THE PERFORMANCE OF A FIELD SCALE BIOFILTRATION CELLS IN REDUCING NUTRIENT RICH SURFACE RUNOFF FROM AN INFORMAL SETTLEMENT IN SOUTH AFRICA

By

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DEDICATION

I dedicate this work to my parents, Mr S and Mrs V Mgese, to my wife, Carmen Mgese and our beloved children, Bukani, Sumeya and Milani.

DECLARATION

I, **Sivile Mgese**, hereby declare and acknowledge that this is my own work and it has not been previously submitted in whole, or in part, for the award of any degree in any University. I know the meaning of plagiarism, the work in this document from other authors used in the thesis is fully acknowledged using Harvard referencing format.

Signature: Signed by candidate Date:……**21 February 2023**………

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ABSTRACT

Concerns about the deterioration of water quality are exacerbated by the effects of rapid and unplanned urbanisation in South African urban catchments as the number of informal settlements next to watercourses increase. Residents living in non-sewered informal settlements typically discard their household greywater, solid waste and blackwater into makeshift drainage conduits which find their way into receiving water bodies. This study examined the ability of Nature based Solutions (NbS) as a viable option to treat and reduce elevated nutrient concentrations discharged from informal settlements. Currently, there is limited knowledge and understanding about the performance of NbS in treating and reducing nutrient rich surface runoff with associated sediments that originates from informal settlements. This thesis contributes to the application and understanding of the novel NbS scientific body of literature on water treatment, firstly by utilising field scale biofilter cells to mitigate the impact of elevated nutrient concentrations from an informally settled catchment; and secondly, to recover, and assess the risk of reusing treated water for irrigation of food gardens in a food insecure and water scarce South Africa. The field scale biofilter cells were positioned at an abandoned Wastewater Treatment Works (WWTW) downstream of the non-sewered informal settlement in Franschhoek, South Africa. The biofilter cells consisted of six purpose-built cells that were filled with various substrate media selected for their ability to treat and reduce nutrient concentrations. This was to compare the efficacy of each biofilter cell in the treatment and reduction of concentrations under different Hydraulic Residence Time (HRT) and flow rates. Linear regression was used to measure the effectiveness of each substrate in the biofilter cells and to evaluate the change in cell performance over time against the influent feedstock. A one-way ANOVA was used to compare the means of the biofilter cells over the sampling period to ascertain the best treatment cell. The Large Stone Vegetated (LSV) biofilter cell was one of the best performing cells for treatment and reduction of PO_4^{3-} concentrations with the lowest median (0.26 mg/L), mean (0.71 mg/L) and 95th percentile (3.60 mg/L), against influent mean, median and 95th percentile concentrations of 3.18 mg/L, and 2.86 mg/L and 5.61 mg/L respectively.

The PO_4^{3-} median value of 0.26 mg/L was below 2 mg/L which meets the recommended norms of the Food and Agriculture Organization of the United Nations (FAO) water quality guidelines for irrigation of food crops. In addition, the LSV cell had the lowest ammonia median concentration (2.74 mg/L), against the influent median concentration of 8.1 mg/L, which was below the 5 mg/L set guidelines as recommended by the South African Water Quality Guidelines for irrigation water quality and WHO guidelines for safe use of wastewater. This study was confined to nutrient degradation and reduction and did not include other contaminants or bacteria such as the *E.coli* and *faecal coliforms*.

ABBREVIATIONS AND ACRONYMS

̊C	Degrees Celsius
CBD	Central Business District
CW	Constructed Wetland
DO	Dissolved Oxygen
EC	Electrical Conductivity
USEPA	United Sates Environmental Protection Agency
GI	Green Infrastructure
HLR	Hydraulic Loading Rates
HRT	Hydraulic Residence Time
LS	Large Stone
LSV	Large Stone Vegetated
N	Nitrogen
NbS	Nature-based Solutions
NH_3	Ammonia
NH_4-	Ammonium
NO_2 –N	Nitrite – N
NO_3–N	Nitrate – N
OC	Organic Carbon
OP	Orthophosphate
ORP	Oxidation Reduction Potential
P_4	Phosphorus
FAO	Food and Agriculture Organization
pH	Power of Hydrogen
PO_4^{3-}	Phosphate
PON	Particulate organic nitrogen
PP	Peach Pips
PPV	Peach Pips Vegetated

SANHC	South African National Housing Code
SERI	The Socio-Economic Rights Institute of South Africa
SRP	Soluble Reactive Phosphorus
SS	Small stones
SSV	Small Stones Vegetated
SDG	Sustainable Development Goals
SuDS	Sustainable Urban Drainage Systems
TDN	Total Dissolved Nitrogen
TN	Total Nitrogen
TP	Total Phosphorus
TSP	Total Soluble Phosphorus
TSS	Total Suspended Solids
TWQR	Target Water Quality Range
UCT	University of Cape Town
UN	United Nations
WHO	World Health Organisation
WSUD	Water Sensitive Urban Designs
WWTW	Waste-Water Treatment Works

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CHAPTER ONE INTRODUCTION

1. Background

South Africans living in non-sewered informal settlements discharge household greywater into improvised drainage conduits in the absence of formal drainage or sewage systems. The amount of greywater produced per household/per person varies considerably. For example, 127–151 dm^3(0,127 – 0,151m^3)/person in the United States of America (USA), 70–140 dm^3(0,07 – 0,14m^3)/person in affluent countries, and by contrast, 20–30 dm^3(0,02 – 0,03m^3)/person in underdeveloped countries where between 43–70 percent of total domestic wastewater volume is discarded (Radingoana *et al.*, 2020a). The chemical concentrations and pollutant types in greywater found in formal housing settlements in comparison to developing countries with informal and dense settlements cannot be easily assumed to differ but largely depends on lifestyle and by what is being put in the water. Greywater is the most common type of household water that is generated but yet poorly managed and discarded outside of the dwellings in informal settlements on a regular basis (Samat *et al.*, 2021; Katukiza *et al.*, 2014). This discarded water frequently flows as surface runoff, combining with blackwater from domestic sources such as leakage and spills of untreated sewage, dysfunctional sanitation systems and open defecation (Abia *et al.*, 2017; Winter and Mgese 2011; Winter *et al.*, 2010).

Conventional urban stormwater management relies on grey infrastructure, which aims to transport surface runoff together with hydrocarbons, nutrients, heavy metals and others from road surfaces swiftly to a network of pipelines and canals (Corrêa *et al.*, 2022; Liu and Armitage, 2020). However, grey infrastructure is often non-existent or insufficient in informal settlements, therefore its presence in this state will worsen nutrient transfer and waterway contamination because makeshift channels are used as easy disposal points for discarding for wastewater. In the absence of proper conveyance infrastructure, open culverts are used as channels to discard greywater to prevent ponding and water stagnation in many South African informal settlements (Adegun, 2015; Carden *et al.*, 2008). As a result, surface water runoff mixes with greywater and sewage from numerous sources, such as damaged sewage pipelines, obstructions, and human/animal excrement, where drainage pathways are available, which are often manually built drainage channels (Nhamo *et al.*, 2019; Wester *et al.*, 2019; Bragina *et al.*, 2017; Adegun, 2013; Asante and Stephenson, 2006).

In informal settlements, contaminated surface runoff that often contains diluted faeces, urine from broken toilets, stagnant greywater pools and solid waste are continuously flowing, even during dry weather conditions (Leuta et al., 2020; Narasimhan et al., 2017). Poor solid waste management for example is a huge problem in informal settlements. This is due to inadequate and overfilled communal solid waste skips (which are either not sufficient or not frequently collected) in addition to general litter that are both responsible for additional contamination. The litter often makes its way into receiving watercourses without any stormwater pollution management (structural and non-structural interventions) (Fitchett, 2017a; Salukazana et al., 2006). In a study by Winter et al., (2010), the combination of sewage and greywater in surface runoff was classified as hazardous in terms of concentration levels. This is because sewage-laden runoff has the largest concentration of nutrients that might induce algal blooms. However, both standing water bodies such as dams, lakes and flowing rivers are at risk, as rivers are carriers whilst standing waters are sinks of pollution. This is concerning because it is claimed that over 80 percent of sewage waste in underdeveloped African countries is released into water bodies untreated (du Plessis, 2019).

The presence of higher levels of phosphoric acid, chemical oxygen demand (COD), sulphates, phosphate salts, polyphosphates, and phosphate-based detergents in the contaminated mixed surface runoff, amongst many other pollutants, contributes to nutrient enrichment when it reaches receiving water bodies (Ndiaye *et al.*, 2020; Spychala *et al.*, 2019). Among the variety of contaminated surface runoff emanating from informal settlements that has been described in the literature are higher levels of COD, pathogenic microorganisms, macronutrients, fats, surfactants, fabric softeners, oils, chlorides, and sulphates (Radingoana *et al.*, 2020b; Vuppaladadiyam *et al.*, 2019; Katukiza *et al.*, 2014). These often vary depending on what is being domestically used.

In South Africa, up to 40 percent of informal settlements have population densities of above 250 people per km^2 and are often located in wetlands or flood-prone areas, and have insufficient basic infrastructure for sanitation, drainage, and solid waste services (Fitchett, 2017a; Adegun, 2015). The release of untreated or partially treated wastewater from dysfunctional communal sanitation systems exacerbates the deterioration of water quality in these informal settlements (Auchterlonie *et al.*, 2021). Wastewater from non-sewered informal settlements frequently discharges the highest phosphorus concentrations (Diatta *et al.*, 2020; Nyenje *et al.*, 2014; De Villiers and Thiart, 2007) above the limits set in the South African discharge limits in the General Authorization and Regulation 991.

High-density, non-sewered informal settlements across the African continent are considered major contributors to rising phosphorus levels and eutrophication (Abia *et al.*, 2018; Nyenje *et al.*, 2010a). This is a cause for concern as informal settlements have emerged up all throughout Africa because of the continent's fast and uncontrolled urbanization. In comparison to formal city centres, informal settlements areas are built with little and in worse cases, no regard for stormwater drainage (Charlesworth and Booth, 2017; Parkinson, 2003), restricted or complete lack of residential waste disposal, sanitary facilities, and limited access to water supply (du Plessis, 2019; Hui and Wescoat, 2017; Pegram and Gorgens, 2000). Wastewater (greywater and blackwater) discharges are also common in watercourses traversing informal communities, contributing to increased nutrient rich pollution risk (Abia *et al.*, 2018; Nyenje *et al.*, 2014; De Villiers, 2007).

Over 80 percent of used and discarded wastewater is untreated and disposed of in makeshift stormwater channels that flow into nearby watercourses, these are regarded as the main drivers of eutrophication, according to global anthropogenic nutrient enrichment trends (Griffin, 2017). Eutrophication is becoming common in South African freshwater habitats with eutrophic conditions found in 20 percent of South Africa's 75 main reservoirs and 18 of the country's 25 major river catchments (du Plessis, 2019). It is estimated that more than half of the major South African reservoirs and river systems, including 62 percent of the largest watercourses, are classified as eutrophic or hypertrophic (Mudaly and van der Laan, 2020; Griffin, 2017), which could be attributed to multiple point and non-point sources of nutrient. In many urban catchments it is impossible to assign the causes of eutrophication to a single pollution source because of widespread and diverse anthropogenic nutrient sources within a catchment (Dalu *et al.*, 2019).

Even though anthropogenic activities discharge elevated nutrient levels into watercourses through point and non-point sources (Motitsoe *et al.*, 2020), natural sources of nitrogen and phosphorus are found in small quantities in freshwater and offer biogeochemical support for aquatic ecosystems (Vilmin *et al.*, 2018). In contrast, research findings show that a natural source of nutrients, such as atmospheric deposition, is one of the most significant donors of nutrients, accounting for roughly 90 percent of nitrogen deposition (Motitsoe *et al.*, 2020). Eutrophication of water bodies is caused by the persistent inflow of nutrient-rich surface runoff into receiving watercourses, which stimulates the distribution of algae and other plankton in the water, resulting in aquatic ecosystem degradation. Reduced dissolved oxygen causes reduction in species richness, resulting in the loss of submerged aquatic vegetation, increased hazardous algal blooms, and the extinction of fish (Li *et al.*, 2021; Adams *et al.*, 2020).

This research examines the nutrient concentrations and assesses the efficiency of Nature-based Solutions (NbS) in reducing the elevated nutrient rich surface runoff collected from the Stiebeuel River in the Franschhoek valley, in the south-western cape of South Africa. The context of the study is explored in more detail in this chapter. The Stiebeuel River flows alongside an informal settlement and passes through the study site (Figures 1.1 and 1.2) below before discharging into the Franschhoek River. The site situation provides a unique context from which to investigate the use of NbS for reducing elevated nutrient to acceptable water quality standards and the risk of reusing the water for irrigating a food garden. The broad aim is to understand the treatment performance of a field size biofiltration system that is fed with nutrient-rich surface runoff from an informal settlement. The best operating conditions for the NbS will be examined for optimum reduction rates of elevated nutrients. The NbS will be used to remove excess nutrients and other contaminants of concern, as well as to investigate the safe reuse of treated effluent for irrigating edible crops that fulfils South African and international irrigation guidelines.

1.1. Rationale

Several African research studies have highlighted urban stormwater runoff as a mechanism for nutrient and sediment transfer into watercourses, particularly from informal settlements (Auchterlonie *et al.*, 2021; Adams *et al.*, 2020; Atangana *et al.*, 2020; Fitchett, 2017a; Winter and Mgese, 2011; De Villiers and Thiart, 2007). Several studies on stormwater runoff from urban informal settlements in parts of Africa and South America show that the pollution of receiving water bodies from elevated nutrient loads and associated sediments is on the rise, with negative consequences for human health, aquatic systems, biodiversity and ecosystem support (Abia *et al.*, 2018; Namugize *et al.*, 2018a; Sparkman *et al.*, 2017; Juma *et al.*, 2014; Nyenje *et al.*, 2010a). The degree of nutrient-rich pollution caused by untreated or partially treated surface water runoff from informal settlements including the Berg River, Modder River, upper reaches of the Klein-Jukskei River, Hennops River, and the Borkena River (Ethiopia) and Orogodo River (Nigeria) (van der Hoven *et al.*, 2017; Nyenje, *et al.*, 2014; De Villiers and Thiart, 2007).

The silt carried in stormwater runoff from informal settlements is troublesome since it contributes to eutrophication. This is because sediment acts as a binding agent for nutrients, increasing their load and bioavailability when deposited in lakes and wetlands (Abia *et al.*, 2018; Nyenje *et al.*, 2010b; Twinch, 1986). Many studies that provide empirical evidence of high concentrations of Electrical Conductivity (EC), Ammonium (NH_4-) and Phosphate (PO_4^{3-}) regularly observe the role of increased sediment load, in combination with a mixture of untreated black and greywater (Ngwira and Lakudzala, 2018; Yu *et al.*, 2017; De Villiers and Thiart, 2007; Carden, 2006).

Given these nutrient enrichment causes, it is necessary to intercept, treat and reuse surface runoff from South Africa's urban informal communities. In comparison to the traditional conventional stormwater management approach that has been used in South African urban catchments to manage stormwater runoff by conveying stormwater runoff as quickly as possible out of road surfaces. There is a need to implement a site-specific sustainable stormwater management approach that can effectively reduce pollution risk from source, attenuate flow including sediment load, and provide an opportunity for non-portable wastewater reuse activities that offers multiple socio-economic and environmental benefits.

Kordana and Słyś, (2020) devised a multi-criteria decision-making process that limits the usage of traditional stormwater management systems by focusing on the development of multifunctional nature-based alternatives for minimizing stormwater's detrimental consequences on water quality. This "new" stormwater management approach, as described by numerous researchers including Simperler *et al.*, (2020); Duan *et al.*, (2019); Li *et al.*, (2019); du Toit *et al.*, (2018); Charlesworth *et al.*, (2016); Fletcher *et al.*, (2015); Armitage *et al.*, (2006); is reported to mitigate elevated nutrient levels by reducing nutrient and sediment loads.

Evidence-based research in South Africa (Adegun, 2017; Fitchett, 2017a) claimed to treat and reduce the negative effects of nutrient-rich surface runoff by eliminating excess nutrients from stormwater runoff. However, little is known about the nature-based treatments' long-term success in treating excess nutrients from informal settlements and the reusability of the treated wastewater for non-portable purposes. Moreover, the performance of a field scale biofilter in informal settlements under variable operating conditions such as hydraulic residence time, seasonal changes, media type, water depth and flow regime within the system are largely under researched. According to a study by Fitchett, (2017a), the lack of research on sustainable drainage systems in informal settlements is due to the temporary nature of these settlements combined with budget constraints and unwillingness to commit to capital expenditure on large-scale and long-term stormwater management interventions.

Currently, typical drainage systems in informal settlements, if they exist, are overburdened with greywater, solid waste, and black water, which frequently overflow into streets and finally end up in watercourses and groundwater. This is because informal settlements in South Africa are created outside of planning ordinances and are frequently located on government or privately held property that is unsuitable for residential development. As a result of the transient nature of many of these settlements, stormwater management is almost non-existent. Stormwater drainage systems in South African urban catchments are used to transport surface runoff (mostly rainwater) from road surfaces into watercourses. According to Parkinson, (2003), traditional drainage systems are ineffective because they fail to account for the risk of flooding and increasing pollution load into waterways.

The goal of this research was to develop a context-specific stormwater management technique using NbS like biofiltration systems to treat and reduce surface runoff pollution. In order to understand long-term effectiveness of selected NbS, local and mostly international research (Simperler *et al.*, 2020; Barron *et al.*, 2019; Sletto *et al.*, 2019a; du Toit *et al.*, 2018; Jafarzadeh *et al.*, 2018; Yang Yun-ya and Lusk, 2018; Charlesworth and Booth, 2017; Fisher-jeffes *et al.*, 2017; Fitchett, 2017a; Adegun, 2017; Reed and Dunelm, 2013; Armitage *et al.*, 2013; Milandri *et al.*, 2012) was examined in this study. The treatment of stormwater runoff from the informal settlement for non-portable usage will consider the anticipated health hazards as well as South African water quality criteria that must be met before the treated stormwater may be used for the reasons stated.

An emerging or re-awakening of NbS has influenced this research. When opposed to traditional systems that utilise grey infrastructure and 'end of pipe' solutions, the approach delivers multifunctional opportunities and benefits that are arguably sustainable solutions for South Africa (Wang *et al.*, 2018; Szklarek *et al.*, 2018; UN-World Water Development Report., 2018). Secondly, the NbS The are several SuDS strategies that can be implemented not only upstream but also downstream of informal settlements. The treatment train method (by strategically combining one or more of the NbS components) as illustrated in Table 2.3 of the thesis as is one of the effective measure where pollutants are treated from source in a series of interconnected processes (that often overlap) in order to reduce pollution upstream through to downstream.

This research will provide key insights and contributions to knowledge of the ideal optimal biofilter operating conditions for the reliable treatment of surface runoff coming from an informally settled catchment. In a recent study, Muthu, (2021) emphasized the interdependence of water, energy, and food resources to increase resource resilience, reuse, and attain a level of sustainability. This is important because water scarcity and pollution in South Africa is seen as the concern for sustainable agriculture irrigation to meet food requirements of a growing population.

This body of knowledge assumes that food security is dependent on the availability of high-quality water and a consistent energy supply (Muthu, 2021). In the semi-arid South African region, with average rainfall of 450 mm yr-1, below the world's average of 860 mm yr-1, the water, energy, and food nexus are essential because the agriculture sector accounts for over

60 percent of available water use. As a result, the degradation of water resources because of population growth, deteriorating wastewater treatment systems, and climate change, to name a few factors, will aggravate food insecurity (Mudaly and van der Laan, 2020).

1.2. Problem statement

Numerous research studies in South Africa and elsewhere have examined nutrient enrichment of freshwater resources (Lemley *et al.*, 2019; Mvungi and Pillay, 2019; Oberholster *et al.*, 2019; Rensburg and Barnard, 2019; Dalu *et al.*, 2019; Mukarugwiro *et al.*, 2018; Wagenaar and Barnhoorn, 2018; Huchzermeyer *et al.*, 2017; Griffin, 2017; Harding, 2015; Matthews, 2014; van Ginkel, 2011; De Villiers and Thiart, 2007; Pillay, 1994). These studies show that a variety of anthropogenic activities in urban catchments are causing the deterioration of watercourses, including untreated effluent discharges from non-sewered informal settlements, agriculture, and failing WWTW.

High quantities of nutrients in the form of phosphate ions (PO_4^{3-}), nitrogen in the form of nitrate (NO_3-N), nitrite (NO_2-N), and ammonium (NH_{4+}) generated by activities in non-and partially sewered informal communities and malfunctioning WWTWs are of concern (du Plessis, 2019; Gilbert, 2015; Winter and Mgese, 2011; De Villiers and Thiart, 2007). An increase in cyanobacteria toxic algal blooms, excessive growth of macrophytes that reduces the recreational value of aquatic systems, causes habitat degradation, and deteriorating conditions that result in the death of invertebrates and fish due to oxygen depletion (Ngwira and Lakudzala, 2018; Griffin, 2017; Li and Allen P. Davis, 2014).

The use of informally created surface water runoff channels as suitable conduits for the discharge of effluent water is a serious problem in densely occupied informal settlements (Winter and Mgese, 2011; Parkinson, 2003). The drainage problem in South Africa's informal settlements has long existed because basic municipal services, such as solid waste management, sustainable drainage systems, and sanitation, are absent due to a variety of factors, including fragmentation within municipalities (Fisher-Jeffes *et al.*, 2012).

Traditional methods such as phosphorus reduction in detergents, biomanipulation of the food web, accurate prediction of cyanobacterial growth cycles, and mechanical disturbance of the epilimnion have also been used in South Africa to mitigate the cumulative impacts of eutrophication (van Ginkel, 2011), but these methods do not remove algal toxins or mitigate excess nutrients and associated sediments that are discharged into freshwater systems (Oberholster and Ashton, 2008). Due to the fact that many of these solutions rely on outdated end-of-pipe mitigation tools and automated effluent monitors, which are incapable of addressing episodic and erratic nitrogen loading in rainfall (Shah and Venkatramanan, 1999). Many of the NbS for stormwater runoff management proposed in the literature have drawbacks, including but not limited to maintenance requirements, increasing stormwater rates and volumes due to urbanization, and the fact that many informal settlements are in poorly drained soils in floodplain areas (Scholz, and Grabowiecki, 2007; Heal *et al.*, 2004).

This study argues that interventions such as Sustainable urban Drainage System (SuDS), Green Infrastructure (GI) uses nature-based processes embedded in the NbS such as constructed wetlands, biofiltration systems, swales, permeable pavements, infiltration trenches, and sedimentation basins, to name a few are capable to reduce elevated nutrient levels at different performance levels. General barriers to the acceptance and implementation of NbS include the lack of sufficient land in urban areas, construction costs (depending on the type of SuDS design), maintenance uncertainty, and adoption uncertainty (Bastien *et al.*, 2010).

