challenges associated with this study, and makes recommendations for future research.

5.1 Conclusions

- The infiltration rate is affected by the types of paver. In this experimental study, the exposed aggregate pavers had the highest infiltration rate followed by the Permealock pavers with the Aquapave® pavers having the lowest infiltration rate amongst the three types of pavers. This can be explained by considering the size of the openings between the pavers; the larger the opening, the larger the infiltration rate.
- The infiltration rate is affected by the type of geotextile if present. In this experimental study, the cells with no geotextile had the highest infiltration, followed by the Kaytech bidim geotextile, then the Inbitex geotextile with the Fibertex geotextile having the lowest infiltration rate. The infiltration through a geotextile is closely related to the through flow rate of the geotextile which was determined by its permeability through pore size. Therefore, it can be concluded that using a geotextile that has higher pore size, permeability and through flow rate will result in higher infiltration rate.
- The 'clean water test' results shows the 'base-line' pollutant level for the selected pollutant (pH, temperature, EC, TSS, ammonia-nitrogen, orthophosphate-phosphorus, nitrite-nitrogen and nitrate-nitrogen). The result shows all ten PICP cells introduced higher ammonia-nitrogen, orthophosphate-phosphorus, nitrite-nitrogen and nitrate-nitrogen effluent concentrations to the system, and these added pollutants were assumed to come from the aggregate layers in the PICP system.
- The removal efficiency of ammonia-nitrogen from synthetic stormwater ranged from 27.5% to 78.7% compared with the average of 63.7% removal rate from other studies. It was also found that: the cells with geotextiles present had higher ammonia-nitrogen removal efficiencies than the ones without; the cells with washed aggregates had higher ammonia-nitrogen removal efficiency than the ones with unwashed aggregates; and the cell with the raised outlet (creating a 'sump' in the underlying stone aggregate) had the highest ammonia-nitrogen removal efficiency of all.
- All the experimental cells demonstrated appeared to add significant quantities of nitrate-nitrogen having nitrate-nitrogen addition ranging from 160% to 2580% which may be due to the nitrification process of ammonia-nitrogen (NH_3) to nitrate-nitrogen (NO_3^-). The cell with the submerged zone produced the most nitrate-nitrogen. It was also found that the presence of geotextile has a negative impact on the nitrate-nitrogen removal efficiencies. A relationship between nitrate-nitrogen concentration and pH was found. When pH is within

the optimum range of 7.6-8.8 for growth of nitrifying bacteria, the nitrification process will occur and promote the reduction of ammonia-nitrogen effluent concentrations and an increase in nitrate-nitrogen effluent concentrations. Lower pH results in higher nitrate-nitrogen concentrations.

- The removal efficiency for orthophosphate-phosphorus ranged from -37% to 11% compared with the average of 47.7% removal rate of orthophosphate-phosphorus in other studies. The presence of a geotextile resulted in a higher orthophosphate-phosphorus removal efficiency than those without; the cells with washed aggregates had a higher orthophosphate-phosphorus removal efficiency than the ones with unwashed aggregates. It was also found that the cell with elevated outlet (sump) had the least orthophosphate-phosphorus removal efficiency which might due the fine particles being slowly washed through the PPS and desorption due to changing pH and oxygen levels.
- It was also found that the electrical conductivity strongly depends on the length of the periods between rainfall ‘seasons’; it decreases rapidly during wet periods and increases slowly during the dry periods.

5.2 Methodological and operational challenges

- During the process of the infiltration test, it was quite difficult to maintain a constant head between the two marked lines (10mm and 15mm) in the infiltrometer when pouring water onto the ring. In addition, it was quite hard to prevent water loss during the transport of water from the tap to the PPS structure.
- Due to the time and budgetary constraints, only limited amount of testing on the selected pollutant (TSS, Ammonia-nitrogen, orthophosphate-phosphorus, nitrite-nitrogen and nitrate-nitrogen) could be made.

5.3 Recommendations

- A rainfall simulator could be installed to facilitate rainfall generation. Advantages include: it can provide rain ‘on-demand’ and it is easier to vary the flow rate. On the other hand, it is generally not as accurate as systems where the volume of the water to be applied can be weighed – such as with a watering can.
- More testing for the selected pollutants ammonia-nitrogen, orthophosphate-phosphorus, nitrite-nitrogen, nitrate-nitrogen, heavy metals and microorganisms is needed in order to get a more representative data to thoroughly analyse the treatment performance of PPS.
- Introducing electron donors such as carbon, iron or sulphur into the permeable pavement systems could allow research on the conditions required for denitrification.