The advantages of using NbS to improve water quality have been widely reported in the international literature for more than two decades (Song *et al.*, 2019; Hogain and Mccarton, 2018; Keesstra *et al.*, 2018a; UN-World Water Development Report., 2018; Kandra *et al.*, 2014; O'Reilly *et al.*, 2012; Vymazal, 2011; Mohan *et al.*, 2010; Chaudhry *et al.*, 2005). In comparison to parts of Europe, Australia, and North America, NbS in South Africa and Africa are still in the initial stages of planning and implementation. As a result, the efficacy of NbS in minimizing the impacts of wastewater outflow from South Africa's urban informal communities is largely under researched and explored. In general, this is due to a paucity of evidence-based understanding about the efficacy of natural-based methods for removing pollutants in runoff from informal settlements. In this study, the terms SuDS, NbS, and GI are used interchangeably to refer to the treatment of surface water in constructed wetlands, biofiltration systems, swales, permeable pavements, infiltration trenches, and sedimentation basins, to name a few.

1.3. Hypothesis

The NbS such as biofiltration cells are an effective method of treating and reducing nutrient-rich stormwater runoff coming from an informally settled catchment to a water quality standard suitable for reuse in irrigation of food garden.

1.4. Research questions

This research addresses the following questions:

- What are the nutrient concentrations discharged from the informal settlement that are captured and analysed downstream at the Water Hub?
- In a water-scarce and food-insecure South Africa, how effective are the selected field-scale nature-based methods at treating and polishing elevated nutrient concentrations from informal settlements to a water quality standard that is fit for the safe irrigation of edible crops?

1.5. Research aims and objectives

An overarching aim of this study was to determine how the chosen NbS can reduce excess nutrient concentrations from an informal settlement and the potential to treat contaminated water to a water quality that is acceptable for fit-for-purpose reuse, such as crop irrigation.

The principal objectives are to:

1. Measure the nutrient concentrations in surface runoff coming from the informal settlement over the sampling period.
2. Examine the nutrient (PO_4^{3-} and Total Nitrogen (TN), NH_3-N, NO_3-N and NO_2-N reduction rates from the six biofilter cells (packed with various media) against the influent concentrations.

3. Assess the best performing biofilter cells and evaluate the risk of treated water reuse to acceptable water quality concentrations suitable for irrigation of edible crops in a water-scarce, food-insecure country like South Africa.
4. Determine and compare the influence of nature-based processes, media type, HRT and flow regime on the performance of biofiltration cells in the treatment and reduction of excess nutrients.

1.6. The South African informal settlement landscape

Prior to 1994, during South Africa's Apartheid era, the Group Areas Act of 1950 had a significant impact on the development of townships and informal settlements. The Apartheid regime enacted the Group Areas Act, one amongst others, that prevented black South Africans from residing in formal settlements where the white populace could enjoy the privileges of adequate municipal facilities and amenities (Fisher-jeffes *et al.*, 2017; Button *et al.*, 2005; Sowman, 1994). The vast majority of black South Africans were forcibly uprooted from their homeland and relocated to underserved peri-urban township settlement regions (Adegun, 2017; Vollmer and Grêt-Regamey, 2013; Jonathan Parkinson, 2003).

Apartheid-era planning has since left a legacy of social disparities in South Africa's urban regions (COGTA, 2002). As a result, according to the Housing Development Agency of South Africa, around 1.25 million households in South Africa's peri-urban areas lack access to essential municipal services because they reside in informal settlements and townships (CoCT, 2017; HDA, 2012). Informal settlements, according to the City of Cape Town, are residential enclaves made up of one or more informal constructions that might be single or multiple structures (CoCT, 2017). On a municipal level, however, there are different definitions for informal settlements. The South African National Housing Code (SANHC) defines informal settlements based on illegality, informality, inappropriate locations, limited public and private sector investment, poverty, vulnerability, and social stress (SERI, 2018). One or more of these traits are common in and typical of South African informal settlements.

After the first democratic elections in 1994 and the subsequent repeal of unjust Apartheid regulations such as the Group Areas Act (Sowman, 1994), the state's ability to deliver infrastructure such as state-subsidised housing, water supply, sanitation, and solid waste management services were overwhelmed (Penrose *et al.*, 2010). Rapid urban expansion, population increase, insufficient urban planning and control, poorly enforced development control mechanisms, including poverty, are attributed to the rise of informal settlements in the post-1994 period according to du Plessis, (2019); and Adegun, (2015). The Socio-Economic Rights Institute of South Africa (SERI) estimated that over 1.4 million households, or over 3.6 million people, live in informal settlements in South Africa (SERI, 2018). Informal settlements are characterised by the highest population densities, poor or non-existent sanitation services, and a lack of access to clean water (Omulo *et al.*, 2021), the South African informal settlements are no exception.

1.6.1. The study site

This study was conducted on an experimental site that was once operated as a WWTW. The site now known as 'The Water Hub' located downstream of the Langrug informal settlement in the Stiebeuel River's sub-catchment. The Water Hub is 3 kilometres from Franschhoek's formal town centre. The Langrug informal settlement is located in the north east direction to main Franschhoek town (Stellenbosch Municipality, 2020), the distinction between these two settlements reflects the Apartheid state's spatial policy of separation based on racial classification. The study region is approximately 65 kilometres east of Cape Town Central Business District (CBD). The climate is typical of the Mediterranean, with hot, dry summers and mild, wet winters. The region receives 784 mm of yearly rainfall in low-lying sections and 903 mm in the upper reaches of the catchment (Wu and Xu, 2005). The hottest months are October to March, with temperatures exceeding 40 ^{0}C during the dry summer months (Wu and Xu, 2005).

The residential villages of La Motte (lower reaches), low-income districts of Dennegeur and Groendal (middle reaches), Mooiwater low-income housing development on the east and Langrug (high reaches) make up the Stiebeuel River basin (Figure 1.1 below). These residential areas represent a typical socio-economic spectrum in South Africa, with middle-income homes living alongside impoverished, low-income households. The informal settlement of

Langrug and the low-income regions such as Mooiwater and Groendal are remnants of the former Apartheid Group Areas Act, with residents living on marginal property on the outskirts and working in the neighbouring town and agricultural area (Fell, 2017).

The catchment's socio-economic dynamics are characterized by large disparities between wealthy wine estate owners in the formal town of Franschhoek and impoverished residential areas like Groendal and Langrug. Most of the people residing in the Langrug informal settlement are from the Eastern Cape Province of South Africa. Over 80 percent of these residents are native IsiXhosa speakers who came to the Western Cape in search of work opportunities. IsiXhosa is one of the 11th official language of South Africa, spoken by 16 percent of the South African population(Møller *et al.*, 2018; Naidoo *et al.*, 2018). Unemployment is widespread. Those who are employed work primarily in the hotel, retail, wine, and construction industries in the Franschhoek CBD. According to the annual report of the Stellenbosch municipality, the catchment has a population of 7 519 people, with the Langrug informal settlement accounting for 4 864 persons and 1 807 informal houses sharing 150 waterborne ablution toilets (Stellenbosch Municipality Annual Report, 2018).

The Stiebeuel River basin drains an area of roughly 4.69 km^2, with surface runoff discharged into the Franschhoek River (Figure 1.1 below). The river flows through the Langrug informal settlement, which is situated on a 1:12 slope in the foothills of the Hawequas mountains with loamy sand and clay soils (Armitage *et al.*, 2009). The Langrug informal settlement encroaches Hawequas mountain on the north of the settlement which is predominantly a nature reserve (Stellenbosch Municipality, 2020). In the lower portions of the basin, the Stiebeuel River flows through Groendal, a low-income housing community right below Langrug informal settlement, before discharging into the Franschhoek River. The first residences in the Langrug informal settlement were built in 1993, and the settlement today consists of closely packed shack dwellings made of corrugated iron, wood, and plastic sheeting (Winter *et al.*, 2010; Armitage *et al.*, 2009). Groendal, on the other hand, is a settlement with formal cement brick homes, a tarmac road, and stormwater infrastructure.

This study focuses on surface runoff discharges coming from Langrug informal settlement (Figure 1.1. below). This is because of the relatively high nutrient runoff from myriad sources which is carried by these surfaces that includes sewage overflow, greywater discharges, dysfunctional sanitation systems and poor solid waste management.

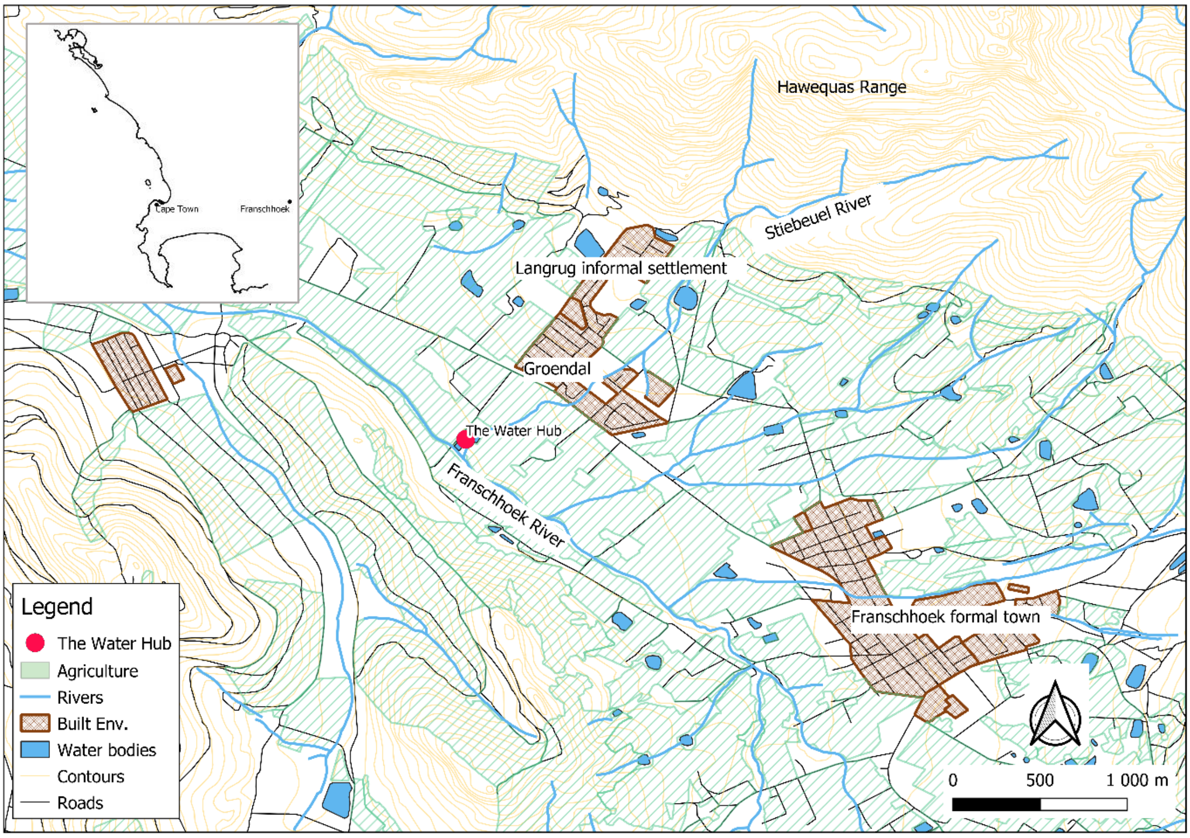


Figure 1.1: The location of the Franschhoek and the Water Hub in relation to Langrug informal settlement and the formal town.

The Stiebeuel River flows through the Water Hub research site before discharging into the Franschhoek River after a three-kilometre journey from source. The river receives nutrient-rich surface runoff from the informal settlement at several points along the Stiebeuel River before it reaches the Franschhoek River's confluence. Surface runoff is routinely discharged into the Stiebeuel River and the stormwater canal via a network of drainage lines consisting of trenches and traditional concrete walled canals. In many cases, drainage lines transport surface runoff from settlements to prevent surface water ponding caused by poor drainage.

In the Langrug informal settlement, stormwater drainage is provided by a combination of makeshift ditches and concrete culverts. Stormwater, blackwater, discarded greywater, and solid garbage are carried by these drainage networks before entering the Stiebeuel River. Various trial programs to improve the quality of stormwater runoff from the Langrug informal settlement were previously conducted in the basin, but they were abandoned due to irregular government funding. One of the government-funded projects to improve the quality of storm water run-off from the Langrug Informal Settlement is the Berg River Improvement. A nature-based approach, garbage recycling, and a SuDS lab were all implemented as part of the project.

The Genius of Space project was established to address the contamination of the Berg River using nature-based stormwater designs to treat stormwater and untreated greywater entering the watercourses from the Langrug informal settlement (Janisch *et al.*, 2017; Dama-Fakir *et al.*, 2016). The local community was actively encouraged to participate in the Genius of Space project, which aimed to provide a meaningful implementation and maintenance program that addressed the community's requirements (Wolfaardt, 2017). The long-term maintenance of the micro-wetlands implemented in Langrug through the Genius of Space project to reduce surface runoff and lower the pollution load into watercourses which often resulted in clogging (Janisch et al., 2017), due to lack of monitoring and commitment from locals in maintaining the systems. Therefore, the commitment from locals and funding have been the major hinderance for treatment and re-use of the resource for several non-portable water uses. The Water Hub research centre has emerged as the research and development centre demonstrating amongst many other, NbS for treatment of contaminated stormwater runoff and water reuse with the aim to restore the health of the river systems in the informally settled catchment.

The Water Hub land space is approximately 2.7 ha and is surrounded by neighbouring vineyard farms that produce wine for the local and export market. The site was refurbished for research and demonstration purposes by the Western Cape Government who provided a seed fund to refurbish a small section of infrastructure on the site. The University of Cape Town (UCT) Future Water research institute has taken the opportunity to use the site to conduct a series of multidisciplinary research projects.

1.7. The study design & overview of methods

This research focuses on the remediation of surplus nutrients that are transported by runoff from the Langrug informal settlement. Biofiltration cells are used in this study to treat and reduce elevated nutrient concentrations by imitating natural processes. Large Stone Vegetated (LSV), Large Stone (LS), Peach Pips Vegetated (PPV), Peach Pips (PP), Small Stones Vegetated (SSV), and Small Stones (SS) biofiltration cells were used to evaluate the efficacy of a range of natural processes in the treatment of nutrient-rich surface runoff. A small portion of the treated water was used in an experimental food garden while the rest was discharged back into the river.

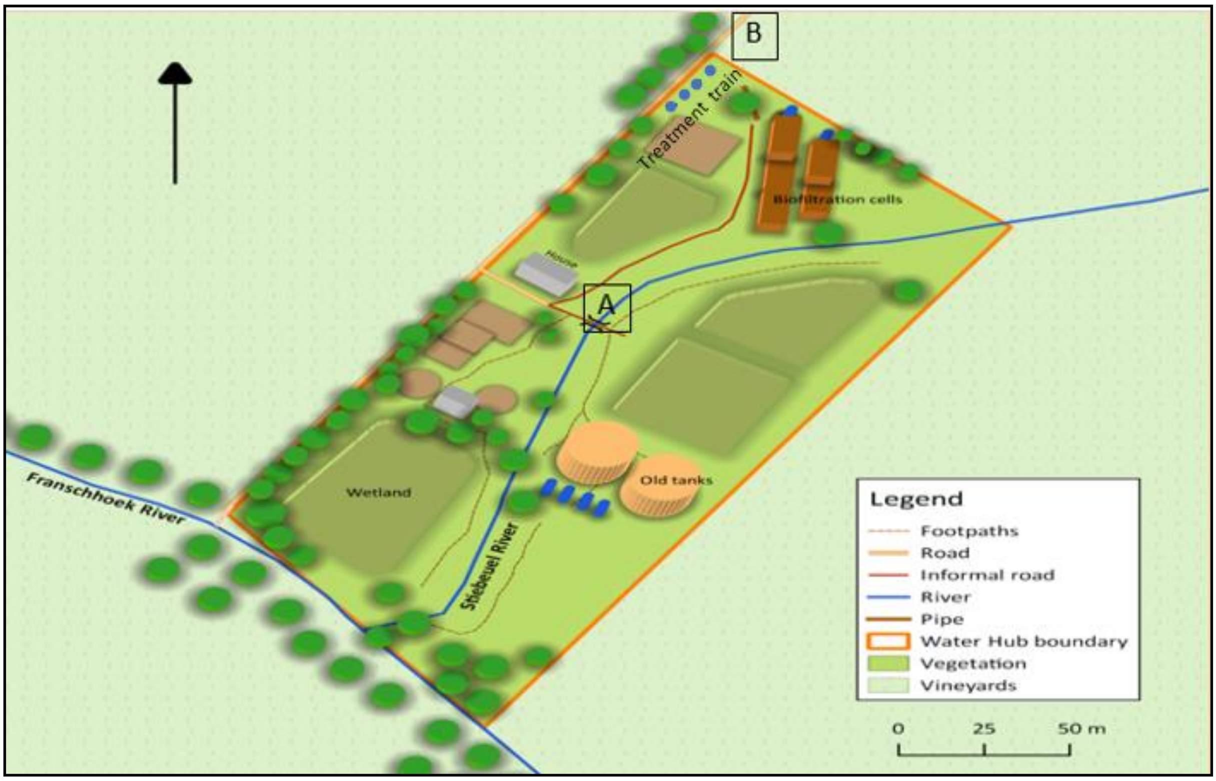


Figure 1. 2: Detailed overview of the Water Hub showing the biofiltration cells in relation to the Stiebeuel River, source: (Fell, 2017).

In this study, the surface water from the river was pumped into two 10Kl storage tanks using a submersible pump from beneath a foot bridge position (A) at the Water Hub (Figure 1.2 above). A 1kW submersible pump which was positioned in the river to ensure that the water was of sufficient depth even during low flow drier conditions. This was done to provide a consistent flow of runoff into the tanks, the first 10Kl tank was used to settle coarse particles, before flowing in the second tank which acted as a primary feeder, referred to as the influent tank, that supplied the biofiltration cells.

The sampling frequency was used to assess the relationship between residence time and treatment efficiency of excess nutrients. The flow rate and residence time were monitored at each sampling event to understand changes and influence of varying the volume and rate of flow. Grab samples were collected within each cell and analysed in-situ and in the UCT water quality laboratory.

Various descriptive statistical methods were used to examine the excess nutrient reduction rates within the cells and in comparison, to the influent quality. Non-parametric approaches were used to compare differences in the removal of surplus nutrients and changes in the physical characteristics of the water in the biofilter cells. A generalized linear mixed model was utilized to compare nutrient reduction rates under varying operation conditions. The treatment of each cell's effluent to a water quality standard for re-use as a 'fit for purpose' resource for irrigating food gardens and safe usage for waterborne sanitation was a crucial goal.

1.8. The study scope and limitations

The study limitations of this study are:

- Biofiltration cells are complex systems that aim to mimic nature-based processes; nevertheless, without the use of modelling tools, it is difficult to depict natural, chemical and biological processes that regulate nutrient removal. As a result, the efficacy of various mediums was determined using several descriptive and statistical modelling methodologies.
- The inability to control environmental conditions that affect how nature-based processes treat nutrient-rich surface runoff. The experiment was not replicated in a different informal settlement setting because the study is context specific.

- Since the study’s key focus was on surplus nutrients discharged in informal settlement stormwater runoff, bacteriological water quality indicators including *E.coli* and *faecal coliforms* were excluded from the study’s monitoring parameters.
- Unlike conventional WWTW which uses chemicals to treat water quality, nature-based processes might take longer period for biofilms for example to develop and treat pollutants. There is a possibility for some of the processes to operate optimally outside of the allocated research period (scheduled data analysis period).
- The flow regime of the Stiebeuel River to apprehend its hydrodynamic conditions with regard to pollution loads and dynamics is outside the scope of this study and would take focus and emphasis on the aim and objectives of this study.

CHAPTER TWO LITERATURE REVIEW

2. INTRODUCTION

An increase in urban population related pollution due to rapid and unplanned urbanization is a significant cause of surface water pollution and water quality deterioration in Africa, compared to other impacts such as agriculture or industrial pollution (Chen *et al.*, 2022). The effects of urbanization in the Sub Saharan African have been reported increase water demand to support economic activities and rapid spread of illegal and non-sewered informal settlements which causes pollution of freshwater resources from multiple anthropogenic sources (Gqomfa *et al.*, 2022; Strokal *et al.*, 2021). In Sub-Saharan Africa and globally, nutrient enrichment is a major water quality threat not only to the availability of clean water but also to the fulfilment of Sustainable Development Goals (SDG) 6, to ensure availability and sustainable management of water (Li *et al.*, 2021; Strokal *et al.*, 2021; Chetty and Pillay, 2019; Goh *et al.*, 2019).

Since over 80 percent of the global population lives in sub-catchments, this can have far reaching consequences as over 3.2 billion people live in cities, accounting for about 42 percent of the world total population, and are putting more pressure on water quality of freshwater systems (Chen *et al.*, 2022). The forecasted freshwater ecosystem pollution in the continent of Africa is set to increase by between 11 – 18 times higher than projected in 2010, worsening the prospects of achieving SDG 6 (Strokal *et al.*, 2021). The NbS concept is gaining attention in the Sub-Saharan Africa as a sustainable intervention to manage urban pollution of freshwater system. The benefits of NbS are widely reported in the literature to vary from environmental, social and economic depending on the design purpose (Geronimo *et al.*, 2022; Keesstra *et al.*, 2018b). However, application of NbS in the Sub-Saharan Africa is in its early stages and the benefits are not fully explored in the African context compared to developed urban catchments in Europe, North America, and Australia.

This section reviews the urban stormwater runoff pollution in informal settlement as the growing problem for water resource. Thereafter, the literature reviews the current state of NbS research and development and positions this thesis on the state-of-the-art research on

NbS approach for urban stormwater management in Sub–Saharan Africa. This review will focus on identifying NbS benefits, areas of success, challenges, and gaps in the application of NbS globally and in the Sub–Saharan Africa.

2.1. The urban stormwater runoff nutrient pollution

The surface runoff pollutants coming from informal settlements vary and includes nutrients, oxygen-demanding organic compounds, sediments, solid waste litter, and microbiological pollutants (Chingombe, 2012). The pollutant concentrations vary and are based on the source of polluted water, timing and the infrastructure condition of an informal settlement. For example in South Africa, it is estimated that over 60 percent of the 20 largest river catchments studied by De Villiers and Thiart, (2007) showed an increase in dissolved PO_4^{3-} trends in nearly 60 percent of the rivers studied, which was attributed to untreated wastewater from malfunctioning sewage works and unsewered informal settlements. Koning and Roos, (1999) have shown that failing sewage treatment facility can discharge around (260 g/l, or 0.26 mg/l) mean PO_4^{3-} which is comparable with the results shown in Table 2.1 below. However, Koning and Roos, (1999) noted that the 260 g/l concentrations were higher than those found in the Vaal River (18 g/l), Orange River (59.8 g/l), and Caledon River (63.5 g/l), South Africa.

According to du Plessis, (2019), more than 80 percent of nutrient-rich surface runoff contaminated by sewage-laden runoff in informal settlements is discharged untreated into watercourses. Long-term median readings showed an almost 10-fold rise in NO_3-N and phosphate concentrations downstream of the informal settlement, with 791 g/l and 72 g/l, respectively (De Villiers, 2007; De Villiers and Thiart, 2007). Namugize *et al.*, (2018) found typical EC and NO_3-N levels of 5.1 mS/m – 29.5 mS/m; 0.57 mg/N/l – 2.6 mg/N/l, respectively, within the specified ranges in Table 2.1 below. EC ranges discharged from an informal settlement in Paarl, Western Cape, reported by Winter and Mgese, (2011) varied from 313 S/m to 1987 S/m, compared to 87 S/m to 120 S/m official settlements in Paarl during dry weather conditions. According to Chingombe, (2012), typical PO_4^{3-} concentration levels in informal settlements ranged from 1.0 to 3.0 kg ha/yr, compared to 0.4 to 1.3 kg ha/yr in formal development types such as suburban neighbourhoods.

Domestic solid waste is one of the key pollutants problematic in informal settlements due to poor solid waste management practices and infrequent waste collection that make their way to nearby watercourses. The pollution contribution of domestic solid waste to freshwater systems is discussed in several studies by (Gqomfa *et al.*, 2022; Sletto *et al.*, 2019a; Okurut *et al.*, 2015; Owusu-Asante and Ndiritu, 2009). However, little is known form these studies any many others about the chemical contribution of domestic solid waste in water quality parameters such as nutrients (TN and TP).

Greywater is one of the largest (volume) polluted wastewater discharged in informal settlements, its concentration depends largely on the type of greywater (Ntibrey *et al.*, 2021; Dwumfour-Asare *et al.*, 2017; Rodda, Carden, *et al.*, 2011; Armitage *et al.*, 2009; Carden, 2006). Vuppaladadiyam *et al.*, (2019) found that greywater from the kitchen and laundry contains the higher concentration of nutrients, organics, and physical contaminants. Ilemobade *et al.*, (2013) classify greywater into light and dark, with light greywater being less polluted than dark greywater due to the absence of water from the kitchen. According to Carden, (2006), the difference between light and dark greywater, including black water, is determined by the rate of pollutants degradation in each wastewater, with light greywater dissolving faster than blackwater. According to Winter *et al.*, (2010), TN concentrations of greywater are often lower than that of residential sewage. Furthermore, the researchers noted that greywater generally contains lower levels of organic matter and nutrients compared to ordinary domestic wastewater.

Chemical oxygen demand (1 500 – 8 500 mg/l), electrical conductivity (50 –1 500 mS/m), and microbiological counts similar to raw sewage were all measured in a greywater study by Armitage *et al.*, (2009). However, according to Rodda *et al.*, (2011); Salukazana *et al.*, (2006), greywater does not typically include human waste unless basins are used to clean baby's nappies/diapers and bathtubs, or showers are used to urinate. Greywater is frequently mixed with a variety of pollution sources, including but not limited to black water in non-sewered and low-income informal communities, resulting in bacteriological counts similar to raw sewage (Winter *et al.*, 2010).

The water quality data showing long term water quality parameters discharged from informal settlements is limited in South Africa. The concentration levels of pollutants discharged from informal settlements is expected to be relatively high due to mixture of contaminant sources.

The water quality parameters that should be chosen in this study are listed in Table 2.1 below which shows the data ranges that should be expected for high and low-density settlements in South Africa. It is evident from this data (Table 2.1 below) that there is lack of water quality data to accurately quantify the pollution contribution in high to low density informal settlements of South Africa. Secondly, the data provided no indication of pollutant ranges collected in wet and dry weather conditions as many parameters are largely influenced by seasonal changes. Thirdly, it is unknown if the samples were upstream or downstream of these settlement types, the period of monitoring including the purpose and methods of analysis which all have an impact on the water quality data. As a result, the water quality data in Table 2.1 can be viewed as indicative (Asante, 2008).

Asante (2008b) claims that there is a scarcity of surface water quality monitoring data in South Africa, and that loading estimates from diverse land use activities are variable and inconsistent. Apart from the constraints of the water quality data in Table 2.1 below, there is a clear distinction between the data ranges reported for formal and informal settlements. High density informal settlements are found to contain relatively high concentration levels of NH_4 (mg/l as N); TKN (mg/l as N); EC (mS/m); SS (mg/l); PO_4^{3-}(mg/l) compared to formal, high-density settlements. Settlements with proper municipal infrastructural services, such as a water reticulation system, water-borne sewage, and non-stand ablution facilities, are referred to as formal development types (Asante, 2008).

Table 2.1: Expected pollutant concentration ranges for categories of residential catchments in South Africa (Asante, 2008b)

Development type	Development density	Development cost	Pollution potential	NH_4 (mg/l as N	TKN mg/l as N	EC mS/m	SS mg/l	PO_4^{3-} mg/l as P	COD mg/l	DO mg/l	Faecal Coliform (/100ml)
Formal	High density	High cost	High	3-7	4-14	3-100	20-1000	0.2-6.0	60-500	3-6	10000-100000
			Low	1-3	2-8	12-50	40-150	0.2-3.0	40-300	3-6	1000-10000
		Low cost	High	1-30	10-40	70-2500	40-1850	0.4-14.0	150-400	1-6	10000-1000000
			Low	1-5	2-8	15-200	21-400	0.2-3.0	15-70	3-6	10000-1000000
	Low density	High cost	High	1-21	1-16	30-200	1-2500	0.1-6	5-800	3-6	1000-10000
			Low	0-3	1-5	10-50	21-350	0-3	20-80	1-6	0-1000
		Low cost	High	No data	No data	No data	No data	No data	No data	No data	No data
			Low	No data	No data	No data	No data	No data	No data	No data	No data
Informal	High density	Low cost	High	5-24	7-103	25-700	800-8000	1-8	70-3000	1-3	10000-10000000
			Low	1-5	4-18	8-180	180-3500	0.2-5	40-400	3-6	10000-1000000
	Low density	Low cost	High	No data	No data	No data	No data	No data	No data	No data	No data
			Low	No data	No data	No data	No data	No data	No data	No data	No data

The contamination ranges show that low-cost, high-density informal development have consistently higher nutrient and faecal coliform pollution potential than high-cost, high-density formal development types. According to the assumption, high density settlements equate to more than 300 households per hectare (Armitage, 2011). High density informal communities had the highest levels of human faeces pollution and the lowest dissolved oxygen concentrations, according to a study by Jagals and Grabow, (1996). Similar findings were also found in studies conducted by Abia *et al.*, (2018) and van der Hoven *et al.*, (2017) in the Apies River.

Whilst microorganisms such as pathogenic viruses, bacteria, protozoa and helminths which are parasites in the body such as worms can appear in greywater from laundry and kitchen waters. Nutrients including nitrogen, phosphorus, and faecal coliforms, on the other hand, were consistently observed in the quality of greywater from non-sewered areas in South Africa (Bakare *et al.*, 2017; Franz *et al.*, 2013; Armitage *et al.*, 2009; Asante, 2008; Carden *et al.*, 2008). If not properly managed, the increase of nutrient concentrations transported in wastewater such as black and greywater might induce eutrophication, according to Katukiza *et al.*, (2014).

2.2. Stormwater management and drainage systems

In South Africa, stormwater management in several urban catchments is largely based on conventional stormwater infrastructure (Corrêa *et al.*, 2022). This means that urban stormwater runoff is generally managed by collecting and transporting surface runoff through a network of reticulated pipelines before being discharged into surrounding watercourses and coastal shorelines. This is the case in urban areas made up of asphalt roads, buildings and drainage systems. In many South African informal settlements, however, asphalt roads and traditional drainage systems are either non-existent or inadequate (Charlesworth *et al.*, 2016). As discussed in a number of studies, it has become important to mitigate or treat nutrients such as phosphorus and nitrogen before they reach watercourses (Gold *et al.*, 2019; Nehra *et al.*, 2019; Landsman *et al.*, 2018; Yang Yun-ya and Lusk, 2018; Mcandrew and Spooner, 2016; Szota *et al.*, 2015; Collins *et al.*, 2010). It is through the failures of the conventional urban stormwater management which focus on ‘end of the pipe’ solutions to manage pollution concerns that the concept such as NbS with multiple benefits have emerged to build resilience and in this case solve water quality deterioration, restore freshwater systems as result of rapid urbanization (Gajewska *et al.*, 2020; Neumann and Hack, 2020).

There exists a variety of definitions in the literature for NbS mainly to cater for the multiple benefits it provides., The United Nations World Water Development Report, it defines NbS as being inspired by nature to mimic natural processes to treat and improve management of water (UN-World Water Development Report., 2018). An all-encompassing definition provided by the International Union for Conservation of Nature (IUCN) defines NbS as the *"actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges by providing human well-being and biodiversity benefits"* (Paula *et al.*, 2022; Heneghan *et al.*, 2021; Neumann and Hack, 2020). However, this definition by IUCN is broad and lacks to define the key ability of NbS to mimic or imitate nature that this study aims to demonstrate. The European Commission (EC) defines (NbS) as *"actions which are inspired by, supported by or copied from nature", potentially "energy and resource-efficient and resilient to change"* (Krauze and Wagner, 2019). Even though there are wide-ranging definitions in the literature for NbS, the common denominator is that NbS mimic or work with nature. Also, the focus on NbS definition is on the triple bottom line for nature being environmental, social and economic balance which is also the foundation for sustainable development.

2.3. Nature based Solutions (NbS)

The NbS concept aims to emulate natural processes to treat and improve water quality by reducing risks to the environment and human health (Zhang *et al.*, 2019). The NbS concept is relatively contemporary and emerges as an umbrella concept encompasses a variety of principles such as sustainability, resilience, ecosystem services (Souliotis and Voulvoulis, 2022). The NbS are closely associated with green infrastructure in the contemporary literature (Gonzalez-flo *et al.*, 2023; Bunclark *et al.*, 2022; Mguni *et al.*, 2022; Souliotis and Voulvoulis, 2022; Nika *et al.*, 2020) and forest landscape restoration (Beceiro and Brito, 2022). This thesis adopts the description that NbS are regarded as actions inspire by nature imbedded within interventions such as green or ecological infrastructure.

There is some confusion in the literature about the NbS in relation to other stormwater management interventions which will be discussed below. A study by Krauze and Wagner, (2019) highlights distinction between NbS and stormwater management approaches which do not fully mimic natural process (Figure 2.1 below). Krauze and Wagner, (2019) highlights the difference between interventions which imitate and manipulate natural processed to achieve a desired outcome. Manipulation of natural processes in green infrastructure is referred to as stimulation of natural processes to achieve a desired outcome through introduction of external agents to an original system (genes, organisms, processes) (Figure 2.1). Whilst NbS that mimic or imitate nature focuses on introduction of biophysical structures into green infrastructure, these then multiply and enhance local processes and natural biota in the indigenous system. Nature can also be imitated at an ecosystem level (e.g., constructed wetlands mimic's natural wetland systems) and how it functions and understanding the elements required for the system to function optimally (Maglic, 2014).

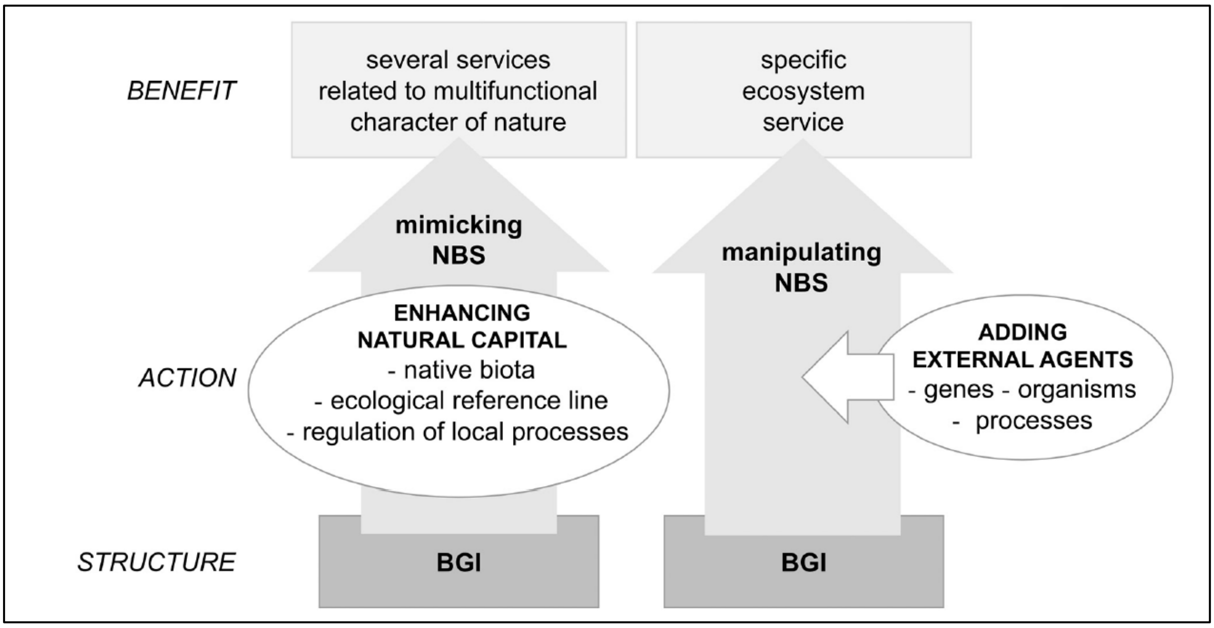


Figure 2. 1: Differences between NbS and engineered green infrastructure, source: (Krauze and Wagner, 2019)

The NbS can be manipulated in several ways such as modification of organisms to solve human problems, such as the use of bacteria for waste water purification (Kenchenten, 2017;

Oguntona and Aigbavboa, 2016) as illustrated in Figure 2.1. The use of plants in its natural habitat to treat nutrient rich surface runoff (phytoremediation) for example is an example of NbS approach. An example of manipulated NbS in green infrastructure Figure 2.1 above can be explained by the concept of bio-assistance, bio-utilisation (Buck, 2017). Buck (2017) argues that bio-utilisation and bio-assisted uses nature rather than learning and emulating natural processes. However, bio-assistance, bio-utilisation and emulation of nature-based processes can be difficult to distinguish. For example, mesocosm experiments can be designed to both emulate natural processes under controlled conditions without the use of external agents. On the other hand, mesocosm experiments often involve manipulation of chemical and environmental variables to achieve a specific goal.

This thesis examines and compares the NbS processes in a constructed wetland system that are used for treating and reducing elevated nutrients in stormwater runoff without the use of the addition of chemicals. There is a significant lack of evidence-based knowledge of the performance of NbS in treating and reducing elevated nutrient levels in surface runoff coming from the informal settlements. This thesis contributes to the relatively novel NbS body of knowledge, in water treatment in the context of elevated nutrients from an informal settlement.

2.3.1. Nutrient treatment dynamics in NbS and NbS theoretical frameworks

Nature based processes which include but not limited to sorption, precipitation, plant uptake and biological transformation, can play a critical role in the treatment of dissolved nutrients and sediments (Koryto *et al.*, 2018). The treatment of excess nutrients by nature based processes can be affected by several design factors, such as the presence of vegetation, dry and wet weather conditions, HRT and the type of substrate medium (Collins *et al.*, 2010). The concept of water quality treatment using constructed wetlands or biofiltration cells is often seen as the ‘’black box’’ concept (Figure 2.2 below) where several complex and interconnected physical, chemical and biological processes take place, especially in the absence of modelling techniques.

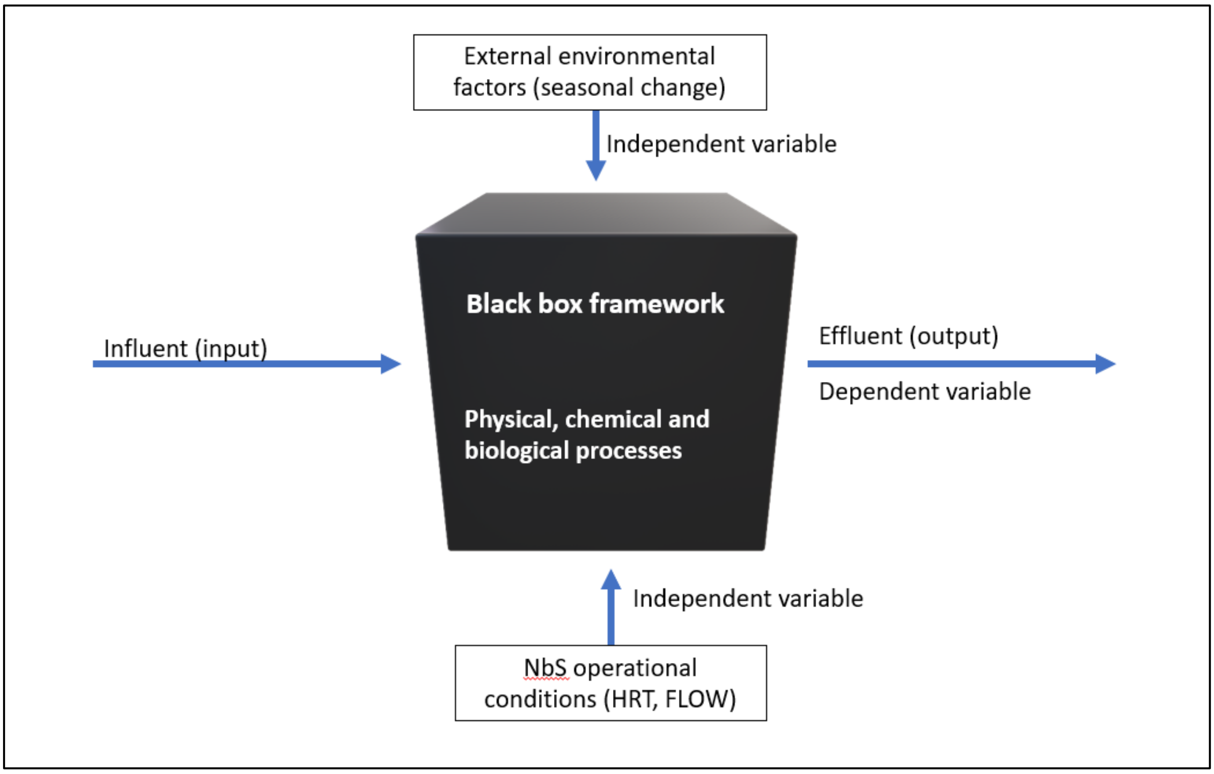


Figure 2. 2: The ‘‘black box’’ conceptual framework in NbS

The concept of the black box in the NbS represents unknown factors adding a layer of uncertainty in understanding of NbS such as biofilters especially in the informal settlement context. The concept in largely applicable in the field scale experiment compared to mesocosm where a number of variables are manipulated or modelled. Payne *et al.*, (2014) argues that NbS many studies on understanding of the performance of biofilters have been limited by the black box, despite several studies illustrating effective pollutant removal. This black box concept does not only provide constraint in understanding of the NbS in South African context but also hamper widespread adoption and management of untreated stormwater runoff. The interaction of nature-based processes within the black box with internal and operational NbS conditions such as the HRT and flow requirements are important in the understanding of field scale biofilter experiments and play a key role in the performance of NbS. These independent variables as illustrated in the ‘‘black box’’ (Figure 2.2 above) interact and influence the complex and interdependent physical, chemical and biological processes which are complicated to isolate and determine in field experiments.

Studies have undertaken several techniques to model and to understand the nature-based processes which govern pollutant treatment in wetland systems. Jarosiewicz *et al.*, (2022) introduces the ecohydrological NbS strategy for water quality treatment and integration with circular economy. The sequential sedimentation biofilter system concept introduced in a study by Jarosiewicz *et al.*, (2022) consists of three zones such as the sedimentation, geo-chemical and biofiltration zones for treatment of pollutants in Figure 2.3 below.

The sedimentation zone is the first zone where larger particles settle to the bottom. Whilst extended-detention such as sedimentation can be effective at removing particulate pollutants in smaller storm events through sedimentation process but it was found ineffective at removing soluble forms of nitrogen such as NO_3-N and NH_3-N, instead sedimentation basins such as dry ponds tend to export nitrogen (Collins *et al.*, 2010). Studies have shown that phosphorus can be retained onto sediments through adsorption of dissolved phosphorus or sedimentation of particles in the sedimentation zone (Meng *et al.*, 2014), however, sediments can often be released continuously back into the water column after disturbance after its introduction (Cavalcante *et al.*, 2018; Griffin, 2017; J. Yu *et al.*, 2017; Huang *et al.*, 2016; Percuoco *et al.*, 2015; Lai and Lam, 2009). This effect can deem the sedimentation zone ineffective in retaining sediments and associated pollutants.

The geo-chemical zone is intended to enhance adsorption and precipitation of TP as biofilm develop on calcium-based rock surface for nutrient treatment and the biofiltration zone in a form of CW, where plants and microorganisms interact to enhance nature-based processes such as mineralization, biodegradation plant uptake through assimilation process. The colour change in each zone from dark in the sedimentation zone to light in the biofiltration zone represents the improvement of the influent as the water passes through the different zones and processes. This framework would fall short in the context of informal settlement where public involvement in the initial stages is critical for the maintenance system particularly of the litter trap structure before sedimentation zone. Litter traps structures in informally settled catchments would be located before the sedimentation zone to prevent clogging of the system overtime.

The sequential sedimentation biofilter system incorporates circular economy using organic matter rich sediments as a resource for agriculture. However, reusability of the sediments in agriculture would be determined by its quality as sediments consists of elevated concentration of nutrients and other chemicals relative to the water column due to high sediment adsorption ratios (Narasimhan *et al.*, 2017; Mcandrew and Spooner, 2016; Adiyiah *et al.*, 2014; Franz *et al.*, 2014; Selbig *et al.*, 2013; Poleto *et al.*, 2009; Vaze and Chiew, 2004; Paul and Meyer, 2001). Jarosiewicz *et al.*, (2022) recognises the importance of sedimentation zone in the below framework, but does not examine or assess the appropriate depth of sedimentation zones to allow for adequate settling. Landsman *et al.*, (2018), argue that adequate depth of sedimentation zones increases the retention time, thereby improving pre-treatment via sedimentation and sorption of dissolved nutrients to suspended solids.