- Long term evaluation to establish the variation in performance over time – particularly considering wet and dry cycles; and
- Testing for biofilm growth and microbial activity to understand the mechanism of nitrogen removal.

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Appendix A

(Sample calculation)

A1. Preparation of the revised synthetic stormwater

The revised synthetic stormwater mix was made from a mixture of ammonium chloride, di-potassium hydrogen orthophosphate-phosphorus and potassium nitrate-nitrogen respectively. The sample calculation for the phosphorous is shown below:

$$\text{Molar mass of P} = 30.974\ \text{g/mol}$$

$$\text{Molar mass of } K_2HPO_4 = 39.098 \times 2 + 1.008 + 30.974 + 15.999 \times 4 = 174.174\ g/mol$$

$$\text{Desired concentration of P}O_4{}^{3-} = 0.8\ mg/l$$

$$\text{Total Mass} = \frac{\text{Desired concentration } \times \frac{MM\ of\ K_2HPO_4}{MM\ of\ P}}{1000}$$

$$\text{Desired Mass} = \text{Total Mass } \times \text{Dilution water}$$

For example, to calculate the mass of di-potassium hydrogen orthophosphate-phosphorus (K_2HPO_4) needed for the day 6th of August rainfall event. It was first seen from that the volume of rainfall needed for each PICP cell is 23 ℓ, as there are 10 cells, it means that a total of 230 ℓ of stormwater needs to be prepared in Jojo tank. In order to prepare the concentration of 0.8 mg/ℓ of orthophosphate-phosphorus standard solution for 230 ℓ of stormwater, a 2 ℓ volumetric flask was used to prepare the concentrated solution. The sample calculation is shown below:

$$\text{Total Mass} = \frac{\text{Desired concentration } \times \frac{MM\ of\ K_2HPO_4}{MM\ of\ P}}{1000}$$

$$\text{Total Mass} = \frac{0.8\ mg/l \times \frac{174.174\ g/mol}{0.974\ \text{g/mo}}}{1000} = 0.0045\ g$$

$$\text{Desired Mass} = \text{Total Mass } \times \text{Dilution water} = 0.0045\ \text{g} \times 230\ \text{l} = 1.0347\text{g}$$

From the calculation above, the mass of K_2HPO_4 is 1.0347g for the 6th of August rainfall event to meet the concentration of 0.8 mg/ℓ of PO_4^{3-}. The mass of Ammonium chloride (NH_4Cl) and potassium nitrate-nitrogen (KNO_3) is calculated the same way in order to meet the concentration of ammonia-nitrogen and nitrate-nitrogen.

In Phase 1, the fertilizer was mixed in a watering can immediately prior to be poured onto one of the PICP cells. For Phase 2, the mixing of the chemicals was carried out in a 2 ℓ volumetric flask (Figure A-1) prior to being added to a pre-determined volume of tap water in a 500 ℓ storage tank.

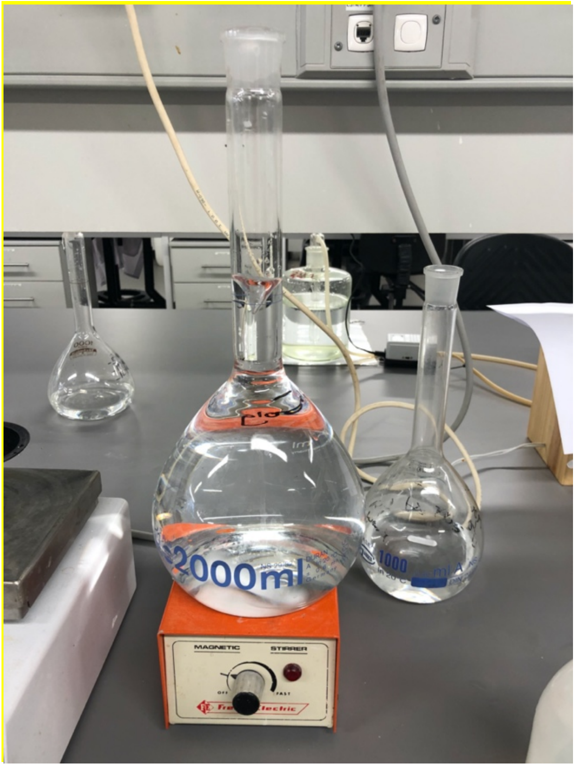


Figure A-1: Preparing the concentrated nutrient solution prior to addition to tap water to create the synthetic stormwater