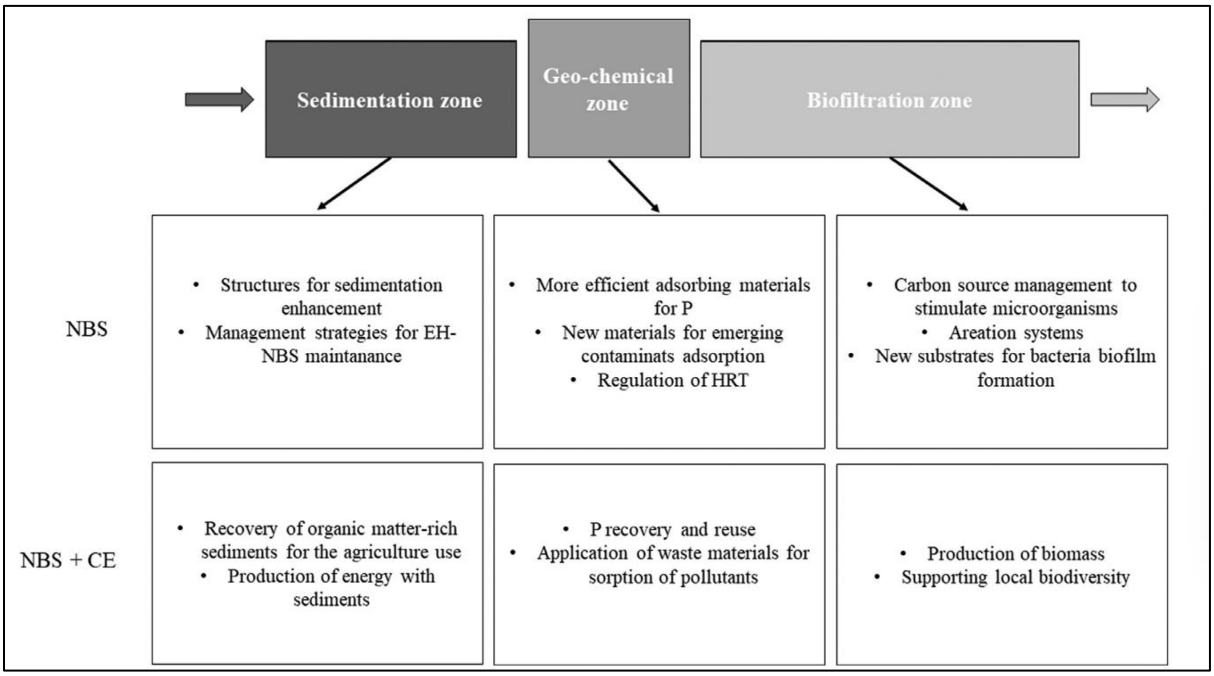


Figure 2. 3: The NbS pathways in different zones of sequential sedimentation biofilter and links to circular economy (Jarosiewicz et al., 2022).

The enhancement of adsorption and precipitation of TP as biofilm develop on calcium-rock surface in the biofiltration zone is crucial for nutrients treatment (Figure 2.3 above). The medium type with size of a surface area is crucial for adsorption of nutrients in the geochemical zone. Besides the calcium-based rock surface used to optimize adsorption, other studies have found that sediment composition is a key factor that controls phosphate adsorption by sediments (Li *et al.*, 2016; Meng *et al.*, 2014; Wang *et al.*, 2009). The adsorption capacity of phosphorus onto sediments increases with an increase in the metal oxide and organic matter content found in the sediment (Li *et al.*, 2016; Wang *et al.*, 2009; Aimin *et al.*, 2005).

Another important consideration not incorporated in the framework is that particle size fractions play a role in the adsorption of phosphorus content. The fine particles with a larger surface areas such as clay (<4 µm) often exhibited high organic matter, metal oxide and calcium content and thus high adsorption capacity of phosphorus (Wang *et al.*, 2009). Therefore, Li *et al.*, 2016 concluded that the maximum adsorption amount of sediment sizes increases as the (Fe, Al and Ca) concentration increases. It is therefore critical to have overlapping processes in several zones to capture fine particles that would not settle in the sedimentation zone not only in the biofiltration zone using plants but also in the geo-chemical zone.

The treatment and transformation of nitrogen can often take place in the biofiltration zone (Figure 2.3) through, mineralization, NH_3-N fixation (ion exchange), microbial uptake, nitrification and denitrification under anoxic conditions (Li and Allen P Davis, 2014). The excess nitrogen in watercourses can be difficult to remove because of its solubility (Lefevre *et al.*, 2015). Therefore, NO_3-N and NO_2-N do not readily sorb to bioretention media or soil and it is influenced by the variable wetting and drying regime inherent in biofilter operation (Lefevre *et al.*, 2015; Hatt *et al.*, 2009).

Contrary findings noted that the removal of soluble NO_3 and NO_2 depends on plant uptake and denitrification (Hatt *et al.*, 2009). Besides plant uptake, microbial activity also plays a crucial role in removal of dissolved nutrients. Guo *et al.*, 2019 and Milstein *et al.*, 2018 claims that the transformation of NO_3 and NO_2 in the biofilter takes place through bio-assimilation (including absorption by plants, bacteria, fungus, microorganisms and through denitrification which changes inorganic nitrogen into gaseous forms (N_2; N_2O). Guo *et al.*, 2019 and Lefevre *et al.*, 2015 noted that NH_3-N removal depends on material adsorption and microbial metabolism which results in the oxidation of NH_3-N into NO_3-N by nitrifying bacteria and nitrifying bacteria in the bioretention systems under aerobic condition. These processes are highly complex and interrelated to such as extent that it is difficult to comprehend without the use of models since many of the processes take place simultaneously. But from the field experiment point of view, these nature-based processes can be partially explained and simplified.

The Table 2.2 below illustrates nature-based processes that can be configured in NbS for this study to treat excess nutrients and sediments in surface runoff. The table below does not illustrate the effectiveness of the removal mechanisms because the efficacy of these nature-based processes vary based on physical, chemical and biological processes. This thesis makes reference to several terminologies such as nutrient treatment, degrade, removal and reduction to illustrate the complex nature-based processes often taking place sequentially or simultaneously in NbS. Many of these processes are highlighted in the table 2.2 below, and the removal or treatment mechanism often associated with pollutant.

For example, El-refaey, (2007) argues that biofilters constitute critical separation processes to remove organic pollutants not only from polluted water but also from air, these removal processes depend on mechanisms such as adsorption and biodegradation. The permanent removal process for example is further described by Jacklin *et al.*, (2022), where vegetation in biofilter is harvested. Because vegetated biofilter for example constitute several physical, chemical and biological processes (Jacklin *et al.*, 2022), to treat pollutants, not all the pollutants are completely removed but are often reduced in concentrations.

The different processes can be assembled for optimal performance to give overlapping and sequential treatment. The selection of any nature based process is reported by Armitage *et al.*, (2014) to be based on site specific characteristics, and is informed by pollutants targeted (Wong *et al.*, 2005).

Table 2. 2: The nature-based processes for treatment of excess nutrients (Kellagher et al. 2007)

Pollutants	**Removal/treatment mechanisms**
Nutrients: Phosphorous, nitrogen	Sedimentation, biodegradation, precipitation, de-nitrification
Sediments: Total suspended solids	Sedimentation, filtration
Pesticides	Biodegradation, adsorption, volatilisation
Litter	Trapping, removal during routine maintenance
Organic matter, BOD	Filtration, sedimentation, biodegradation

The interrelationship between surface runoff and litter particularly in informal settlements has a potential to render the nature based processes ineffective or dysfunctional (Fitchett, 2017a). Solid waste in the form of urban litter can cause physical blockages, interventions by trapping debris, food remains and sewage providing a breeding ground for pathogens to multiply (Armitage *et al.*, 2014). The theoretical framework (Figure 2.4 below) for this study is divided into three separate but interlinked categories, input, nature processes and output which are further subcategorised into planning, operation/amendment, monitoring/evaluation respectively.

The framework below recognises the importance of involving key stakeholders such as local municipalities, research institutes i.e., universities, community-based organisations in the planning stages of the NbS implementation. This is to ensure that best practicable structural and non-structural (i.e., awareness creation) measures are selected for litter management. Brainstorming workshops are typical examples structured mechanisms which are critical to develop ideas, aims and objectives. This is important in selecting NbS such as SuDS tools to treat targeted pollutants such as elevated nutrients and microbiological pollutants which are often discharged from informal settlements as discussed in chapter one of this study. Often the top down/bottom-up approaches are a failure in informal settings especially if the roles of the most vulnerable communities are not clearly outlined and to some extent if there are no prospects of them directly or indirectly benefiting from the projects.

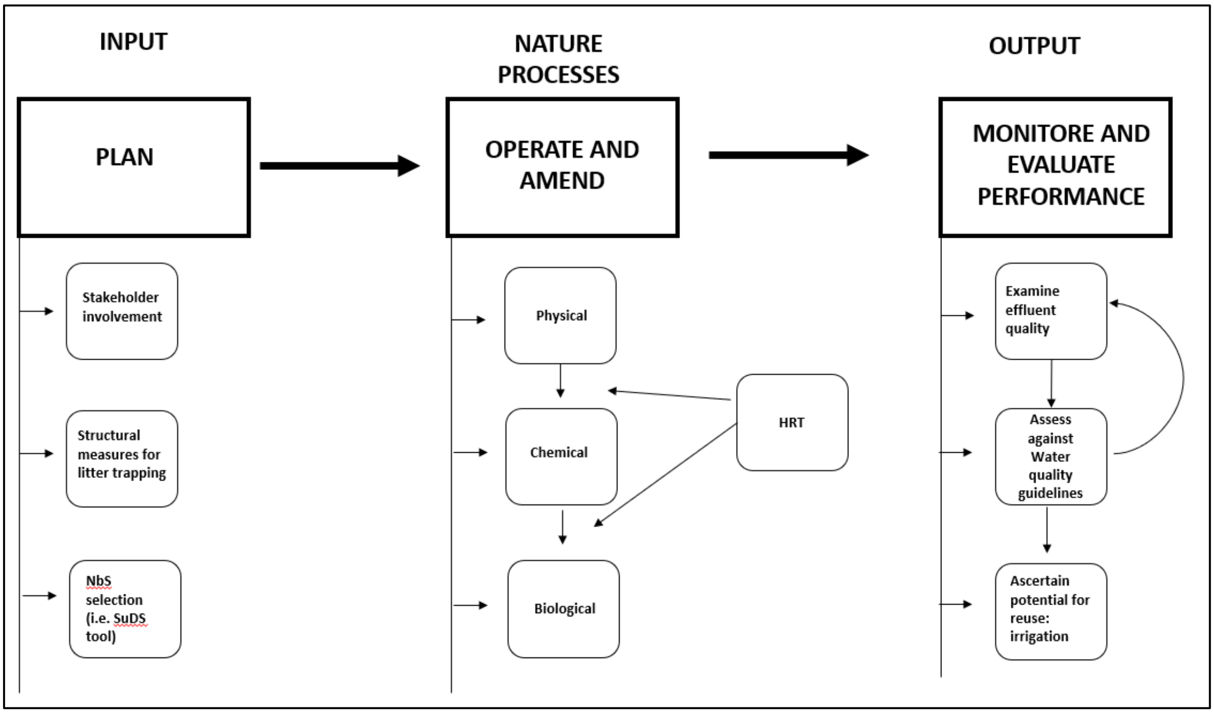


Figure 2. 4: The NbS theoretical framework application for this study

This framework does not conform to the grouping of the SuDS tools into four categories, these subsume good housekeeping, source control, site control and regional control measures as discussed in a study by (Armitage *et al.*, 2014). This framework rather emphasizes on arrangement of the nature-based processes or SuDS tools in a treatment train concept to ensure optimum treatment of pollutants. The treatment train concept is highlighted by Jefferies *et al.*, (2008) as critical because it promises to give sequential treatment for nutrients and to provide backup should one processes of the system becomes ineffective, i.e., due to clogging. Aryal *et al.*, (2010); Begum *et al.*, (2008) argue that SuDS that target the treatment of nutrients carried in surface runoff can be reduced through primary, secondary and tertiary treatment measures, where the latter is often at the end of the treatment train.

The output phase of this framework highlights the importance of continuous monitoring and evaluating the performance of the selected NbS to meet the desired goals, such as irrigation of food garden with water quality that meets the irrigation standards. The treatment of pathogen from the surface runoff using biofilter has currently been investigated to take place through microbial removal, adsorption, desorption and die-off, the latter is deemed temperature dependent (Shen *et al.*, 2018). Feng *et al.*, 2018 argues that treated runoff through biofilters is suitable solely for non-portable purposes, such as restricted irrigation and toilet flushing.

2.3.1.1. Vegetation uptake in NbS

There is a large body of literature related to the role of plants in the reduction of excess nutrients using biofilters and CWs form various urban environments (Barron *et al.*, 2019; Goh *et al.*, 2019; Gold *et al.*, 2019; Guo *et al.*, 2019; Arden and Ma, 2018; Dagenais *et al.*, 2018; Li and Guo, 2017; Glaister *et al.*, 2017; Ladislas *et al.*, 2013; Milandri *et al.*, 2012; Wang *et al.*, 2012; Chen, 2011). The capacity of and effectiveness of plants to treat excess nutrients vary significantly depending on plants species physiological, chemical and morphological variations (Lefevre *et al.*, 2015; Milandri *et al.*, 2012; Bratieres *et al.*, 2008; Read *et al.*, 2008).

Plant selection is important in the removal of excess nutrients (Li *et al.*, 2018; Glaister *et al.*, 2017; Li and Guo, 2017; Bratieres *et al.*, 2008). A study by Milandri *et al.*, 2012 used various locally-occurring plant species (Cape Town, South Africa) to highlight the importance of plants in the absorption of nutrients**.** The study consistently found certain plants to absorb higher rates of nutrients due to rapid growth rates (Milandri *et al.*, 2012). This is attributed to increased absorptive surface and higher nutrient requirement in plants with higher growth rates and biomass (Barron *et al.*, 2019). Vymazal, 2007a concurred with the study and indicated that plants nutrient uptake is highest early in the growing season, decreasing as the plant mature and senesce (Vymazal, 2007b). This is evident for macrophytes such as water hyacinths which are hyperaccumulators of nutrients consisting of high growth rates (Fox *et al.*, 2008).

Dagenais *et al.*, (2018) argues that harvesting of the accumulated biomass is important for maintenance of the long term growth rate and nutrient uptake (Dagenais *et al.*, 2018). Plants senescence reduce dissolved oxygen levels and releases nutrients back into the water column (Fox *et al.*, 2008). High levels of the rebound nutrients can reduce efficacy of older plants. Plant harvesting and disposal can be problematic in achieving sustainability and long-term operation of vegetated NbS. Besides plant harvesting, which is often suggested in the literature when the plants reach an equilibrium state. Little is known about the ability of plants to reach the equilibrium state as the capacity of plant to perform removal vary. Goh *et al.*, 2019 argues that optimal nutrient removal rates can be achieved by using mixed plants of a monoculture.

Plant adopted to low concentrations of nutrient were reported to be negatively affected by phosphorus intake and they consequently have low inherent growth rates (Read *et al.*, 2008). Read *et al.*, 2008 noted that such plants species can ineffectively reduce excess nutrients compared to plant species with higher nutrient intake and growth rates. A study by Dagenais *et al.*, (2018) noted that certain plant species are associated with mycorrhizal fungal which may augment nutrient uptake performance. Contrary findings by Read *et al.*, 2008 shows that some slow growing plants common in communities with low-nutrient soils have higher nutrient uptake rates per unit root mass. The comparison of the long-term performance of slow growing plants and fast-growing plant in the removal of nutrient is under researched. This is to ascertain the most sustainable option (plant type) that would slow equilibrium state and plant harvesting whilst increasing the uptake.

The nutrient plant uptake through the root system is limited by the plant growth rate and the concentration of nutrients in the plant tissue (Vymazal, 2007a). The presence of extensive root system and root hairs contributes greatly to excess nutrient removal compared to shorter root system, since root hairs can absorb up to 60 percent of the plants phosphorus concentration (Bratieres *et al.*, 2008).The plant species with higher growth rates are unable to persist under alternating wet/dry weather and nutrient conditions that occur between nutrient pulses in surface runoff (Read *et al.*, 2008). Studies have shown that plant species with higher growth rates have extensive root system that can potentially cause leakage of carbohydrates which might influence microbial community composition and nutrient removal (Read *et al.*, 2008).

2.3.1.2. Microbial activity, HRT and temperature in NbS

Macrophytes are commonly used in biofilters as they provide one of the best medium for microbial growth as they often consist of filamentous and complex root structure that provides a greater surface area for microbial community to strive, to host beneficial insects and microorganisms and adsorb nutrients whilst physically filtering and trapping suspended material (Gao *et al.*, 2017; Schwammberger *et al.*, 2017; Armitage *et al.*, 2013; Mohan *et al.*, 2010; Wong *et al.*, 1999; Todd and Josephson, 1996). The efficacy of microbial community to remove nutrients vary depending not only on substrate (biotic (plant surface) or abiotic (rock surface and sediment) in the water body) but also on physiochemical conditions (Cooper, 2010). Cooper, 2010 discovered that the substratum physical and chemical properties, the number and type of cells/species (bacteria or fungal) within the biofilm including the external physical factors influence nutrient removal efficacies of biofilms. However, HRT in the NbS system is central in the performance of vegetation and microbial growth, as HRT can directly influence both vegetation and microbial growth.

Another study reported that wetlands with dense vegetation and root structure can significantly remove excess nutrients compared to wetlands with little or no vegetation because microbial communities are often more high in numbers and diverse in planted treatment wetlands as compared to wetlands with little or no vegetation (Picard *et al.*, 2005). Even though vegetated biofilters generally perform better in the removal of pollutants, but pollutants such as phosphate that does not only depend on vegetation uptake can illustrate different removal pattern with change in HRT and season. Picard *et al.*, (2005) established that the rapid uptake in dense vegetation is enhanced by microhabitats within the soil structure formed by plant root growth. He added that plants supply carbon to microbes which are beneficial to microbes for survival and to enhance nutrient removal.

Temperature is an external physical factor influencing microbial activities (Wang and Sample, 2014; Picard *et al.*, 2005) and performance of nature based processes in removal of pollutants. Picard *et al.*, (2005) argues that the optimum temperature for nutrient treatment through microbial action is 30 ˚C whereas, nutrient treatment becomes negligible at temperatures below 5˚C.Yang Yun-ya and Lusk, (2018); Collins *et al.*, (2010) reported that nitrogen reduction in biofilters and CW's can be enhanced by increasing water temperatures up to 60 °C. The treatment rate of excess nitrogen is therefore reported to increase not only with an increase in temperature but also the length of retention time in saturated zone (Szklarek *et al.*, 2018). Temperature is an independent variable that cannot be manipulated in the field studies as compared to the mesocosm studies. Therefore, the outcome of mesocosm experiment should provide a general guideline of what can be expected should the experiment be performed in the field.

On the other hand, a study by Picard *et al.*, (2005) indicates that phosphorus treatment is less affected by temperature as oppose to nitrogen, because phosphorus is dominated by sediment adsorption as compared to biological processes. He noted that CW's in temperate climates operates at lower level of nutrient reduction efficiencies in the colder months. The leaching of NO_3 and NO_2 to be prominent during cooler and wet seasons as de-nitrification and plant uptake are slowed in such conditions (Armitage *et al.*, 2014). Lower temperatures are investigated to negatively influence the rate of plant uptake and biological nitrogen fixation in the biofilters (Blecken *et al.*, 2010). A study by Koryto *et al.*, 2018 reports active microbial growth from temperature of about 14°C. However, Chen *et al.*, 2019 attributes significant nutrient uptake and higher efficiencies to microbial diversity, and community distribution.

Microbial community nutrient uptake by bacteria, fungi, algae and macroinvertebrates is rapid because the organisms grow and multiply at high rates with low magnitude (amount stored) (Vymazal, 2007b). A high content of absorbed pollutants such as phosphorous can adhere on to biofilms (Prodanovic *et al.*, 2019; Milstein *et al.*, 2018). Vymazal, 2007a reports that microbial storage depends on trophic status of a wetland, such that microbial uptake is higher in less enriched wetland compared to eutrophic wetlands. Other studies have shown that the development of biofilms under prolonged HRT was demonstrated to significantly reduce the faecal coliforms to between 80 percent - 90 percent (Rasool *et al.*, 2018).

Hydraulic residence time is one of the important parameters that influences microbial activity and the efficacy of NbS. One of the biggest design challenges in establishing efficiency is determining suitable residence periods for diverse NbS systems. Longer residency times in biofilters have been associated with increased nutrient reduction rates. This was validated in a study by Steidl *et al.*, (2019); Rasool *et al.*, (2018), which found that longer residence times promote the development of biofilm, which lowered the level of nitrogen and faecal coliforms in biofilters by 80 percent - 90 percent. However, the effect of longer and shorter HRT on various pollutants varies, as pollutants removal/treatment mechanisms in NbS differ.

In constructed wetlands, Luca *et al.*, (2017) set a 7-day minimum resident time which was effective in the treatment of pollutants. According to Muvea *et al.*, (2019), a minimum residence duration of 15 to 20 days should be specified to allow for microbial decomposition of wastewater and macrophyte nutrient intake. The performance of NbS in the literature varies with HRT, there is no generally accepted HRT for best performance. It is not clear whether HRT can best be determined based on specific surface medium. Because plants increase contact time for biofilm production, it is logical to expect biofilters with dense macrophytes to require less residence time than those without macrophytes.

A study by Meng et al., (2019) has assessed the adsorption characteristics of a novel composite biochar (products of sludge fermentation), due to its advantages of low cost, large surface area, high adsorption capacity and increased microorganism's growth in non-aerated vertical baffled flow CW. The presence of composite biochar as a substrate removed about 3.4 percent, 4.0 percent and 11.8 percent, of ammonium-nitrogen, total nitrogen and total phosphorous respectively, at a hydraulic retention time of 3 days. However, an establishment of an effective hydraulic residence time that varies over time (seasonally) with associated treatment would have improved knowledge of hydraulic residence time for the optimal treatment of nutrients.

2.3.1.3 Nitrification and denitrification in NbS

Nitrification and denitrification widely reported in the literature to contribute in the removal of elevated nutrient concentrations at various rates (Liu *et al.*, 2021; Tan *et al.*, 2020; Chen *et al.*, 2019; Rodziewicz *et al.*, 2019). The removal of nutrients through denitrification is cited in various studies Tan *et al.*, (2020); Steidl *et al.*, (2019); Morse *et al.*, (2018); Tallec *et al.*, (2006) including Hang *et al.*, (2016) to rely significantly on a number of physical, chemical parameters and design features which include but are not limited to temperature, retention time, oxygen and pH availability, presence of carbon source in order to reduce NO_3-N to NO_2-N and subsequently into N_2 using the heterotrophic denitrifying bacteria. These biological processes are one many taking place in the NbS ''black box''. Even though they often take place simultaneously, they operate best in different temperatures, yield different by products, require different mode of respiration and bacteria involvement.

Ashok and Hait, (2015) outlines a review of general principles and pathways of solid phase denitrification process, factors that govern success rate of denitrification, denitrification efficiency, applicability, advantages and disadvantages of the process taking into consideration a change of environmental conditions. The study sets up a foundation on techniques which this research study can undertake to enhance denitrification process in the six field scale biofiltration cells. Ashok and Hait, (2015) further illustrates solid phase denitrification as taking place on solid substrates because solids are a constant source of denitrification, thereby providing a surface for microbial development.

The solid phase denitrification can be seen in a study that uses wood chips or mulch together with saturated zone to promote nutrient removal through denitrification process (Kathryn, 2012). Low redox potential and anoxic zones with addition of electronic donors i.e. wood chips to the media are found to improves denitrification (Lefevre *et al.*, 2015). Payne *et al.*, (2014) demonstrates the effectiveness of plant roots as source of carbon for heterotrophic processes due to their large surface area to volume ratio. Longer residence time and internal storage zones (engineered area which promotes longer periods of anaerobic conditions) in bioretention columns are reported in a study by Collins *et al.*, (2010) and to enhance denitrification. It can be deduced from these studies that the efficacy of denitrification process in the removal of nutrients is not simple but rather complex and depends on several variables such as temperature variation, different types of plant carbon source and hydraulic residence times.

Contrary to the anoxic or oxygen depleted zones where denitrification process is prevalent, nitrification is described as an autotrophic aerobic process which converts NH_3-N into NO_3-N (Boxman *et al.*, 2018; Tallec *et al.*, 2006). The effectiveness of the nitrification process in NbS vary and is described by Tao *et al.*, (2012) to depend on dissolved oxygen concentration, temperature variation, and an influent ammonium concentration. Vymazal, (2007b) argues that temperature of between 25 ˚C to 35 ˚C are optimum for nitrification. However, the study does not make sufficient comparison to other environments such as field scale biofilter systems where temperatures vary with context and diurnal changes unlike mesocosm experiment.

A study by Rasool *et al.*, 2018 indicates that favourable temperature increases the population of nitrifiers. Picard *et al.*, (2005) discovered that nitrification rates in wetlands become inhibited at water temperatures of about 10˚C whilst nutrient removal rates drop rapidly at 6˚C. Goh *et al.*, (2019) suggests that there is limited nitrogen reduction under low temperature range (2°C and 8°C), this is attributed to insufficient denitrification and high leaching rates from the columns. The effectiveness of a stormwater biofiltration in a laboratory study to remove nutrients and sediment in cold temperatures was investigated by (Blecken *et al.*, 2010). The study reported poor nitrogen treatment rates with high leaching rates due to lower nitrification rates connected to the lower temperatures. However, little is known about the performance of nitrification and denitrification rates to remove nutrients on field scale biofilter.

General understanding is that the effectiveness of nature-based solutions in South Africa, which is a semi-arid country characterised by variable climate and scarce water resource due to longer dry weather conditions would vary to those operated in Europe or a mesocosm study in other parts of the world with different climatic conditions. However, there is a lack of evidence-based literature in the South African context to substantiate the notion that temperature influences nutrient removal in NbS.

Submerged zones in biofilters and CW's were shown to improves reduction of excess NO_3-N and NO_2-N rates with between 71 percent - 75 percent compared to between 33 percent - 7 percent of unsaturated zones (Goh *et al.*, 2019). However, submerged zones were consequently reported in a study by Goh *et al.*, 2019 to significantly decrease NH_3-N reduction. Therefore, denitrification is greater under anoxic conditions and can be driven by carbon source in stormwater systems (Morse *et al.*, 2018; Collins *et al.*, 2010). Since denitrification requires anoxic conditions, biofilter and CW's need to manage hydrologic residence time, infiltration and drainage are deemed for reducing excess nutrient by denitrification (Collins *et al.*, 2010; Yi *et al.*, 2009).

A study by Collins *et al.*, 2010 further investigated that the design modification that involves establishment of anaerobic zones or inclusion of organic matter can result in leaching of stormwater pollutants such as phosphorus. A study by Collins *et al.*, 2010 reveals that the treatment of excess nitrogen through assimilation by plants and microbes temporarily removes nitrogen levels, whilst microbial denitrification can reduce excess nitrogen permanently in gaseous forms (Collins *et al.*, 2010). The accumulation of carbon source (organic matter) on substrates creates anaerobic zones which increases denitrification and reduction of NO_3, NO_2 and sporadically phosphorus (Milstein *et al.*, 2018). However, a study reported by Bratieres *et al.*, 2008 has indicated leaching of NO_3-N out of bioretention systems resulting to ineffective total nitrogen removal.

Nitrification (nitrogen transformation) and ammonia volatilization are correlated with temperature including pH of above 6, whilst temperature and Dissolved Oxygen (DO) influence nitrification (Wang and Sample, 2014; Fox *et al.*, 2008; Vymazal, 2007b). An optimum temperature for nitrification rage from 25 to 35˚C (Vymazal, 2007b). A study by Rasool *et al.*, 2018 indicates that favourable temperature increases the population of nitrifiers. Picard, Fraser and Steer, 2005 discovered that nitrification rates in wetlands become inhibited at water temperatures of about 10˚C whilst nutrient treatment rates drop rapidly at 6 ˚C. As such, there is no nitrogen reduction under low temperatures (between 2 and 8 °C) because of insufficient denitrification and high leaching from the column (Goh *et al.*, 2019).

Denitrification enhancement is recorded in the literature through the use of wood chips which are known electron donors for denitrification process during anoxic conditions (Koryto *et al.*, 2018; Hang *et al.*, 2016). However, a laboratory scale column experiment study by Lefevre *et al.*, (2015) discovered shredded newspaper as the best electron donor among the different organic and inorganic materials such as, alfalfa, leaf mulch compost, sawdust, wheat straw, wood chips, and elemental sulfur. A study by Weiss *et al.*, (2010) has reported newspaper as the effective electron donor, with efficacy rates of between 70 percent to 80 percent NO_3-N mass reduction compared to alfalfa, leaf mulch compost, saw dust, wheat straw and wood chips in bioretention cells with submerged anoxic zone. Simultaneous nitrification, anammox and denitrification process is an effective novel approach that has been assessed in a number of studies for treatment of nitrogen (Chen *et al.*, 2019; Pavlineri *et al.*, 2017; Tao *et al.*, 2012).

2.3.2. The origins and application of SuDS as the stormwater component of NbS

A recent study by Mguni *et al.*, (2022) claim that Water Sensitive Design (WSD) concept which has its origins in Australia has gained attention as NbS. Nature based processes have been in existence longer than the WSD and NbS concept but were later recognised and formalized in countries such as Australia and others. The study by Mguni *et al.*, (2022) notes that WSD encompasses green infrastructure elements with engineered urban water systems and focuses on management of the total water cycle instead of a specific component of the water cycle. Concepts such as Sustainable Urban Drainage Systems (SuDS) which also uses NbS, is a component of the WSUD that focuses on one or two aspects of the urban water cycle in comparison to NbS and WSD (Armitage *et al.*, 2014).

Different countries use distinct SuDS nomenclature which can result in confusion. Water Sensitive Urban Design (WSUD), Low Impact Development (LID), Stormwater Control Measures (SCM), Stormwater Best Management Practices (BMP), Sustainable Urban Drainage Systems (SuDS), Landscape-based Stormwater Management (LSM), Local Management of Stormwater (LMS), Sponge City Concept (SCC), Active Beautiful Clean Waters Program (ABC Waters Program), and Blue-Green Infrastructure (BGI), and are some of these. The SuDS language has recently been adopted and placed inside the Water Sensitive Urban Design (WSUD) framework for stormwater management in South Africa (Sletto *et al.*, 2019b; Shen *et al.*, 2018; Wang *et al.*, 2018; Armitage *et al.*, 2014). Even if a SuDS stormwater management approach is adopted in informal settlements, it might not be sufficient to address a range of socioeconomic difficulties (Charlesworth and Booth, 2017).

The SuDS strategy for managing urban stormwater runoff has been used in a variety of environments with varying degrees of success in terms of pollutant reduction efficiency. According to a study by Reed and Dunelm, (2013), detention basins are ineffective in reducing surface runoff when significantly contaminated with faecal discharges. The application of SuDS interventions in informal settlements can be difficult due to a general lack of municipal infrastructure, hence interventions such as biofilters and constructed wetlands may be utilized for the disposal of grey and black water, as well as solid waste.

According to Aryal *et al.*, (2010), when SuDS tools are arranged in a treatment train that targets distinct types of pollutants, efficient treatment of substantially contaminated runoff and dissolved nutrients can be obtained compared to use of single component such as buffer strip for example. The establishment of SUDS framework and guidelines designed for the South African context by (Armitage *et al.*, 2014) is evidence that the (SuDS) provides overarching options that are not currently enforceable through legislation to mitigate urban stormwater pollution at source.

The ability of biofilters to remove sediment associated with surface runoff and nutrients has long been documented (Yu *et al.*, 2020; Guo *et al.*, 2019; Landsman *et al.*, 2018; Milandri *et al.*, 2012; Read *et al.*, 2008; Shanableh *et al.*, 1997), their ability to reduce faecal microorganisms from surface runoff has only recently been demonstrated, but the level of contamination varies with the configuration (Bu *et al.*, 2021; Graham *et al.*, 2021; Feng *et al.*, 2018; Rasool *et al.*, 2018; Shen *et al.*, 2018). However, there is no clear evidence that stormwater runoff biofilters in informal settlements can remove elevated nutrients and associated sediment particles (Fitchett, 2017b). As discussed below, this is attributed to limited studies that have been undertaken in this field of study particularly in the informal settlement context.

A large body of international literature has over the years evidently reported on the performance of the NbS in excess nutrients in developed urban catchments worldwide (Huamán *et al.*, 2022; Kim *et al.*, 2021; Dhadwal *et al.*, 2021; Di Capua *et al.*, 2020; Shen *et al.*, 2018; Milandri *et al.*, 2012). Studies have demonstrated urban stormwater runoff treatment efficiencies of up to 70 percent, 80 percent and over 95 percent for TN, TP and suspended solids respectively using biofiltration cells (Aryal *et al.*, 2010; Blecken *et al.*, 2010).

Table 2.3 below illustrates the effectiveness of several nature-based processes embedded in SuDS that can be configured in this study to treat and remove nutrient rich surface runoff and associated sediments discharged from the informal settlement. Many of these nature-based process overlaps in terms of their ecosystem functions, the inability to systematically arrange these processes to target a specific pollutant would deem SuDS ineffective.

Table 2. 3: The effectiveness of various pollutant treatment/ removal mechanisms in selected SuDS interventions (McFarland et al., 2019).

Pollutants	SuDS option	Effectiveness of pollutant treatment/ removal mechanisms for treatment of urban stormwater pollutants
Suspended solids	Retention basin	Sedimentation **
	Constructed wetlands	Sedimentation and vegetation ***
	Bioswale	Sedimentation **
	Rain garden	Sedimentation and vegetation***
	Green roof	Sedimentation and vegetation ***
	Permeable pavement	Sedimentation and filtration **
Pathogens	Retention basin	Retention and infiltration **
	Constructed wetlands	Retention and infiltration **
	Bioswale	Infiltration *
	Rain garden	Infiltration *
	Green roof	Infiltration *
	Permeable pavement	Retention *
	Biofiltration systems	Biofilm adsorption & increased retention time **
	Infiltration trenches	Infiltration *
Organic Matter	Retention basin	Vegetation, retention and infiltration ***
	Constructed wetlands	Vegetation, sedimentation, infiltration and biological degradation (aerobic and/or anaerobic) for the treatment/removal of dissolved organic matter ***
	Bioswale	Vegetation and infiltration **
	Rain garden	Vegetation and infiltration **
	Green roof	Vegetation and infiltration **
	Permeable pavement	Retention and infiltration **
Synthetic organics	Retention basin	Vegetation and retention ***
	Constructed wetlands	Vegetation and retention ***

	Bioswale	Vegetation **
	Rain garden	Vegetation **
	Green roof	Vegetation **
	Permeable pavement	Infiltration *
Nitrogen	Retention basin	Spares vegetation **
	Constructed wetlands	Denitrification, ammonification, nitrification, dense vegetation and export through biomass harvest ***
	Bioswale	Spares vegetation **
	Rain garden	Dense vegetation ***
	Green roof	Dense vegetation ***
	Permeable pavement	Infiltration *
Phosphorous	Retention basin	Spares vegetation **
	Constructed wetlands	Substrate adsorption, dense vegetation and export through biomass harvest ***
	Bioswale	Spares vegetation **
	Rain garden	Dense vegetation ***
	Green roof	Dense vegetation ***
	Permeable pavement	Infiltration *
	Biofiltration systems	Biofilm adsorption & increased retention time **
Litter and debris	Good housekeeping: awareness, operation and maintenance	Trapping and removal ** Sweeping ** Maintenance (comprising of regular inspection) **

Key:

*Less effective

**Moderate effective

***Highly effective

Milandri *et al.*, (2012) demonstrated the following average treatment and reduction efficacies 81 percent, 90 percent and 69 percent of PO_4^{3-}, NH_3-N, and NO_3-N respectively using indigenous vegetated biofilters. The suspended solids removal efficiency was recorded above 95 percent, (Rasool *et al.*, 2018). An investigation into sand filters found that they can remove between 30 percent and 45 percent of the nitrogen (Weiss *et al.*, 2010).

Goh *et al.*, (2019) reported between 59 percent – 79 percent of total nitrogen and 77 percent – 94 percent of total phosphorus treatment rates in vegetated biofilters compared to non-vegetated biofilters that exports substantial amount of NO_3/NO_2. Whilst a study by Morse *et al.*, (2018) has shown vegetation uptake of nutrients to account for 39 percent - 60 percent through plant assimilation. Blecken *et al.*, (2010) on the other hand reported reduction rates of between 96 percent and 30 percent in vegetated biofilters, which is largely based on the type of plant used and complex interaction between physical, chemical and biological processes.

Another important consideration is that SuDS in South Africa as an important tool for NbS is still in its early stages of research and implementation. Therefore, many of the nature-based processes Table 2.3 above were assessed in other developed countries. SuDS application is relatively extensive in numerous developed catchments, mainly in Europe, North America, and Australia, to limit a variety of important stormwater runoff pollutants. In comparison to informally drained catchments in South Africa, these countries have lower settlement densities and nutrient concentration levels, as well as higher average annual rainfall that drives surface runoff conditions. Despite these shortcomings, there remains a gap in knowledge about the application of SuDS in developing nationals like South Africa.

2.3.2.1. The benefits and limitations of SuDS

According to Armitage, (2010), a common critique of SuDS is the relatively greater cost of constructing and maintaining various SuDS components, which might be a barrier to implementation in low-income nations. However, Fitchett, (2017a) revealed that low cost micro-scale SuDS components manufactured from recycled materials like soakaways and pebbles can be used to attenuate nutrient-rich surface runoff in South African informal settlements. The study by Fitchett, (2017b) was unable to determine the effects of important variable such as HRT and vegetation in the treatment of nutrients and other sampled water quality parameters. The SuDS interventions (permeable channels and soakaways) were not systematically selected to target specific pollutants discharged from the settlement. This shown that the design of the SuDS interventions was based on trial and error. The complexity of the NbS planning can be a major limitation since catchments or regions vary with different options, locations and scales available in a range of configurations (Liu *et al.,* 2023).

Heal *et al.*, (2004) raised concerns about the lack of sustainability of SuDS due to uncertainties about maintenance requirements and the destiny of contaminants that do not degrade and can build and infiltrate into groundwater from unlined systems. Sand filters, for example, are often used to filter nutrients and other chemical substances utilizing a sand bed as the principal filter medium (Nassar and Hajjaj, 2013). NbS such as constructed wetlands and biofilters often lack the diversity to achieve stable and robust systems but rather mainly depend on the use of different vegetation types, substrate and hydraulic conditions for the treatment of stormwater runoff pollutants including nutrients.

Sand filters require more maintenance than many other SuDS components, according to studies, since silt builds up in the filters, clogging them (Landsman *et al.*, 2018; Kellagher *et al.*, 2007). Finally, Heal *et al.*, (2004) pointed out that the accumulated sediments in the SuDS system may need dredging or removal, which could result in the release of sediment-bound pollutants back into the system or disposal to landfills if the residual cannot be recovered and reused. Other research suggests that nutrient absorption by plant roots in biofilters or built wetlands does not imply permanent nutrient removal from the water column unless the plants are harvested on a regular basis (Herzog *et al.*, 2021; Muvea *et al.*, 2019; Malaviya and Singh, 2012). This is the case when dissolved oxygen levels are reduced and nutrients are released back into the water column when plants reach maturity or die off (J. Yu *et al.*, 2017; Chen *et al.*, 2016; Fox *et al.*, 2008).

Besides the lack of evidence-based knowledge of NbS Sub-Saharan Africa mentioned above, the benefits of NbS are vast and widely reported in the literature, many of them provide multiple overlapping ecosystem services. Therefore, application of a single NbS can offer a bundle of ecosystem services which can achieve several environmental, social and economic benefits which include but not limited to protection of wetlands to improve resilience against natural disasters (Gómez Martín *et al.*, 2020). However, the resilience of NbS and their ability to provide multiple benefits such as reduction of water quantity and quality under natural disasters such as flood events in the face of climate change is under researched. This is true because studies such as Beceiro and Brito, (2022) have highlighted the need for an assessment of the ability of NbS (infrastructure capability) to be resilient under acute shocks such as flood events.

Mguni *et al.*, (2022) argue that NbS such as Water Sensitive Design (WSD) in South Africa requires strategic integration into the water supply and sanitation (WASH) agenda at the same time address the inadequate stormwater infrastructure. However, often lengthy bureaucratic processes, red tape to mentioned a few could be major hinderances. On the other hand, some level of training (capacity building) is required on municipal level and community leaders on the application of the NbS. This is because, the challenge is to systematically arrange the treatment train SuDS options to target pollutants of concern.

Since the SuDS options are not universally applicable due to variable site characteristics, i.e., green roofs might not be implementable in informal settlements due to their weak structural integrity. But swales, soakaways and permeable pavements for instance are easily implementable in areas already used to channel domestic wastewater between the shacks with suitable soil conditions to enhance infiltration.

Scholz, and Grabowiecki, (2007) expressed concern regarding SuDS management, citing the increasing impervious surface and volume of stormwater due to urbanization, as well as the increased frequency of extreme weather events such as torrential rainfall or violent flash floods, which could overburden these systems. High-density, poorly drained informal settlements, which are frequently found in floodplain areas, may pose a danger to the performance of biofilters and other SuDS interventions. According to research by Reed and Dunelm (2013), silt and poor solid waste management are typical design issues that could reduce biofilter efficacy, particularly in low-income nations with poor land use regulation and the consequences of erosion in metropolitan areas. There is no documented evidence in the literature that treated silt and sediments can be recovered and reused as a resource utilizing SuDS interventions like biofilters instead of being discarded in waste disposal facilities as garbage.

Vegetation is key in nutrient reduction using biofilters, according to several researchers (Nicula *et al.*, 2022; Jacklin *et al.*, 2021; Kim *et al.*, 2021; Goh *et al.*, 2019; Morse *et al.*, 2018; Abdelhakeem *et al.*, 2016; Malaviya and Singh, 2012; Zinger *et al.*, 2007). Uncertainty about the type of plant species to be used, its maintenance requirements to mention a few could reduce the performance of biofilters to effectively reduce nutrient levels and mitigate pollution. Plants ability to tolerate extended dry and wet seasons, for example, is critical since drier weather conditions (no stormwater input into the biofiltration system) could cause plants to die, resulting in non-functional systems that could leach pollutants after the next rainfall event (Barron *et al.*, 2019).

HRT is one of the important parameters that influences the efficacy of a SuDS system to mitigate pollutants. One of the biggest design challenges in establishing efficiency is determining suitable residence periods for diverse SuDS systems. Longer residency times in SuDS components like biofilters have been associated with increased nutrient reduction rates. This was validated in a study by Steidl *et al.*, (2019); Rasool *et al.*, (2018), which found that longer residence times promote the development of biofilm, which lowered the level of nitrogen and faecal coliforms in biofilters by 80-90 percent. In constructed wetlands, Luca *et al.*, (2017) set a 7-day minimum resident time which was effective in the treatment of pollutants. According to Muvea *et al.*, (2019), a minimum residence duration of 15 to 20 days should be specified to allow for microbial decomposition of wastewater and macrophyte nutrient intake. Because plants increase contact time for biofilm production, it is logical to expect biofilters with dense macrophytes to require less residence time than those without macrophytes.

2.2.3. SuDS in the South African context

The SuDS concept is relatively new in South Africa even though several studies have been reported in the literature, its effectiveness is yet to be tried and tested. As a result, it is difficult to know how to design SuDS interventions like biofilters or artificial wetlands to manage the amount and quality of runoff from informal communities. As such, there is a low level of confidence in the ability of biofiltration systems, which are a type of CW designed to improve the quality of stormwater runoff coming from an informal settlement to a water quality standard suitable for a variety of non-potable uses, including irrigation (UN-World Water Development Report., 2018).

Armitage *et al.*, (2014) developed and refined a SuDS framework specific to the South African context. The framework provides overall SuDS alternatives guidelines which are not enforceable, and their efficiency is yet to be evaluated in the African context. The SuDS interventions consists of overlapping treatment processes. However, the choice of each SuDS option is dependent on the type of the stormwater pollutants being treated (Wong *et al.*, 2005). As opposed to source control techniques, biofilter cells are best suited as local control measures. Due to space constraints, many biofilter systems and their designs are forced to adapt as source controls in big centres or highly inhabited informal settlements. Biofilters can be installed beside drainage canals and downstream of informal settlements, depending on their size, as was the case in this study.

The applicability of each technique is subject to the unique characteristics of a site, as in high density towns, land availability typically limits and sometimes defines the type of ecological infrastructure or SuDS option to be used (Lloyd *et al.*, 2002). Despite the socio-economic and ecological benefits reported in studies by Armitage *et al.*, (2013) and Fitchett, (2017a); and Button *et al.*, (2010), the major challenges facing the implementation of the SuDS framework and guidelines in South Africa were highlighted in a study by Fisher-Jeffes *et al.*, (2012). Lack of data and understanding on the effectiveness of NbS in the South African context could possibly be the major hinderance on large scale application of interventions such as SuDS.

Adegun (2018) and du Toit *et al.*, (2018) describe the concept of green infrastructure and ecosystem services in informal settlements, as relatively new concept in Sub-Saharan Africa compared to Europe and North America, including Australia, and discusses the numerous challenges involved in putting the concept into practice in the region. These issues are comparable to those identified by Fisher-Jeffes *et al.*, (2012), which included a lack of capability, a fragmented governance style, urban planning and social inequalities, including a lack of data or case studies. According to du Toit *et al.*, (2018), socio-cultural values, traditions, and perceptions, as well as climate change, add a layer of uncertainty to the adoption and effectiveness of ecological infrastructure systems in Sub-Saharan Africa. Adegun, (2017) argue that interventions such as NbS to management stormwater in informal settlements have not been a priority for governmental and non-governmental organizations in Sub-Saharan Africa over the years (Adegun, 2017).

The study by Button *et al.*, (2005) focuses on the holistic benefits of the selected ecological infrastructure and its applicability in an informal context, but it does not evaluate the effectiveness of swales, soakaways, infiltration trenches, and built wetlands in reducing nutrient loads. Through a methodical design of the swale, soakaway, infiltration trenches, and built wetlands for optimum of nutrient load reduction, the study recognizes the value of overlapping nature-based processes. In the Diepsloot informal settlement of South Africa, a study by Fitchett, (2017a) evaluated the effectiveness of permeable channels and soakaways that were chosen based on site conditions, patterns of behaviour and choice already used by residents, simplicity of construction and ease of maintenance, and availability of re-usable material on reducing the nutrient load coming from domestic wastewater. The water quality gathered before and after storm events showed a reduction in NO_3-N and phosphates levels, however the effectiveness of the chosen techniques could not be determined due to inconsistent results from two sets of water quality testing.

A variety of community lead in-situ wastewater and greywater management systems were documented in South Africa in an attempt to control surface runoff pollution and demonstrate novel stormwater drainage approaches (Charlesworth and Booth, 2017). Many of the selected approaches, such as crate and trench-based soakaways were filled with aggregate stones planted with various vegetation types, and micro wetlands linked to a stormwater swale with the goal of removing nutrients through adsorption and biological uptake, to filter, clean, and slow down the flow. The inability of these approaches to accomplish their intended duties was attributed in large part to social behavioural challenges, which resulted in a lack of societal interest in maintaining them post-project. The failure of these systems, as reported by Charlesworth and Booth, (2017), highlighted the importance of the SuDS option in the success of community-led stormwater drainage.