A2. Event mean concentration

The event mean concentration (EMC) efficiency method is used to determine the average reduction of pollutant concentration for a given stormwater treatment practice. EMC is in units of mass per volume (mg/L) and is determined by using the total pollutant loading per event divided by the total runoff volume per event. It was used to quantify the average pollutant load washed off during a storm event concerning the event runoff volume (Maniquiz et al., 2010). The equation used for the determination of the EMC is shown below.

$$EMC = \frac{total\ pollutant\ loading\ per\ event}{total\ runoff\ volume\ per\ event} = \frac{\sum_{i=1}^{n} ViCi}{V}$$

Where

EMC is event mean concentration, mg/ℓ

V is total runoff volume per event, ℓ

Vi is runoff volume proportional to the flow rate at time i, ℓ

Ci is pollutant concentration at time i, mg/ℓ

n is total number of samples during a single storm event

The "Efficiency ratio" (ER) method was used to calculate the removal efficiency for each pollutants to assess the treatment performance for different design of the PPS bins.

$$\text{Removal } \% = \frac{Average\ inlet\ EMC - Average\ outlet\ EMC}{Average\ inlet\ EMC}$$

Equation A-1

.

Appendix B

(Infiltration test)

Infiltration Test Data Form

Tested by: Kimberly Liu

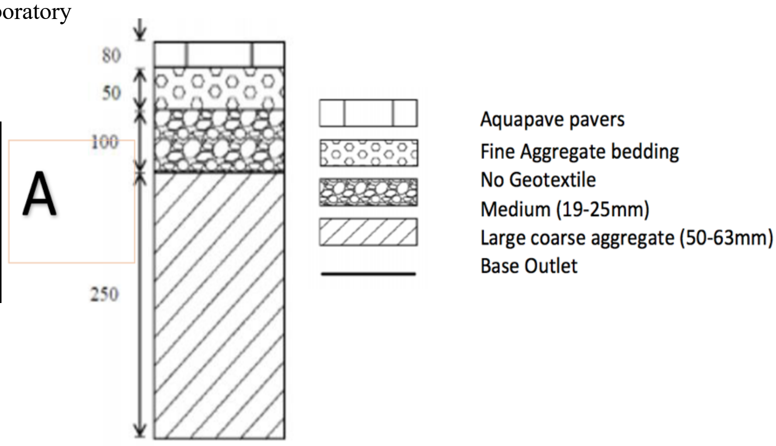
Date: __01__ /__08__/2017

Project Identification: Cell A

Test Location: Civil Engineering Laboratory

Liquid Used: Water

Paving Units	
Age:	NA
Type:	Aquapave
Thickness:	80 mm



Photograph before

Photograph After

Trial No.	Time elapsed (s)	Weight of infiltrated water (kg)	Inner ring diameter (mm)	K (mm3s/kgh)	Infiltration rate mm/h
Pre-wetting	17.3	3.610	300	4583666000	10627,51076
Test	78.4	18.020	300	4583666000	11706,01776

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Infiltration Test Data Form

Tested by: Kimberly Liu

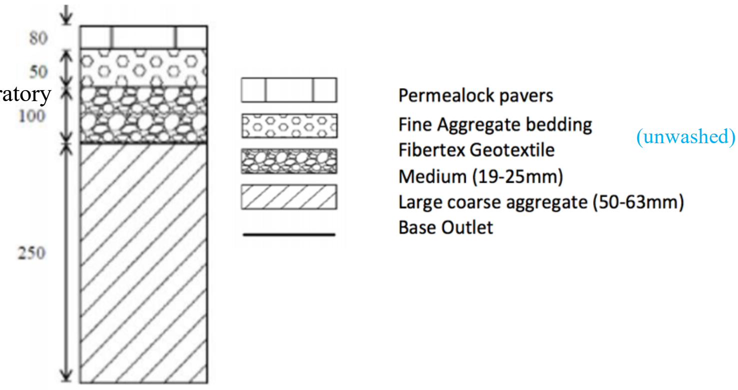
Date: __01__ / _08___/2017

Project Identification: Cell B

Test Location: Civil Engineering Laboratory

Liquid Used: Water

B



Paving Units	
Age:	NA
Type:	Permealock
Thickness:	80 mm

Photograph before

Photograph After:

Trial No.	Time elapsed (s)	Weight of infiltrated water (kg)	Inner ring diameter (mm)	K (mm3s/kgh)	Infiltration rate mm/h
Pre-wetting	12.5	3.620	300	4583666000	14749
Test	59.15	18.010	300	4583666000	15507