The Genius of Space project, has introduced not only biomimicry methodologies in an informally settled catchment of South African, but also transdisciplinary stormwater and greywater management approaches to enhance community resilience through local community engagement (Hermanus and Campbell, 2017; Wolfaardt, 2017). Despite evidence of the use of tree gardens, there is a substantial dearth of empirical data on the performance of these systems to remediate highly contaminated surface runoff as a fit-for-purpose water supply to warrant their widespread deployment.

Button *et al.*, (2005) demonstrated the multifunctionality of SuDS systems in the Monwabisi informal settlement to reduce water quantity (flooding) and quality (nutrient load) using source, local, and regional controls such as artificial swales, soakaways, infiltration trenches, and constructed wetlands. The success of the SuDS choices is dependent on community involvement from planning to implementation and maintenance of stormwater approaches, according to Fitchett, (2017a) and Button *et al.*, (2005).

These researchers did not reveal how community participation was maintained throughout the programs or what caused disruptions or discontent with community-led initiatives. When working in disadvantaged communities, obstacles such as community involvement on programs that do not directly benefit the receiving communities, such as job development, can sometimes deter many participants. Adegun, (2015) asserted that neither top-down (state-led) nor bottom-up (community-based) stormwater management approaches are sufficient in dealing with stormwater management, and instead emphasizes the integration of state-led and community-based efforts for long-term stormwater drainage in informal settlements.

Charlesworth and Booth, (2017) agree that the integration of top down and bottom-up stormwater management approaches is effective but that co-management, on the other hand, can be a helpful approach if both sides (locals and authorities) are prepared to deal with drainage difficulties and find common ground on potentially conflicting issues. Many residents are likely to be despondent in the long run especially if participants in the community are not incentivised. This is largely because many residents in low-income informal settlement require jobs as the priority and to be able to provide food and other necessities for their families. Secondly, the elusiveness of co-management in informal settlements stems from peoples' who are already discourage and resentful because of poor service delivery, corruption, and a variety of socio-political challenges that frequently stymie the success of community-based projects. This is compounded by authorities' reluctance to engage civil society as crucial players in drainage system management at times (Charlesworth and Booth, 2017).

2.3. Discussion on literature

Even though the SuDS framework has recently been introduced in the South African context, there exists a lack of understanding of the applicability of NbS as an umbrella term and SuDS as a tool in the South African context. Taking into consideration that informal settlements in many urban catchments are not formally planned and relocation (many of these settlements are located on privately owned land or land not suitable for development) or formalization of the settlement often take time and resources and stormwater drainage infrastructure is lacking or inadequate. The use of the SuDS concept in the interception of surface runoff coming from the informal settlements remains a viable option to treat several pollutants and benefits. However, the effectiveness of NbS and SuDS as a tool is largely unknown, despite success stories reported in the literature in Europe and other developed countries which might not be applicable in the South African context. The common challenge with relevance in Sub-Sharan Africa is that NbS are relatively new compared to the dominant grey infrastructure and requires engagement of multidisciplinary stakeholders from community and government departments for their success.

The treated wastewater reuse for irrigation of edible crops is a significant potential source of reclaimed water (Adewumi *et al.*, 2012). Unlike conventional WWTW, where wastewater is treated to using chemicals and gauged to the exact set water quality standards at shorter period. Nature works differently and might take relative longer periods to treat the desired effluent quality compared to conventional WWTW. It is through constant water quality monitoring and constant design modification that a desired effluent is achieved in fiend scale experiments.

In some countries in Sub Sharan Africa wastewater is used for irrigation of food gardens. This in several other developed countries, has limited the general acceptability of treated water for irrigation of food gardens due to public health concerns. It is therefore important to manage the operation of recycled water systems in such a way that it will not adversely affect public health. A study by Sarwar *et al.*, (2020) has shown that the accumulation of high levels on pollutants in irrigation water can pose human health risk due to vegetable intake contaminated by untreated or partially treated wastewater irrigated crops. A recent study by Abdallah and Mourad, (2021) has highlighted the need for farmers to assess health risk associated with re-use of wastewater. High levels on E. coli, (3.2 × 103 CFU 100 m/l) NH_3-N (5.98 mg/l), and NO_3-N (7.52 mg/l), which exceeding the WHO irrigation water limits was used for irrigation of vegetable garden in Ghana, the study highlighted the urgent need for an affordable wastewater treatment systems that will treat wastewater to a water quality standard fit for irrigation of vegetable garden/food crops. The use of treated wastewater for irrigation of food garden is important since the presence of excess NO_3-N in wastewater used as fertiliser for irrigation of food crops is reported in a study by Ontiveros-Valencia *et al.*, (2014) to cause methemoglobinemia in infants and contribute to eutrophication in water bodies. But these chemicals have different toxicity levels and exposure durations to cause arm to human health.

Khalid *et al.*, (2018) has shown that in the study when many farmers in Sub-Sharan Africa prefer irrigation of food garden with untreated wastewater. He indicated that untreated or partially treated wastewater contains macronutrients that are beneficial to small scale farmers in developing countries as it can save cost of irrigation with municipal water and reduce crop production cost by 10 percent to 20 percent. However, high concentrations of nutrients can be toxic especially uncooked vegetables, since 50 percent of NH_3-N and 30 percent of organic nitrogen are assimilated by plants (as the rest of nutrient percentage is lost through transformation processes) and other potential toxic elements (zinc, lead, cadmium, mercury, chromium, copper, and parasitic worms, which can cause human health. The toxicity of these chemicals to human health in cooked vegetables is unknown and largely under researched.

Therefore, the South African Water Quality Guidelines: irrigation use used to assess the treated effluent for it not to exceed the DWA irrigation limit (Irrigation Water Use (Volume 4) and WHO irrigation water limits to ensure treated effluent does not pose treat to soil structure and human health risk during irrigation of edible crops. The TWQR guideline limits set in the South African for irrigation of food crop are generic, not site specific in terms of regional climate and soil type. Regional research studies on the site-specific guideline limits (from local to national government sphere) are crucial to eighter relax the guidelines limits without compromising public health or may require a need for stringent standards to protect public health (World Health Organization, 2006). The World Health Organisation (WHO) Guidelines for the reuse of wastewater, excreta and greywater were used as general guidelines to assess the risk associated with the treated water quality from the six-field scale biofiltration cells. Wastewater reuse guideline limits vary in countries to suit not only local conditions but also sociocultural, local environmental and epidemiological conditions (World Health Organization, 2006).

CHAPTER THREE RESEARCH METHODS, DATA COLLECTION AND ANALYSIS

3.1. Introduction

This chapter describes the experimental design and procedures for determining mass balances as a measure of the cells' ability to reduce pollutants in contaminated water. In this study, the volumetric throughput of the biofiltration system over time, the input and output of water quality were compared using the mass balance method. Changes in the HRT and Hydraulic Loading Rates (HLR) between the cells, as well as the six different biofilter cells packed with different substrate medium, were the key operating design conditions. This was aimed at optimizing and advancing biofilter knowledge in the biodegradation and the treatment/removal of excess nutrients from the urban informal settlement.

The output from the six biofilter cells was analysed and compared using several statistical models to determine water quality improvement and performance of each cell relative to each other. In comparison to the WHO guidelines for safe reuse of greywater, a critical goal was to assess the ability of the biofiltration cells to reduce nutrient concentrations to comply primarily with South African irrigation water quality guidelines for irrigating of crops (du Plessis *et al.*, 2017).

This chapter explains the sampling procedure, the devices used for sampling and the methods used to conduct the comparative analysis. The chapter concludes with a discussion of the study's limitations and the reliability of the study methods and design.

3.2. Site selection

The Stiebeuel River was chosen for this study because it is one of the principal carriers of nutrient-rich surface runoff from the informal settlement through a series of interconnect stormwater drains. This through a series of interconnect stormwater drains (Figure 3.1 below)

below. A drainage network that conveys surface runoff through various makeshift ‘hand dug’ channels and formal underground stormwater drains into the Stiebeuel River was mapped by the researcher (Figure 3.1 below). This was done to ground truth the existing drainage network contributing to the Stiebeuel River in the Groendal and Langrug informal settlement. The absence of formal drainage network in the Langrug informal settlement compared to the low-cost housing settlement downstream (Groendal) is shown in Figure 3.1 below. This drainage assessment was to validate the notion that most of the surface runoff from both Langrug and Groendal settlements end up in the Stiebeuel River.

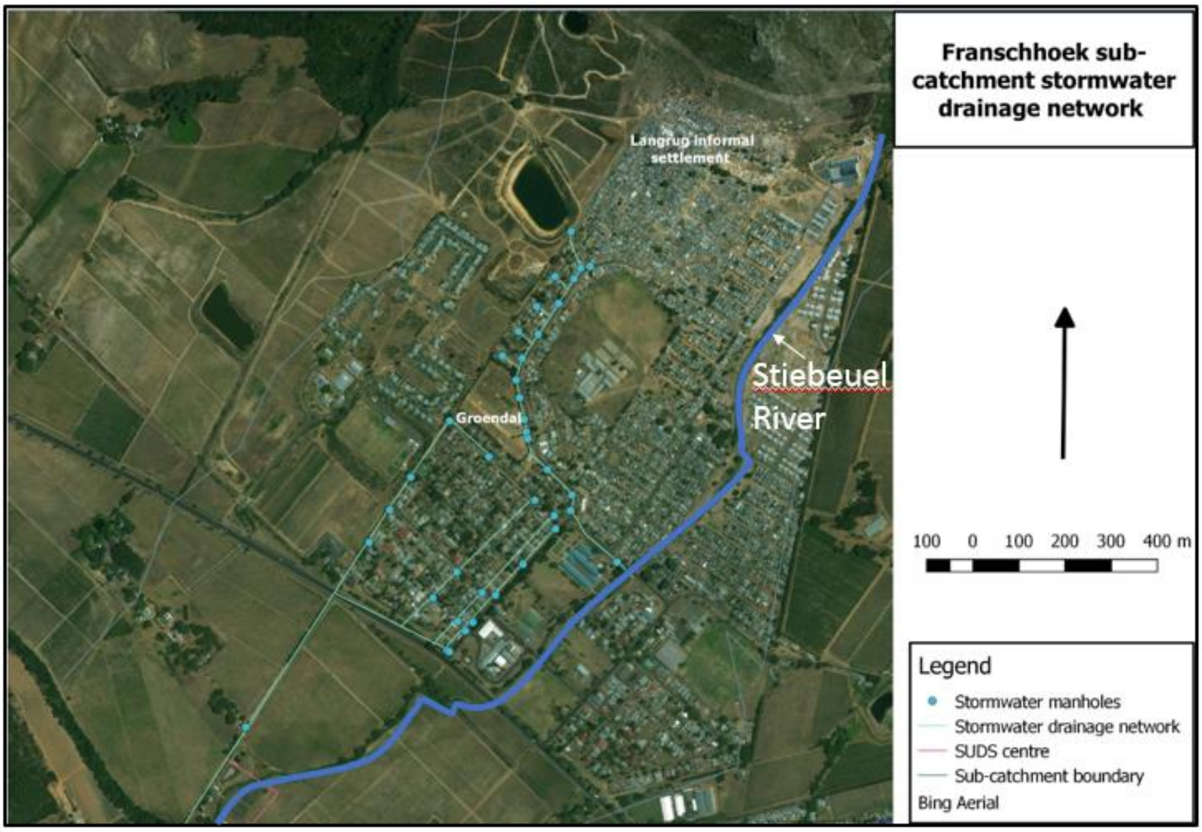


Figure 3.1: Visual presentation of stormwater drainage network within the Stiebeuel River catchment

The Stiebeuel River was also chosen based on evidence from research by Fell (2017) that showed that elevated nutrient levels enter the Stiebeuel River through diffuse and point sources from the settlement (Figure 3.2 below). As a result, a combination of stormwater, blackwater from failing sanitation facilities, and greywater is discharged into the river. The grab samples were collected from surface water along the Stiebeuel River over a nine-month period in the study by Fell, (2017) from site 1 through to site 4 (Figure 3.2 below). The grab samples from site 1 through to site 4 were used in this study as baseline in order to understand and to provide reference for this study on river nutrient characterisation.

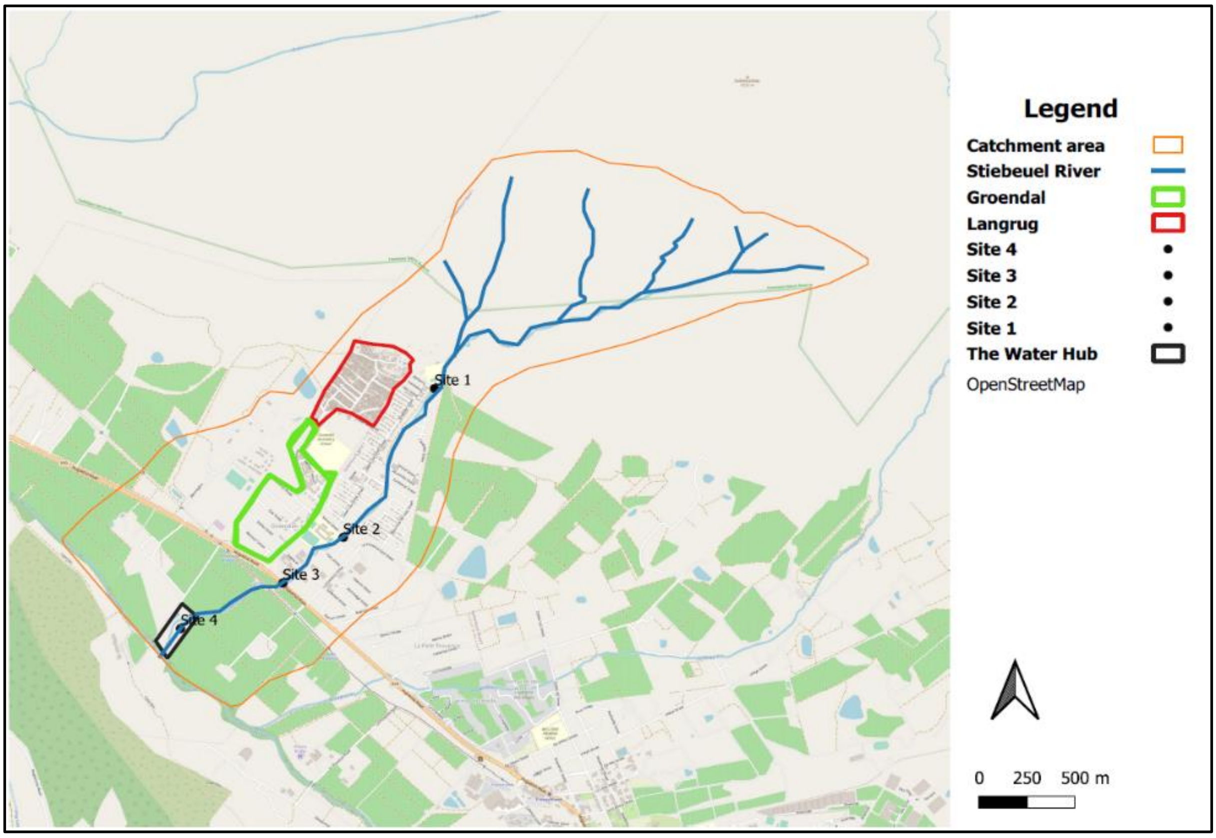


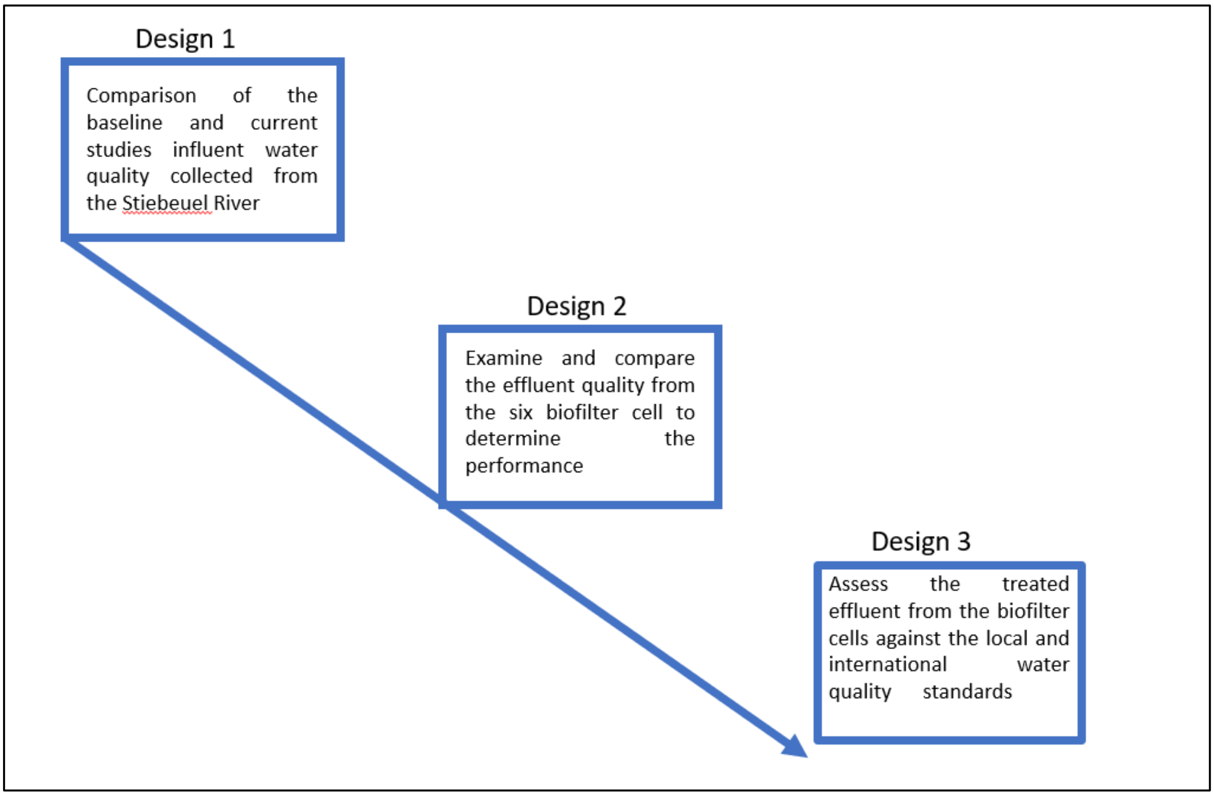
Figure 3.2: Map of the Stiebeuel River catchment showing the sampling sites along the Stiebeuel River

The nutrient concentrations along the Stiebeuel River vary due to anthropogenic activities within the catchment. The baseline study undertaken by Fell (2017) examined the nutrient concentrations at four sampling sites (from site 1 through to site 4 above) along the length of the Stiebeuel River (Figure 3.2) above which broadly represented different land uses. Grab samples were collected every week for 13 consecutive weeks (between 20th August – 24th November 2016) and analysed for NH_3-N, NO_3-N, NO_2-N, PO_4^{3-} pH, DO, and EC. A total of 52 water quality samples were obtained at the four selected sites along the Stiebeuel River (Fell, 2017).

The Water Hub provided a secure area for water collection and storage demonstration infrastructure, hence the downstream location of the biofilters. The surface runoff pumped into the storage tanks, which represented influent conditions, was sampled and analysed weekly from August 2017 to June 2018 in an analysis of the physical and incoming nutrient concentrations. The raw water (influent) from this study in the storage tanks was compared to baseline water quality samples collected in the Stiebeuel River in an MSc project from August to November 2016 (Fell, 2017).

3.3. Research design

The research design is comparative in nature and is separated into four design stages (Figure 3.3 below). The study was designed to compare the influent water quality collected as part of this study which was stored in the 10,000L storage tanks against the baseline water quality collected as part of the MSc research study referred to above. The baseline data samples were analysed for NO_2-N, NO_3-N, NH_3-N, PO_4^{3-}, EC, pH, and DO. Nutrients were examined using the Hach DR 2700 Portable Spectrophotometer, according to standard methodology in the HACH Water Analysis Handbook whilst the physical parameters were measured insitu (Fell, 2017). The design of an effective biofiltration system to remove excess nutrients for irrigation purposes in accordance with the South African and international irrigation guidelines was used to inform the suitability of the treated effluent for irrigation of crops.



Comparison of the baseline and current studies influent water quality collected from the Stiebeuel River

Examine and compare the effluent quality from the six biofilter cell to determine the performance

Assess the treated effluent from the biofilter cells against the local and international water quality standards

Figure 3.3: The stages in this study research design

The aim was to evaluate the biofilter cells effectiveness in biodegrading excess nutrients and determining the concentrations of recovered nutrients. The biofiltration cells effectiveness was evaluated under a variety of operating settings, including hydraulic residence duration, vegetated and non-vegetated cells. The efficacy of the biofilters (vegetated and non-vegetated cells) over time was examined using statistical analysis which is described later in this chapter.

The effectiveness of the six biofilters to treat effluent was evaluated by using the World Health Organization (WHO) guidelines for safe reuse of greywater and the South African Water Quality Guidelines, Volume 4 Agricultural Use: irrigation for the reuse of treated wastewater for irrigation of food crops and associated risks (Table 3.1 below). The South African Water Quality Guidelines, Volume 4: Agricultural Use: Irrigation are generic, cover a variety of environmental conditions, however, there risk based, site specific, irrigation water quality guidelines were also incorporated for comparison purposes.

Table 3.1: The South African Water Quality Guidelines: agricultural use, irrigation water uses and WHO guidelines for safe use of wastewater.

Set limit or guideline	NH_3–N	NO_3–N	NO_2–N	PO_4^{3-}
DWA irrigation limit (Irrigation Water Use (Volume 4) TWQR	<5 mg/L	<5 mg/L	<5 mg/L	-
WHO guidelines for irrigation	0–5 mg/L	0–10 mg/L	0–10 mg/L	-
Physical parameters				
Set limit or guideline	DO	pH	EC	ORP
DWA irrigation limit	-	6.5 – 8.4	40 (400 µs/cm)	-
WHO guidelines for irrigation	-	6.5 – 8	<0.7dS/m (700µs/cm)	-

The need for this assessment against the guidelines is because, South Africa is currently water scarce and food insecure and polluted water treatment is crucial to ensure that the recovered water does not have a negative impact on human health or the environment. According to a study by Sarwar *et al.*, (2020), high levels of contaminants in irrigation water represent a risk to human health due to intake of edible vegetable crops that are polluted by untreated or partially treated wastewater. The risk of vegetable consumption using polluted irrigation water depends on several factors which include but not limited to infectious dose and pathogen persistence in the environment (Sarwar *et al.*, 2020). Another reason for adequately treat polluted water for irrigation of food garden is that, in a study by Ontiveros-Valencia *et al.*, (2014), excess nitrates in wastewater used as fertilizer for irrigation of food crops were found to cause methemoglobinemia in babies and contribute to eutrophication in water bodies.

The use of untreated or partially treated water for vegetable garden irrigation includes macronutrients that are advantageous to small scale farmers in poor nations since it saves money on municipal water and reduces crop production costs by 10 percent to 20 percent (Khalid *et al.*, 2018). High concentrations of nutrients can cause human health risks and environmental impacts through soil hardening and shallow groundwater pollution due to a lack of affordable wastewater treatment (as the rest of the nutrient percentage is lost through transformation processes).

The effluent from each of the six biofilter cells was evaluated for appropriateness to irrigate vegetable crops using the South African Water Quality Standards: agricultural usage, irrigation water use, and WHO guidelines for safe use of wastewater. Plants require phosphorus and nitrogen in the form of ammonia, ammonium, nitrite, and nitrate for growth and development. Irrigation water with both nitrogen and phosphorus concentrations (within the TWQR) is helpful to crop yield (Rodda, Salukazana, *et al.*, 2011).

Table 3.2: Potential effects of nitrogen on crop yield (DWAF, 1996)

Target water quality range	Crop yield and quality
≤ 5 mg/L	The unintended nitrogen application should, at normal irrigation applications, be low enough not to affect even sensitive crops such as grapes and most fruit trees
5 – 30 mg/L	Sensitive crops increasingly likely to be affected (depending on magnitude of irrigation application). Other crops remain largely unaffected in the lower concentration range, but are increasingly affected as concentration increases
> 30 mg/L	Most crops are affected. A limited range of crops can utilise the nitrogen applied. Severe restrictions are placed on the utilisation of these waters

Nitrogen levels between 5 and 30 mg/L will impact sensitive crops, while concentrations >30 mg/L will affect most crops, as shown in Table 3.2 (DWAF, 1996). Excess inorganic nitrogen in water used for vegetable crop irrigation is a concern because it stimulates plant growth (when applied in accordance with plant requirements), it can leach out and contaminate groundwater sources due to its high mobility, and it can cause nuisance growth of algae and aquatic plants in irrigation structures such as dams and water reservoirs (DWAF, 1996). The risk associated with exceeding the South African Water Quality Guidelines as per the Department of Water Affairs and Forestry: Volume 4, irrigation is highlighted in Tables 3.1 and 3.2. The health risks linked with eating crops irrigated with untreated wastewater vary depending on whether the vegetable is cooked or eaten straight from the ground.

In South Africa, the water used for irrigation in the agriculture sector is the largest consumer of available water. The available water for agriculture irrigation is said to have decreased from 80 percent in over two decades to 50 percent, putting more pressure on irrigators as there is less available water for irrigation purposes (DWAF, 1996). Finally, the human health risks associated with the treated effluent was examined in detail according to the above-mentioned standards and guidelines, first in the literature portion of this study and then briefly in the results and discussion chapter.

The surface runoff from the Stiebeuel River was pumped into the storage tanks, which were connected to the biofiltration cells system. The storage tanks provided pre-treatment by settling larger sediment particles carried in the runoff to the base of tank (average of 8 days of settling) (Figure 3.4 below). Over eight months were spent collecting and characterizing incoming nutrient concentration levels. This was done to determine the loading rate of the biofiltration system.

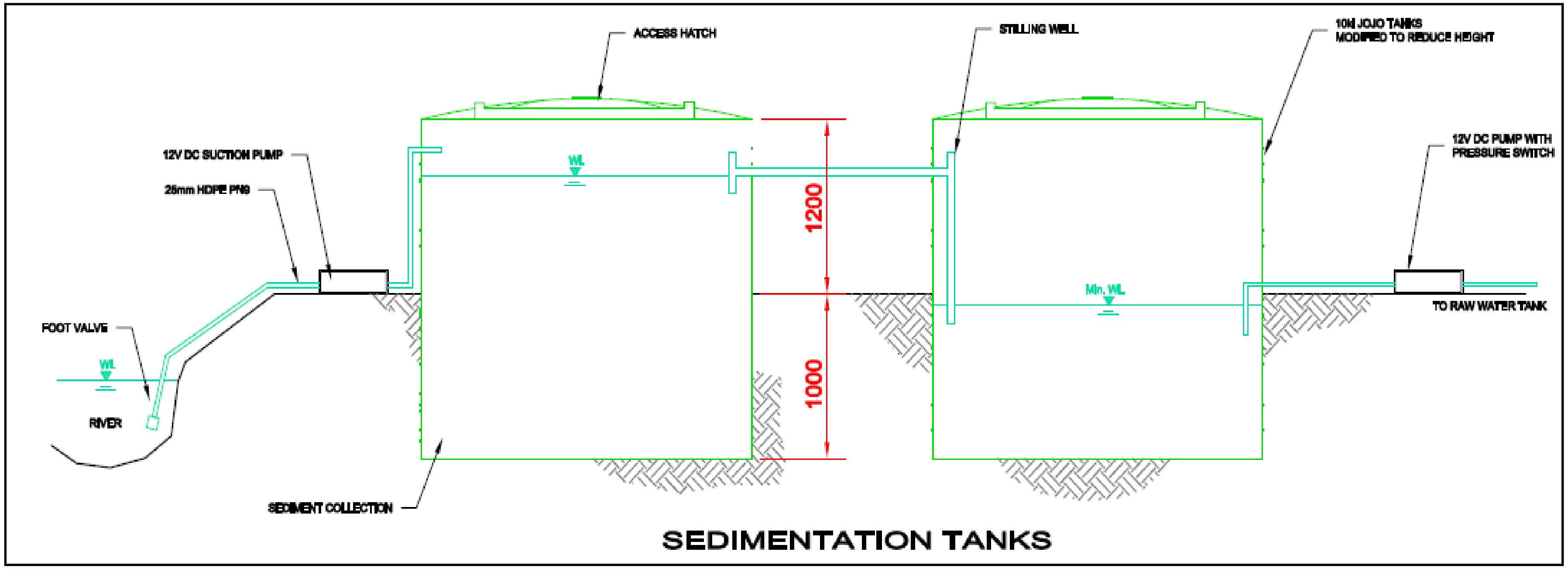


Figure 3.4: Biofilter sedimentation/storage tanks (detailed view)

The system comprised of two 10Kl water storage and sedimentation tanks connected by 50mm PVC tubing to the biofilters. The tanks, which were upstream of the biofilters (shown in Figure 1.2 blue round shape) and received surface runoff that was pumped directly from the Stiebeuel River. The first tank (right) was used to settle sediment, with the sediment-free runoff flowing to the second tank (left), which was connected to the biofilter.

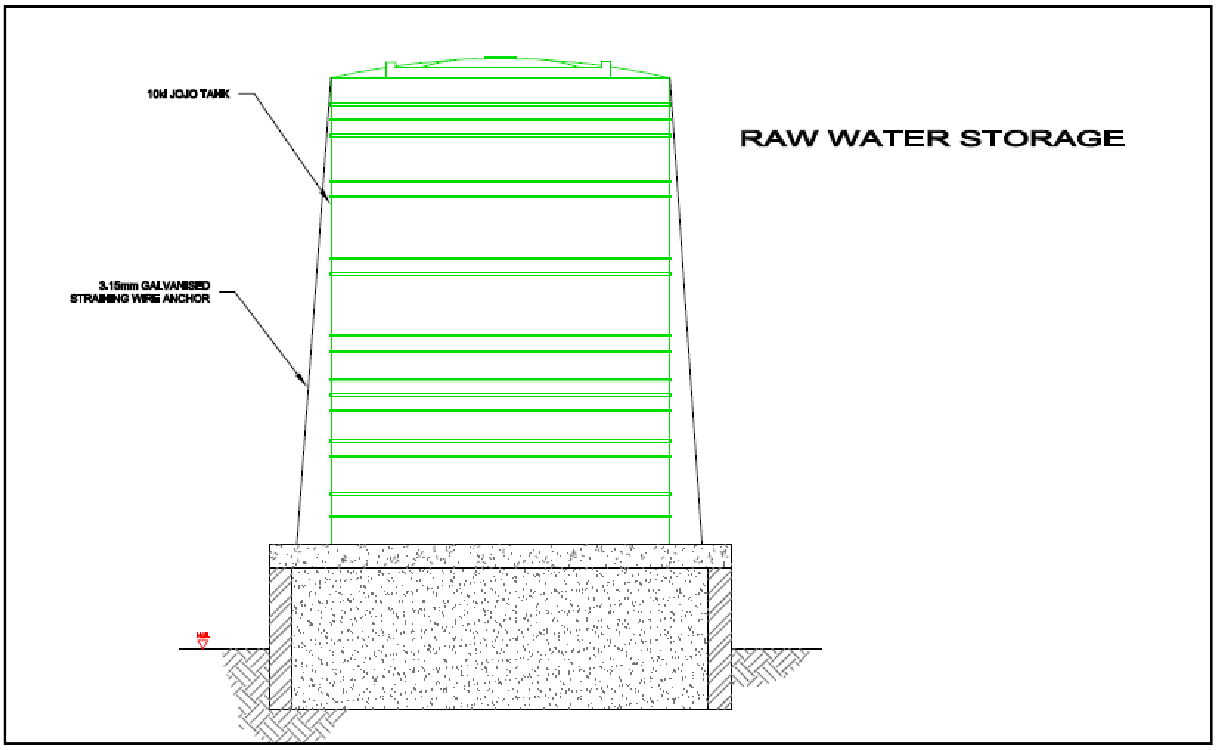


Figure 3.5: A detailed view of a single runoff storage tank

The biofiltration cells (shown in Figure 3.6 below) were positioned alongside the river for ease of abstraction and distance to the storage tanks. The treated effluent measured in-situ in terms of (pH, TDS, EC, ORP, Temperature and DO and in the laboratory (PO_4^{3-}, NO_3^-N, NO_2^-N and NH_3-N), to evaluate the efficacy of the vegetated and non-vegetated cells for the removal of excess nutrient. The manual operating valves were put between the biofiltration cells to control the residence time of each cell.

During each sample session, the flow rate between the cells was measured to determine the link between treatment efficiency and flow. Statistical models were used to investigate the mass balance outcomes (influent versus effluent) concentration levels. The comparison of data from different treatment settings in vegetated and non-vegetated biofilters could reveal the best natural-based conditions for treating nutrient-rich surface runoff from informal settlements.

3.4. Research methodology

The Water Hub is an abandoned WWTW with sludge drying beds that were refurbished into biofiltration cells. Isidima engineering was the company that redesigned the drying beds into six purpose-made biofiltration cells, with financial support from the Western Cape government and a small portion also became available for research work. The Future Water Institute at the University of Cape Town is now managing water research at the Water Hub. Vegetated and non-vegetated large stone cells (LSV and LS), vegetated and non-vegetated peach pips cells (PPV and PP), and vegetated and non-vegetated small stone cells (SSV and SS) were used as packing media for each of biofiltration cells. The goal was to use nature-based processes such as sedimentation, adsorption, biological absorption, biodegradation, de-nitrification, and filtration processes embedded in the cells to degrade excess nutrients and recover nutrients. The sediment and nutrient removal mechanisms outlined in chapter two of this work (Dama-Fakir *et al.*, 2016; Kellagher *et al.*, 2007) guided the selection of nature-based processes.

The following factors influenced the choice of using biofiltration as a treatment process: the pollutant (excess nutrient) to be treated, cost effectiveness, and low maintenance, as well as the efficacy of the components as discussed in previous research in treating excess nutrients (Andrés-Doménech *et al.*, 2018; Yang Yun-ya and Lusk, 2018; Fitchett, 2017b; Armitage *et al.*, 2014; Kellagher *et al.*, 2007). Most crucially, the pollutant types in the surface runoff from the informal settlement, such as excessive nutrient, *E. coli*, and *faecal coliform* levels, were influenced by effluent discharges from a frequently overflowing sewage line running parallel to the Stiebeuel River.

3.5. Biofiltration cells

The six purpose-built biofiltration cells were organized in pairs (Figure 3.6 below), with a total capacity of about 33.6m^3. The length, breadth, and height of each cell measured 16m x 3m x 0.7m. The six cells were separated into planted and non-planted cells and filled with a variety of substrate medium. Treated water from each cell was extracted from their respective sampling chambers for collection and analysis (Figure 3.6). Local indigenous reeds were used as the vegetation of choice in the planted cells (combination of *Phragmites australis*, *Thypa capensis* and *Cyperus*). These species are typically found in wetland habitats. Biophysical parameters such as residence duration, microbial activity, temperature effect by seasonal variations, flow rate, and incoming nutrient concentration levels were used to compare nutrient treatment performance between cells with different substrates.

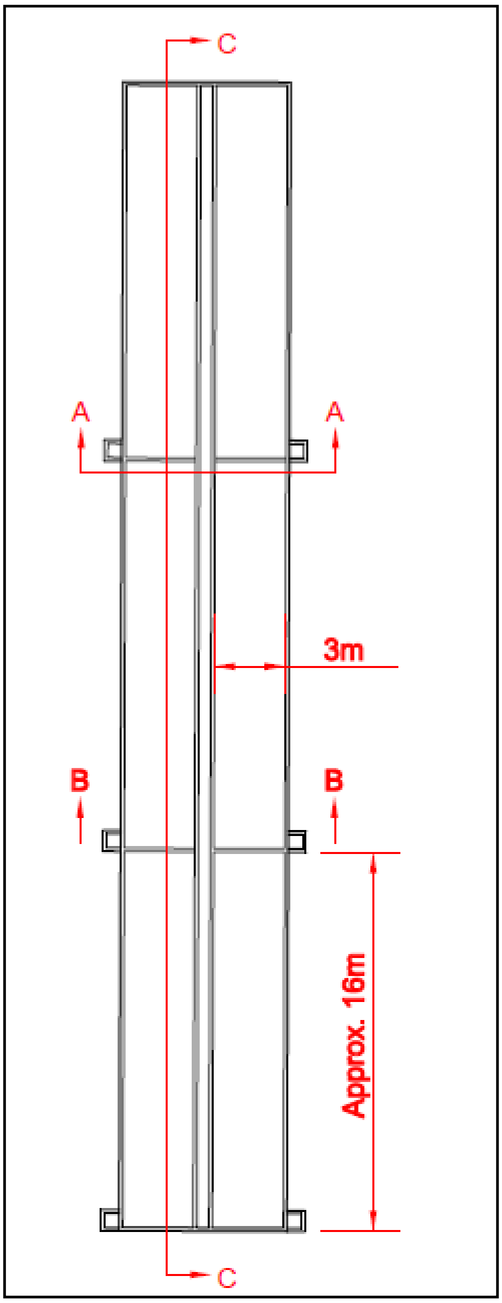


Figure 3.6: The biofilters plan view (not to scale)

To assess the water level, two perforated PVC pipes of 71cm length and 110mm in diameter were installed in each cell and surrounded by a 0.6m layer of substrate media (LSV, LS, PPV, PP, SSV, and SS). A water meter installed into each cell was used to measure the volume of water flowing through it. The hydraulic parameters of the cells comprised an average water head of about 29 cm and flow rates or rates of change of about 6 cm^3/min across the cells. Using a tape measure, the water level was measured above the PVC pipe level, which protruded 10 cm from the base of each cell. RT=V/Q, where RT = Resident Duration, V = biofilter volume (cm^3), and Q = influent flow rate cm^3/min, was used to compute the residence time in each cell across the sample period (El-refaey, 2007). The average residence duration in the cells was calculated to be RT = 28.8/6, which equates to five days across the sample period. The residence duration was altered to see how it affected the reduction of surplus nutrients from each cell.

On average, once a week, water samples (treated effluent) were taken from the 110 mm PVC rotating pipe inside the six sampling chambers (marked by A, B, and C in Figure 3.6 above), which was connected to each of the six treatment cells (LSV, LS, PPV, PP, SSV, and SS). Before sampling a representative sample from each cell, about 26 L of the volume of stagnant water inside the revolving pipe was dispersed by tilting the pipe downward. To measure the amount dispersed from the cells, a 10 L bucket was placed beneath the revolving pipe. Before collecting water samples, the water level in each cell and the flow rate were physically recorded. Physical parameters such as pH (Power of Hydrogen), Total Dissolved Solids (TDS), Electrical Conductivity (EC), Oxidation Reduction Potential (ORP), and Dissolved Oxygen (DO) were measured in situ, while chemical parameters such as PO_4^{3-} and TN were measured in the water analysis laboratory at the University of Cape Town (UCT).

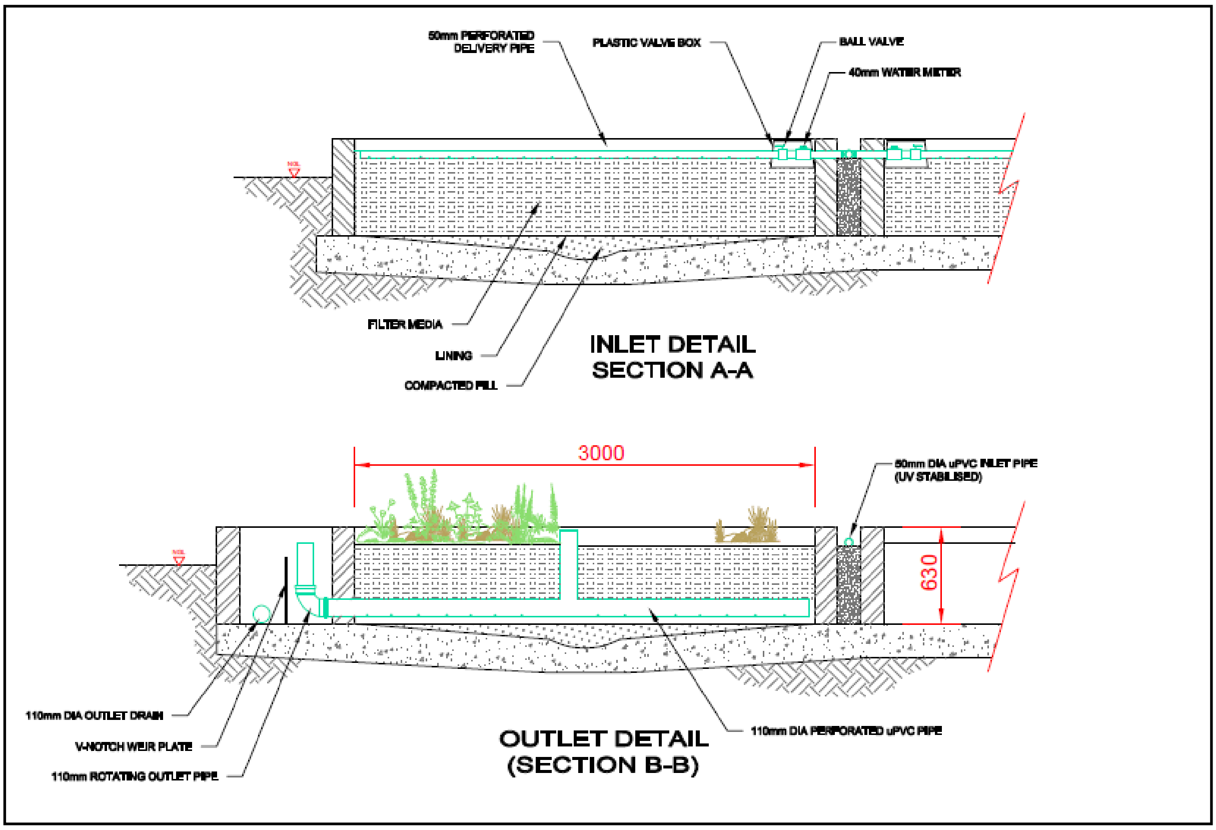


Figure 3.7: The inlet and outlet details of the biofilter design

The six treatment cells (LSV, LS, PPV, PP, SSV, and SS) used three different substrate media for surface area adsorption through biofilm: 19 mm stones, peach pips, and 6 mm small stones. Adsorption and biological absorption of dissolved nutrients were the goals of the vegetated cells. The treated effluent from all six cells was distributed to a separate collection chamber alongside the cells. A submersible solar pump was used to distribute the cleaned wastewater to an experimental food garden for non-human consumption.

3.5.1. Data collection

Water samples were taken from the square shaped sampling chambers adjacent to each of the six biofilter cells for ten months (11/08/2017 to 06/06/2018) (Figure 3.7 above). The biofilter samples were collected weekly for the first 5 months, then the residence duration was varied (HRT was divided into 4 broad HRT categories, < 5 days; 6 – 10 days; 11 – 15 days and >15 days)) to determine if residence time influenced treatment efficacy. In each sampling event, the samples were collected using sterile 500 ml polypropylene sampling vials. After each sampling event, collected samples were labelled and stored in the fridge (to keep the samples cool and in natural circumstances) at the Water Hub facility before being sent to the UCT laboratory for chemical analysis. In each sampling event, the samples from the six biofiltration cells were compared to the quality of influent water kept in the sedimentation tank.

3.5.1.1 Water quality analysis

The following physical parameters were measured in situ for over 6 months to determine the and compare efficacy of the biofilter in reducing nutrient concentration in each cell: pH, TDS, EC, ORP, and DO. The data was analysed to aid with surface water restoration and to verify compliance with the South African Water Quality Standards: agricultural usage, irrigation water use, and WHO guidelines for safe use of wastewater (Table 3.1 and 3.2) above. The physical parameters of TDS, EC, ORP, and DO were measured using a calibrated portable ST20 probe range. A hand-held Martini pH 55 meter was used to measure the pH, which was calibrated to two points, pH 7.01 and pH 4.01, before each use. Before each use, the EC was calibrated with a 1413 ms/cm solution, and the DO was slope calibrated to 100 percent (saturation).

The amount of oxygen dissolved in the water, which determines the life of aquatic organisms responsible for contaminated water treatment, was measured using DO. DO is an important water quality indicator that indicates the degree of organic matter pollution, the destruction of organic compounds, and the level of water self-purification. The total concentration of dissolved ions in water is measured by the EC. When evaporation rates exceed precipitation and surface runoff is influenced by discharges from an informal settlement, elevated EC values (indicative of salinity concerns and polluted sites) are common (van der Hoven et al., 2017). The EC measurement proved helpful in identifying significant nutrient contamination zones in the biofilter cells, as well as the impact of high evaporation rates during dry weather.

The pH values were determined to evaluate the solubility and biological availability of phosphorus, ammonia, and nitrogen in the components over time, while the TDS was assessed to determine the total suspended particles in the water. TSS levels above a certain threshold indicate the presence of sewage, industrial wastewater, and soil erosion particles. Sedimentation, filtration, adsorption, and vegetation uptake can all help reduce TSS, TDS, and turbidity levels (Leong *et al.*, 2018). The ORP assessed the water's cleanliness as well as its ability to break down contaminants. The DO levels in the water were evaluated using an ORP meter; large organic discharges result in low DO because the organics consume available oxygen, lowering ORP levels.

The following nutrient characteristics were chosen because of their importance in inducing nutrient enrichment: ammonia nitrogen (NH_3-N), orthophosphate (PO_4^{3-}), nitrate (NO_3—N), and nitrites (NO_2—N). Phosphorus is a limiting nutrient, and excessive levels of it causes eutrophication (Aimin *et al.*, 2005). The nitrogen indicator, NH_3-N was evaluated since it can signal contamination from sewage, stormwater runoff, and industrial waste. If dissolved oxygen is present, nitrifying bacteria can break down ammonia into NO_2—N and NO_3—N. (Chapman, 1996).