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Infiltration Test Data Form

Tested by: Kimberly Liu

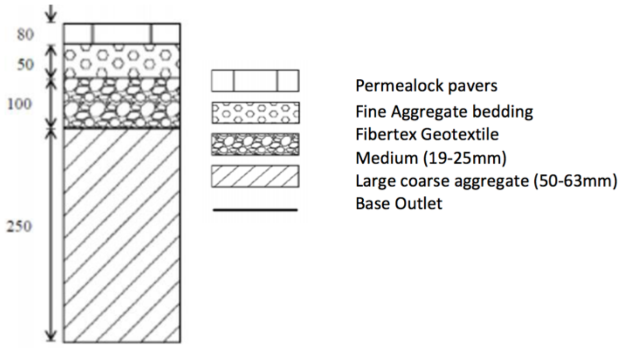
Date: __01__ /__08__/2017

Project Identification: Cell C

Test Location: Civil Engineering Laboratory

Liquid Used: Water

C



Paving Units	
Age:	NA
Type:	Peamealock
Thickness:	80 mm

Photograph before:

Photograph After:

Trial No.	Time elapsed (s)	Weight of infiltrated water (kg)	Inner ring diameter (mm)	K (mm3s/kgh)	Infiltration rate mm/h
Pre-wetting	12.6	3.610	300	4583666000	14592
Test	60.3	18.010	300	4583666000	15211

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Infiltration Test Data Form

Tested by: Kimberly Liu

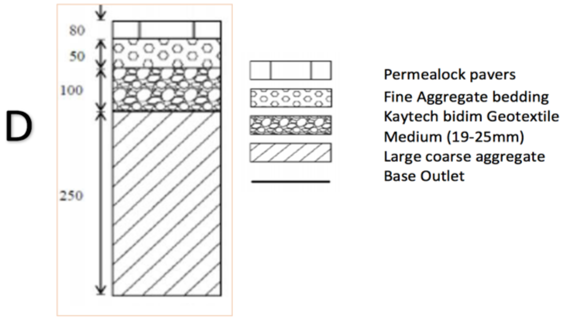
Date: __01__ /__08__/2017

Project Identification: Cell D

Test Location: Civil Engineering Laboratory

Liquid Used: Water

Paving Units	
Age:	NA
Type:	Peamealock
Thickness:	80 mm



Photograph before:

Photograph After:

Trial No.	Time elapsed (s)	Weight of infiltrated water (kg)	Inner ring diameter (mm)	K (mm3s/kgh)	Infiltration rate mm/h
Pre-wetting	11.5	3.610	300	4583666000	15987
Test	57.2	18.010	300	4583666000	16036

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Infiltration Test Data Form

Tested by: Kimberly Liu

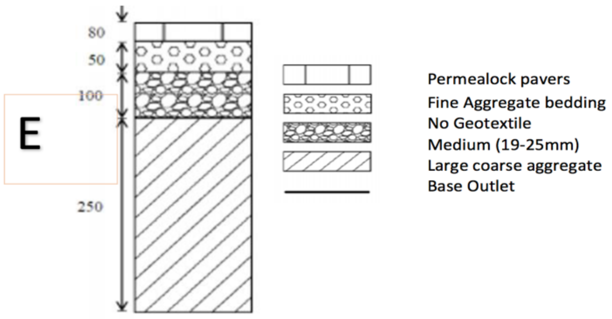
Date: __01__ / __08__/2017

Project Identification: Cell E

Test Location: Civil Engineering Laboratory

Liquid Used: Water

Paving Units	
Age:	NA
Type:	Permealock
Thickness:	80 mm



Photograph before:

Photograph After:

Trial No.	Time elapsed (s)	Weight of infiltrated water (kg)	Inner ring diameter (mm)	K (mm3s/kgh)	Infiltration rate mm/h
Pre-wetting	13.9	3.610	300	4583666000	13227
Test	66.5	18.010	300	4583666000	13793

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Infiltration Test Data Form

Tested by: Kimberly Liu

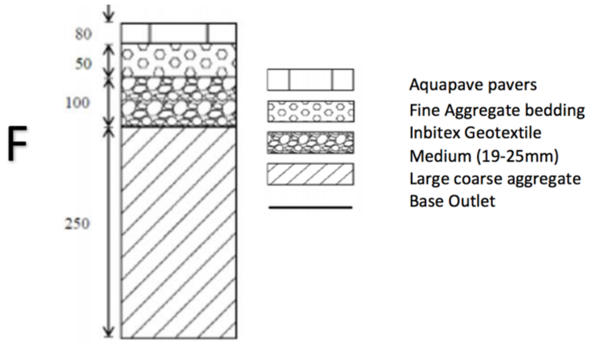
Date: ___01_ / _08___/2017

Project Identification: Cell F

Test Location: Civil Engineering Laboratory

Liquid Used: Water

Paving Units	
Age:	NA
Type:	Aquapave
Thickness:	80 mm



Photograph before:

Photograph After:

Trial No.	Time elapsed (s)	Weight of infiltrated water (kg)	Inner ring diameter (mm)	K (mm3s/kgh)	Infiltration rate mm/h
Pre-wetting	18.02	3.610	300	4583666000	10203
Test	92.4	18.010	300	4583666000	9927

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Infiltration Test Data Form

Tested by: Kimberly Liu

unwashed

Date: __01__ /__08__/2017

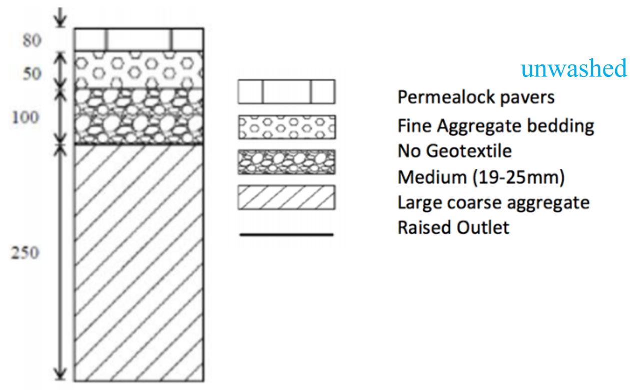
Project Identification: Cell G

Test Location: Civil Engineering Laboratory

Liquid Used: Water

Paving Units	
Age:	NA
Type:	Permealock
Thickness:	80 mm

G



Photograph before:

Photograph After:

Trial No.	Time elapsed (s)	Weight of infiltrated water (kg)	Inner ring diameter (mm)	K (mm3s/kgh)	Infiltration rate mm/h
Pre-wetting	17.5	3.610	300	4583666000	10506
Test	88.2	18.010	300	4583666000	10400

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Infiltration Test Data Form

Tested by: Kimberly Liu

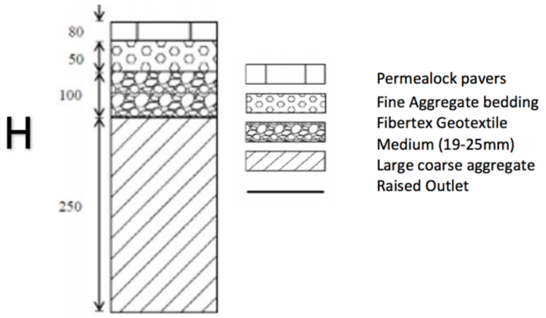
Date: __01__ /__08__/2017

Project Identification: Cell H

Test Location: Civil Engineering Laboratory

Liquid Used: Water

Paving Units	
Age:	NA
Type:	Permealock
Thickness:	80 mm



Photograph before:

Photograph After:

Trial No.	Time elapsed (s)	Weight of infiltrated water (kg)	Inner ring diameter (mm)	K (mm3s/kgh)	Infiltration rate mm/h
Pre-wetting	16.6	3.610	300	4583666000	11076
Test	78.8	18.010	300	4583666000	11640

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Infiltration Test Data Form

Tested by: Kimberly Liu

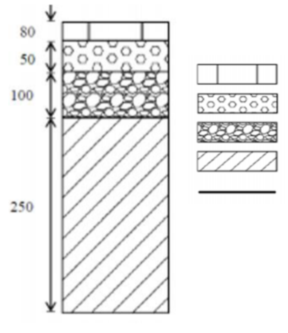
Date: __01__ /__08__/2018

Project Identification: Cell I

Test Location: Civil Engineering Laboratory

Liquid Used: Water

Paving Units	
Age:	NA
Type:	Exposed paver
Thickness:	80 mm



Trial No.	Time elapsed (s)	Weight of infiltrated water (kg)	Inner ring diameter (mm)	K (mm3s/kgh)	Infiltration rate mm/h
Pre-wetting	11.79	3.60	300	4583666000	15551
Test	52.07	18.00	300	4583666000	17605

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Infiltration Test Data Form

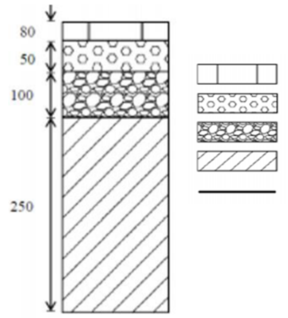
Tested by: Kimberly Liu

Date: __01__ /__08__/2018

Project Identification: Cell J

Test Location: Civil Engineering Laboratory

Liquid Used: Water



Paving Units	
Age:	NA
Type:	Exposed paver
Thickness:	80 mm

Trial No.	Time elapsed (s)	Weight of infiltrated water (kg)	Inner ring diameter (mm)	K (mm3s/kgh)	Infiltration rate mm/h
Pre-wetting	14.75	3.60	300	4583666000	12430
Test	63.00	18.00	300	4583666000	14551

Appendix C

(Data)

C1. EC 2017

Date	Cell A	Cell B	Cell C	Cell D	Cell E	Cell F	Cell G	Cell H
Day 1	590	723	699	737	525	608	652	704
Day 2	574	746	669	781	619	614	671	725
Day 3	828	901	772	831	745	746	786	804
Day 4	872	971	848	897	851	861	835	880
Day 5	708	895	774	727	692	861	845	933
Day 6	552	955	556	113	616	814	810	894
Day 7	605	925	573	639	601	740	714	927
Day 8	632	817	560	606	511	667	661	904

C2. Ammonia-nitrogen 2017 & 2019 April

Date	Influent	Cell A	Cell B	Cell C	Cell D	Cell E	Cell F	Cell G	Cell H
2017 Day 1	16.15	8.00	3.60	1.98	8.26	6.72	1.77	11.69	0.55
2017 Day 5	2.00	1.83	1.07	1.77	1.24	1.14	1.15	1.8	0.32
2017 Day 9	2.00	2.28	2.86	3.58	2.07	3.49	1.12	1.48	0.29
2019 Day 1	16.15	18.05	22.35	7.84	15.36	17.64	15.99	14.73	0.69
2019 Day 5	2.00	0.47	0.39	0.63	27.48	30.11	14.04	1.46	0.33
2019 Day 9	2.00	0.18	0.34	0.26	0.19	0.28	0.29	1.28	0.30

C3. Orthophosphate-phosphorus 2017 & 2019 April

Date	Influent	Cell A	Cell B	Cell C	Cell D	Cell E	Cell F	Cell G	Cell H
2017 Day 1	31.07	18.41	13.75	5.88	17.24	15.97	4.68	26.47	2.52
2017 Day 5	3.59	14.27	10.91	15.42	11.63	12.23	21.6	10.93	14.86
2017 Day 9	3.59	4.47	3.30	4.19	3.65	3.82	4.20	3.27	7.42
2019 Day 1	20.63	15.89	6.17	19.40	20.49	18.5	17.41	22.75	7.07
2019 Day 5	5.28	11.87	8.23	14.70	16.53	13.11	21.20	10.09	13.41
2019 Day 9	4.21	3.04	4.41	4.74	3.49	4.58	4.20	4.05	8.55

C4. pH 2019 April

Date	Cell A	Cell B	Cell C	Cell D	Cell E	Cell F	Cell G	Cell H	Cell I	Cell J
Day 1	7.87	7.96	7.84	7.82	7.76	7.37	7.85	8.04	7.98	7.98
Day 2	7.35	7.90	7.40	7.68	7.70	7.85	8.13	7.80	8.08	8.20
Day 3	7.55	7.85	7.75	7.40	7.66	7.71	7.58	7.80	7.65	7.87
Day 4	7.37	7.60	7.39	7.52	7.73	7.69	7.79	7.80	8.20	8.02
Day 5	7.87	8.04	7.82	7.49	8.05	8.03	8.01	7.89	8.25	8.45
Day 6	7.50	7.78	7.78	7.85	7.86	7.77	7.92	7.72	8.14	8.12
Day 7	7.74	7.75	7.73	7.82	7.80	7.76	7.85	7.71	8.06	7.97
Day 8	7.81	7.88	7.51	7.60	7.58	7.52	7.65	7.22	7.63	7.53

C5. EC 2019 April

Date	Cell A	Cell B	Cell C	Cell D	Cell E	Cell F	Cell G	Cell H	Cell I	Cell J
Day 1	1030	1311	893	895	1087	859	1033	1076	1110	785
Day 2	1204	1327	1074	1024	1087	932	1033	1055	1110	785
Day 3	1171	1278	1038	1140	1068	976	992	1055	866	780
Day 4	967	1084	1015	1016	1012	1173	947	1075	524	877
Day 5	735	892	974	775	742	939	712	1086	485	544
Day 6	673	796	879	709	619	842	578	1051	464	477
Day 7	597	740	781	657	642	819	613	981	457	484
Day 8	526	761	675	618	628	754	577	983	461	449

C6. Ammonia-nitrogen 2019 August

Date	Influent	Cell A	Cell B	Cell C	Cell D	Cell E	Cell F	Cell G	Cell H	Cell I	Cell J
06-Aug	1.95	1.50	2.12	2.44	1.81	1.54	0.88	1.44	0.90	1.71	1.82
17-Aug	2.02	1.83	1.75	1.31	1.58	1.56	1.75	1.45	0.36	1.74	1.93
24-Aug	1.97	1.15	1.16	0.57	1.28	2.68	1.88	0.87	0.48	1.17	1.43
05-Sep	1.93	0.91	0.22	0.34	0.60	0.88	0.45	1.94	0.10	0.86	0.83
14-Sep	2.00	1.31	1.04	0.84	1.33	1.16	1.39	0.94	0.29	1.66	1.25

C7. Orthophosphate-phosphorus 2019 August

Date	Influent	Cell A	Cell B	Cell C	Cell D	Cell E	Cell F	Cell G	Cell H	Cell I	Cell J
06-Aug	0.83	0.91	0.97	0.96	0.94	0.96	1.04	0.99	1.39	0.92	0.98
17-Aug	0.75	0.66	0.84	0.68	0.69	0.70	0.70	0.74	1.21	0.87	1.11
24-Aug	0.87	0.75	0.77	0.77	0.70	0.73	0.71	0.73	1.13	0.83	0.94
05-Sep	0.81	0.65	0.71	0.62	0.72	0.75	0.69	0.77	0.89	1.00	0.87
14-Sep	0.78	0.53	0.65	0.62	0.55	0.55	0.56	0.58	0.92	0.66	0.98

C8. Nitrite-nitrogen 2019 August

Date	Influent	Cell A	Cell B	Cell C	Cell D	Cell E	Cell F	Cell G	Cell H	Cell I	Cell J
06-Aug	0.00	0.04	0.07	0.03	0.05	0.03	0.03	0.04	0.05	0.02	0.02
17-Aug	0.00	0.18	0.43	0.38	0.19	0.41	0.07	0.28	0.16	0.03	0.04
24-Aug	0.00	0.18	0.17	0.26	0.31	0.27	0.08	0.25	0.02	0.09	0.09
05-Sep	0.00	0.13	0.01	0.03	0.15	0.16	0.27	0.10	0.00	0.41	0.03
14-Sep	0.00	0.05	0.09	0.09	0.13	0.14	0.02	0.08	0.02	0.03	0.02

C9. Nitrate-nitrogen 2019 August

Date	Influent	Cell A	Cell B	Cell C	Cell D	Cell E	Cell F	Cell G	Cell H	Cell I	Cell J
06-Aug	0.60	4.50	3.28	6.49	3.32	7.78	31.45	1.63	51.3	1.39	3.7
17-Aug	0.60	1.56	3.77	0.94	0.99	0.31	2.2	1.89	8.81	0.00	1.31
24-Aug	0.60	1.82	4.25	0.22	0.71	1.26	2.11	0.14	8.07	0.95	0.42
05-Sep	0.60	2.712	6.49	8.07	7.27	3.69	7.34	4.38	5.98	3.49	2.53
14-Sep	0.60	3.45	3.02	2.93	1.95	3.25	3.24	2.39	6.32	1.94	1.23

C10. EC 2019 August

Date	Influent	Cell A	Cell B	Cell C	Cell D	Cell E	Cell F	Cell G	Cell H	Cell I	Cell J
06-Aug-19	301	556	363	313	379	854	282	734	247	190	556
12-Aug-19	401	561	622	289	399	369	293	770	228	235	561
13-Aug-19	352	689	596	385	387	369	325	589	321	214	689
14-Aug-19	365	635	519	397	335	393	338	644	292	279	635
15-Aug-19	298	519	421	327	324	465	338	599	228	238	519
16-Aug-19	309	513	417	368	311	370	338	607	209	235	513
17-Aug-19	229	469	313	227	272	239	301	483	186	211	469
19-Aug-19	273	577	647	384	299	586	383	584	221	236	577
20-Aug-19	269	500	457	521	307	414	336	465	238	219	500
23-Aug-19	320	468	430	419	339	368	307	408	207	216	468
24-Aug-19	234	458	256	302	282	245	276	392	167	204	458
28-Aug-19	242	448	349	281	264	337	306	369	188	192	448
30-Aug-19	245	364	320	263	247	287	255	351	174	194	364
02-Sep-19	253	341	380	212	238	232	262	341	239	194	341
03-Sep-19	191	342	208	201	184	197	215	263	141	171	342
05-Sep-19	228	290	321	802	235	254	225	273	178	200	290
08-Sep-19	253	403	350	255	268	279	289	283	191	210	403
12-Sep-19	265	343	413	357	248	423	257	305	241	495	343
14-Sep-19	409	598	426	424	368	385	377	600	343	357	598

C11. pH 2019 August

Date	Influent	Cell A	Cell B	Cell C	Cell D	Cell E	Cell F	Cell G	Cell H	Cell I	Cell J
06-Aug-19	8.27	8.17	7.77	7.93	7.86	7.78	7.51	7.68	7.42	8.16	8.27
12-Aug-19	8.52	7.69	7.48	7.47	7.63	7.6	7.58	7.62	7.36	8.21	8.64
13-Aug-19	8.08	7.92	7.82	7.97	7.82	7.78	7.82	7.78	7.55	8.3	8.34
14-Aug-19	8.22	7.63	7.53	7.88	8.37	8.59	7.55	7.69	7.54	8.45	8.76
15-Aug-19	8.57	7.87	7.77	8.08	7.96	7.92	7.85	7.78	7.44	8.92	8.82
16-Aug-19	8.33	7.80	7.73	7.87	7.95	8.07	7.96	8.3	7.49	8.51	8.53
17-Aug-19	8.22	7.90	7.72	8.01	8.01	8.09	7.79	8.18	7.66	8.43	8.76
19-Aug-19	8.50	7.90	7.7	7.64	7.78	7.85	7.62	7.80	7.61	8.64	8.00
20-Aug-19	7.93	7.78	7.77	7.67	8.04	7.74	7.69	7.76	7.78	8.37	7.82
23-Aug-19	8.26	8.01	7.85	7.89	7.99	7.95	7.82	7.94	7.83	8.47	8.62
24-Aug-19	8.56	7.97	7.94	8.00	8.07	8.07	7.88	8.21	7.72	8.76	8.78
28-Aug-19	8.14	9.36	8.13	8.14	8.18	8.02	7.86	7.99	7.84	8.74	8.72
30-Aug-19	8.44	8.15	8.09	8.01	8.14	8.01	7.89	7.97	7.86	8.61	8.68
02-Sep-19	8.24	8.72	8.05	8.3	8.07	8.14	7.87	8.04	7.88	8.65	9.11
03-Sep-19	7.98	8.19	8.21	8.09	8.19	8.07	7.93	7.86	7.83	8.21	8.54
05-Sep-19	8.04	8.09	7.99	7.85	7.99	7.85	7.86	7.82	7.95	8.18	8.16
08-Sep-19	8.54	8.02	8.15	8.08	8.16	8.22	7.87	8.33	7.84	8.59	8.64
12-Sep-19	8.08	8.01	8.12	7.95	8.31	8.04	8.00	8.02	7.92	8.30	7.87
14-Sep-19	8.50	8.07	8.22	8.16	8.34	8.25	7.99	8.28	7.93	8.64	8.81

C12. Nitrate-nitrogen NEB parking

Date	NEB-I (surface runoff)	NEB-A (with geotextile)	NEB-B (without geotextile)
26-Aug	0.00	0.18	0.21
30-Jul	0.00	0.00	0.00
11-Aug	0.12	0.00	0.00
31-Aug	0.18	0.46	0.12
15-Sep	0.45	0.62	0.13

C13. Ammonia-nitrogen NEB parking

Date	NEB-I (surface runoff)	NEB-A (with geotextile)	NEB-B (without geotextile)
26-Aug	0.89	0.70	0.88
30-Jul	0.81	0.12	0.24
11-Aug	0.65	0.02	0.13
31-Aug	0.16	0.16	0.15
15-Sep	1.13	0.38	0.86

C14. Orthophosphate-phosphorus NEB parking

Date	NEB-I (surface runoff)	NEB-A (with geotextile)	NEB-B (without geotextile)
26-Aug	0.05	0.14	0.08
30-Jul	0.06	0.04	0.07
11-Aug	0.00	0.05	0.05
31-Aug	0.19	0.05	0.20
15-Sep	0.76	0.24	0.14

C15. TSS NEB parking

Date	NEB-I (surface runoff)	NEB-A (with geotextile)	NEB-B (without geotextile)
30-Jul	0.0116	0.0034	0.0047
11-Aug	0.0157	0.0005	0.0013
31-Aug	0.0031	0.0009	0.0011
15-Sep	0.0035	0.0001	0.0006

C16. pH NEB parking

Date	NEB-I (surface runoff)	NEB-A (with geotextile)	NEB-B (without geotextile)
30-Jul	8.32	7.92	8.31
11-Aug	7.71	8.20	7.70
31-Aug	7.65	7.65	8.15
15-Sep	7.95	7.80	7.81

Appendix D

(Assessment of ethics in research project form)