3.5.1.2 Laboratory analysis

The levels of NO_3–N, PO_4^{3-}, and NH_3–N in the biofilter were measured using a data logging portable spectrophotometer (HACH DR 2700) according to the HACH water analysis handbook's standard approach (fifth edition). The reagents utilized were NitraVer 5 Nitrate Reagent Powder Pillows for NO_3–N analysis and PhosVer 3 Phosphate Reagent Powder Pillows for PO_4^{3-} analysis, which included the NH_3–N salicylate and cynurate, according to the protocols in the HARCH handbook. Nutrient concentration levels that exceeded the specified measurement limits were diluted to a concentration that could be evaluated using deionized or distilled water. The concentration in the original sample was determined by running the diluted sample and multiplying the findings by the dilution factor. The concentration levels were above the test's upper limit, resulting in the above range concentrations. After reagents were applied to samples that were above the measuring range, a deeper colour than the device could read developed.

3.6. Data analysis

To assess the efficacy of the vegetated and non-vegetated biofilter cells, the following procedures were used.

3.6.1. Descriptive statistical analysis

The treatment patterns between the biofilter cells of the dataset distribution were shown using box and whisker plots. The following non-parametric methods (median, range and 95th percentile) were used to summarise the water quality data set distribution. Concurrently, a comparison of data distribution (NO_3–N, NO_2–N, PO_4^{3-} and NH_3-N including physical attributes such as pH, EC, DO and ORP, and variation of the parameters between cells was utilised by comparing the corresponding percentiles. The box and whisker plots allowed for determination of the statistical attributes such as the maximum, minimum, median, upper and lower quartiles of the dataset which was compared between the cells. The 95th percentile which is discussed by Chapman, (1996) as a measure of confidence or a value below which lies a given percentage of an observation in a dataset was also used in this study.

Linear regression models were used to examine statistical analysis for nutritional treatment patterns in each cell. Linear regression was performed on the effectiveness of each substrate (vegetated vs non-vegetated cells) and to evaluate the relationship/change in cell performance over time against the influent (incoming surface runoff from the Stiebeuel River) and physical parameters such as flow rate, residence times. To choose the optimum treatment cell, a one-way ANOVA was performed to compare the means of the biofilter cells across the sampling period. A one-way analysis of variance was used to compare the nutrient reduction rates values (ANOVA). The Kruskal-Wallis one-way analysis of variance was used to compare the means, and pairwise differences were calculated using the Multiple Comparison Test in the R package.

To determine differences in the treatment of excess nutrients and changes in the physical parameter of the water in the biofilter cells, non-parametric techniques such as the Box and whisker plots and Wilcoxon signed rank test were applied. The differences in chemical and physical parameters such as pH, DO, ORP, and EC of the biofilters were compared against the biofilter type, HRT days, and change in volume as predictors using a generalised linear mixed model. The model features built-in Bonferroni correction to adjust for repeated pairwise comparisons and eliminate the likelihood of making type ii errors, and statistical significance was accepted at P0.05. Rstudio was used to analyse the data.

The physicochemical data for treated effluent were given as mean values across time and analysed with descriptive analysis. The temporal fluctuations of the observed water quality parameters were described using the coefficient of correlation and the t-test. The seasonal variation of water quality parameters was investigated by dividing the observation period into two seasons: summer (August, September, October, November, December, January, February, and March) and winter (October, November, December, January, February, and March) (April, May and June). The purpose of regression analysis (RA) was to determine the nature and size of the relationship between various physicochemical parameters. To see if there was a meaningful association between water quality metrics, the best fit model was chosen.

3.7. Limitations of the methods

The biofiltration cells' design and experimental/operational stages revealed the limitations in the approach used to conduct this comparative investigation.

- The research is restricted to comparing influent and effluent utilizing biofiltration cells. Although biofilm activity is important for removing nutrients from the water column, this study did not examine the types of biofilms that naturally develop on diverse substrates in cells and their capacity/effectiveness. To obtain optimal nutrient reduction rates, this would have established knowledge of the biofilm operating parameters.

- Due to human error or measuring device failure, few abnormal values outside the outlying data range were eliminated.
- The analysis of the soil and crops was excluded from the study scope. This is because the soil and crops are the “biomarkers” that determine the treatment’s success and risk.
- For all the biofilter cells, a uniform residency time was implemented (LSV, LS, PPV, PP, SSV, SS). This method may not have worked well with substrates that require a longer residence period (before draining the water in each cell) to achieve better water quality. Vegetation provides a good substrate for effective nitrogen treatment from the water column, as has been widely shown in the literature.
- To determine the effectiveness of vegetation in removing nutrients, each cell was planted with a mix of macrophytes locally harvested. The study did not examine the ability of the different plant species in the reduction of nutrient levels from the water.

CHAPTER FOUR RESULTS ANALYSIS AND DISCUSSION

4.1. INTRODUCTION

This chapter presents the results of the biofilter performance in the treatment and reduction of nutrients against the influent through physical, chemical and bacteriological processes. This chapter also examines the correlation between reduction efficacy against variables such as HRT, change in water height, and flow in each cell. An overarching aim was to examine the efficacy of nature-based processes using field-scale biofilter cells to improve surface runoff to water quality standards that were suitable for irrigation of food crops reuse. The ability of the biofilter cells to treat and reduce elevated nutrient concentrations was assessed against the water quality guidelines from the World Health Organisation (WHO) for the safe reuse of wastewater and greywater, and the South African Water Quality Guidelines for agricultural irrigation.

This chapter begins by comparing the nutrient concentration baseline data current research study nutrient concentrations data collected from the Stiebeuel River at the Water Hub. The baseline data grab samples were collected as part of the MSc research study between 20th August 2016 and 24th November 2016 (Fell, 2017). The second set of grab samples was collected from the settling tank (presented as an influent) at the Water Hub as part of this PhD research study between 11 August 2017 and 06 June 2018. However, in this study, the stored water is a composite sample that often represents 8 days average residence time in the tank of abstracted water from the river. The comparison in this research is to establish a reference for the concentration of nutrients in the Stiebeuel River.

4.2. Nutrient concentration in the Stiebeuel River

A comparison between sampling site 1 (upstream), which served as a reference point and represented the low to moderate concentrations in the top section of the river, and sampling site 2, a stormwater point source that receives contaminated surface runoff from the Langrug informal community. The following parameters were ten times higher in average concentration at sampling site 2 in comparison with the reference site (site 1) conditions with ranges from NH_3-N (0.01 mg/L – 8.4 mg/L); $PO_4{}^{3-}$ (0.34 mg/L – 7.4 mg/L) and EC (36.38 mg/L – 362.92 mg/L) (Fell, 2017). The high nutrient concentrations were found in this study to have persisted downstream to the Water Hub (Figure 4.1), site 4. The results from this study (Table 4.2) have shown the highest mean and median NH_3-N concentrations of 16. 27 mg/L and 8.1 mg/L. The mean value was twice above the baseline data concentration of 2.16 mg/L and twice above the South African DWA irrigation limit and WHO guidelines for irrigation of <5 mg/L was recorded in the influent.

The highest variation in the standard deviation values compared to any other section of the river was at sampling site 2 (Figure 4.1), which is adjacent to a pollution discharge point source from the informal settlement. The average concentrations of NO_2-N (mg/L), NO_3-N (mg/L), NH_3-N (mg/L) indicated in Table 4.1 below at sampling site 1 (background sampling point upstream) were below the 5 mg/L, as per the South African Water Quality Guidelines for agricultural use: irrigation. The surface water at sampling site 1 was suitable for irrigation of sensitive crops such as grapes and most fruit trees without affecting the crop quality.

The water quality data in Table 4.1 presents the 13 weeks grab samples collected as part of the MSc study along the Stiebeuel River at each of the sampling sites. The Stiebeuel River water quality data shows a significant rise in the EC, PO_4^{3-}, NH_3-N, NO_3-N and NO_2-N concentrations including the lowest DO concentrations at sampling Site 2 in the baseline data compared to Sites 1, 3 and 4 (Figure 3.2) above due to discharge of surface water runoff from the informal settlement that is channelled into a stormwater conduit that enters the river at this point. The increase in pollutants is indicative of nutrient enriched water that is found in similar studies (Abia *et al.*, 2018; Fitchett, 2017; Winter & Mgese, 2011; Carden *et al.*, 2007).

The average baseline concentration of NH_3-N (8.4 mg/L) at sampling site 2 (downstream of the Langrug informal settlement) for the duration of the sampling period was above the 5 mg/L. This 13-week NH_3-N average concentration at sampling site 2 is above the 5 mg/L as per the South African Water Quality Guidelines: agriculture: irrigation and WHO guidelines for safe use of wastewater. The average concentration of phosphorus discharged at sampling site 2 during the 13-week sampling period in low flow conditions was 5.94 mg/L or 5940 µg/L. This average concentration is representative of hypertrophic conditions (> 250 µg/L), as depicted in Table 2.3 above that is illustrative of symptoms associated with selected ranges of nitrogen and phosphorus concentrations as per the South African water quality guidelines: Aquatic ecosystems. The water quality at sampling point 2 also exceeded the 2 mg/L recommended by Food and Agriculture Organization of the United Nations, (FAO) water quality guidelines if it were to be used for irrigation food crops or agricultural produce without treatment. The South African water quality: irrigation guidelines indicates that other crops would remain unaffected in this lower concentration range, but the crop yield and quality of other crops would be affected as the concentration increases.

Table 4. 1: The 13 weeks average and standard deviation values collected over non-rainy days at sampling sites 1 – 3 along the Stiebeuel River (Fell, 2017)

Sampling site	**Statistical method**	**NO_2-N (mg/L)**	**NO_3-N (mg/L)**	**NH_3-N (mg/L)**	**PO_4^{3-} (mg/L)**	**pH**	**DO (mg/L)**	**EC (µs/cm)**
Site 1	Average	0.005	0.30	0.01	0.34	6.62	6.49	36.38
	Standard deviation	0.004	0.11	0.02	0.52	0.77	2.08	4.98
Site 2	Average	0.050	1.05	8.40	5.94	6.69	3.49	362.92
	Standard deviation	0.059	1.13	5.18	7.36	0.71	2.36	312.68
Site 3	Average	0.072	1.78	3.74	1.80	6.33	4.72	194.08
	Standard deviation	0.097	1.38	3.11	1.24	0.82	2.34	68.64
Site 4	Average	0.058	2.52	2.16	0.85	6.63	5.76	185.54
	Standard deviation	0.088	1.41	2.88	0.48	1.84	57.34	26.89

Table 4. 2: The average and standard deviation values of the selected water quality parameters at the influent of the biofilter cells at the Water Hub

Sampling site	**Statistical method**	**NO_2-N (mg/L)**	**NO_3-N (mg/L)**	**NH_3-N (mg/L)**	**PO_4^{3-} (mg/L)**	**pH**	**DO (mg/L)**	**EC (µs/cm)**
Influent water quality of the biofilter cells.	Average	0.14	2.22	16.27	3.18	7.39	3.23	544
	Standard deviation	0.17	2.62	13.90	1.73	0.31	1.42	322.8

The average PO_4^{3-} levels at sampling sites 1, 3 and 4 shown in Figure 4.2 (D) were below the 2 mg/L maximum recommended concentration for irrigation of edible crops as the per FAO water quality guidelines. Both the background water quality data in Table 4.1 at sampling site 2, and current water quality data collected at Water Hub near sampling site 4 in Table 4.2 show averages of NH_3-N (8.4 mg/L) and PO_4^{3-} (5.94 mg/L) above the 5 mg/L and 2 mg/L for NH_3-N and PO_4^{3-} respectively. Therefore, despite the distance between sampling site 2 and the Water Hub, dilution was insufficient to reduce the average concentration levels below the recommended limits.

The reuse of wastewater without adequate treatment for irrigation purposes has unavoidable risk for crop yield (Leonel and Tonetti, 2021). The toxicity of the pollutants in cooked vegetables, for example, is widely reported in the literature. There is a potential human health risk resulting from increased wastewater components such as pathogens, salts, heavy metals, toxic organic compounds, nutrients, organic matter and suspended solids. This is a cause for concern because, the use of wastewater for irrigation of vegetable garden or subsistence agricultural crops is a common practise in peri-urban areas due to the scarcity of good quality irrigation water and lack of resources to treat waste water (Khalid *et al.*, 2018). It is for this reason that the assessment of the treated effluent will be undertaken against the South African Water Quality Guidelines for using treated effluent for irrigation of food crop and the WHO guidelines for safe use of wastewater.

4.3. Biofiltration results: nutrient degradation

The box and whisker plots below Figure 4.2 (A– D) provide descriptive analysis of the relative performance of each biofiltration cell in relation to influent concentrations. The variable performance of each biofilter cell against the influent is indicative of the various physical, chemical and biological processes discussed below.

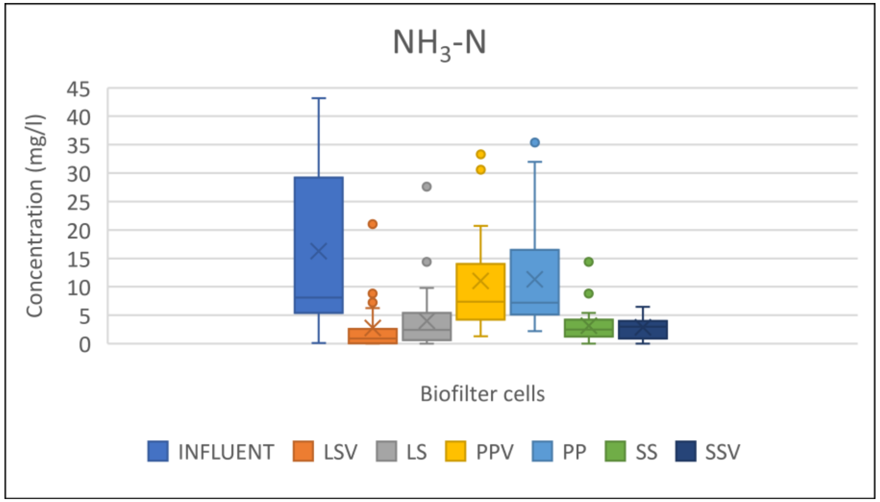


Figure 4.2(A): NH_3-N reduction efficacy

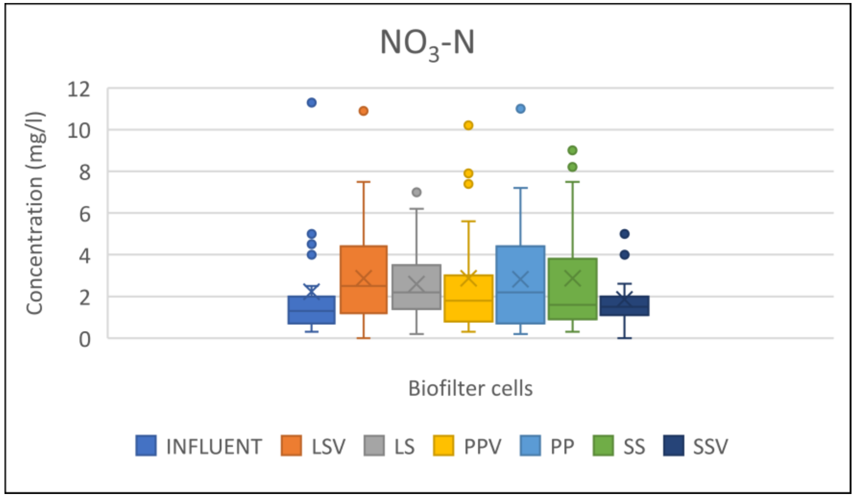


Figure 4.2(B): NO_3-N reduction efficacy

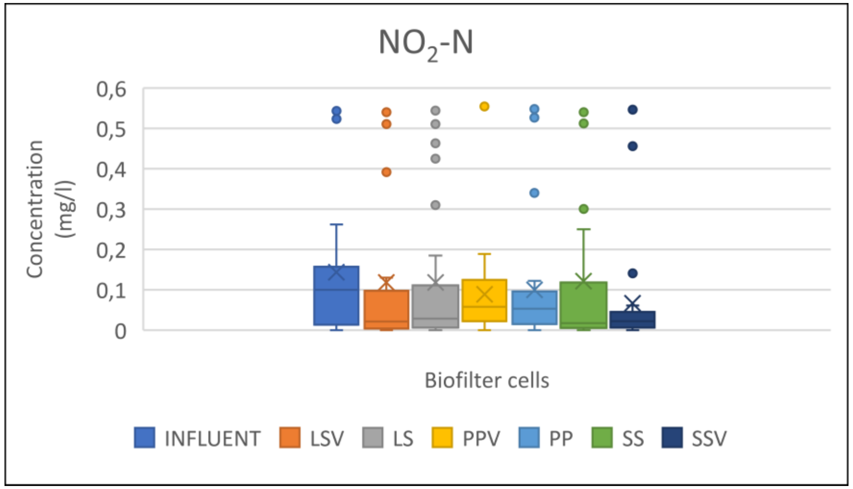


Figure 4.2(C): NO_2-N reduction efficacy

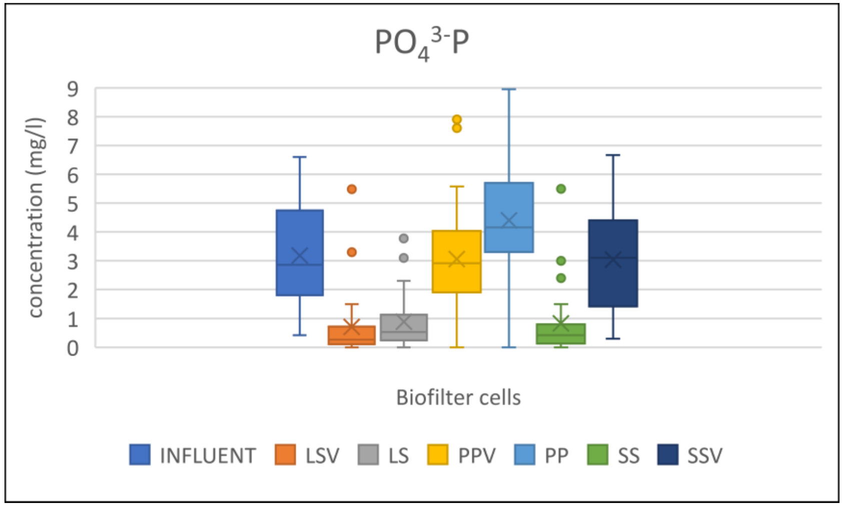


Figure 4.2(D): PO_4^{3-} reduction efficacy

Figure 4. 1:(A-D): nutrient reduction concentrations in each cell against the influent concentrations

LSV: Large Stone Vegetated; LS: Large Stone; PPV: Peach Pips Vegetated; PP: Peach Pips; SSV: Small Stone Vegetated and SS: Small Stones

4.3.1. Ammonia (NH_3-N)

The highest NH_3-N reduction was observed in the LSV followed by LS with median values of 0.88 mg/L and 2.4 mg/L, respectively. The median NH_3-N concentrations reduction in the LSV and LS were below the <5 mg/L recommended in the South African Water Quality Guidelines (1996) and WHO guidelines for safe use of wastewater (2006). Figure 4.2 (A). The corresponding 95th percentile values for the LSV and LS were 11.24 mg/L and 10.72 mg/L respectively. The 95th percentile concentrations for LSV and LS were slightly above the <5 mg/L recommended in the South African Water Quality Guidelines and WHO guidelines for safe use of wastewater (2006). The highest NH_3-N concentrations in the influent were recorded during warm, dry summers months from 26th January – 27th April 2018 with an average concentration of 29 mg/L compared to an average of 16 mg/L for the entire sampling period (11th August 2017 – 06th June 2018). In addition, the maximum NH_3-N concentration of 43.2 mg/L in the influent was recorded on the 27th of April 2018, which can be associated with timing of abstraction and activities in the catchment, as the summer conditions are drier, and the stream flow is reduced resulting in high concentrations.

Relatively higher NH_3-N (8.1 mg/L) median concentrations were recorded in the influent compared to the treatment cells, which demonstrated effective NH_3-N reduction as the result of high nitrification processes. The 90th and 95th percentile for the NH_3-N concentration in the influent was 36.58 mg/L and 40.26 mg/L respectively. This elevated NH_3-N concentration in the influent was indicative of the nutrient rich surface runoff due to activities in the catchment that resulted in higher than the <5 mg/L recommended in the South African Water Quality Guidelines (1996) and WHO guidelines for safe use of wastewater (2006).

The relatively better performance of vegetated biofilter (mean percentage removals of >96.7 percent) compared to the non-vegetated biofilter (mean percentage removal of 81.8 percent) was also confirmed in a study by Jacklin *et al.*, (2021) which examined the efficiencies of several South African plant biofilters in urban stormwater quality treatment. The study by Jacklin *et al.*, (2021) further attributes the conversion to nitrification process as the result of microbial activity.

On average, a reduction rate of 78 percent for NH_3-N was recorded in the LSV cell with 100 percent reduction rate on three occasions: 19th January, 30th March and 23rd April 2018. PP and PPV biofilter cells had the lowest percentage of NH_3-N reduction compared to the LSV, LS, SSV and SS. Poor NH_3-N reductions were observed in the PP and PPV biofilter cells with the highest median values of 7.2 mg/L and 7.4 mg/L respectively. This is due to poor nitrification process (poor development of nitrifying bacteria in the substrates) of the PP and PPV cells. It was outside the scope of this study to determine the types of nitrifying bacteria responsible to carry out the nitrification process. A study by Mielcarek *et al.*, (2021) has shown that the conversion process from NH_3-N to NO_2-N involving autotrophic bacteria and limited heterotrophs. The rationale for selection of the PP and PPV media was discussed in chapter 3 (methods) of this study. The 95th percentile of the PP and PPV cells were 30.88 mg/L and 31.78 mg/L respectively which were the highest concentrations compared to the LSV, LS, SS and SSV cells. These percentile concentrations in the PP and PPV were six times higher than the recommended < 5 mg/L by the South African Water Quality Guidelines for irrigation water quality and WHO guidelines for safe use of wastewater.

The peach kernels or pips, *Prunus persica,* were selected as a carbon source and because of its large and rough surface area for optimal biofilm growth. This is also the case with experiments which have used biochar substrate (carbon base), which consists of larger surface area and cation exchange capacity to enhance nutrient uptake through adsorption (Buss et al., 2022; Berger et al., 2019; Kasak et al., 2018a). Peach kernels or pips were used in this study because of findings about the performance of carbon sources such as wood chips which were reported in a study by Koryto et al., (2018) to provide a medium for microbial growth. Loh et al., (2021) also demonstrated that carbon-based media performed better during the initial period as the organic media (greater surface area) which requires a shorter period (15 days to 3 months) for biofilm formation compared to 20 days to 6 months on other filter media.

The poor performance of PP and PPV biofilter cells and the inability of the cells to reduce relatively higher nutrient concentrations compared to the LSV, LS, SSV and SS biofilter cell is contrary to findings which demonstrated that carbon source is a significant substrate for optimal reduction of nutrients (Buss *et al.*, 2022; Loh *et al.*, 2021; Berger *et al.*, 2019; Koryto *et al.*, 2018). A study by Amina *et al.*, (2021) has shown that peach kernels or pips contains proteins, lipids, fatty acids, and crude (oil, protein and fiber) to mention a few which are capable of producing hydrogen cyanide upon hydrolysis. The study by Amina *et al.*, (2021) has also indicated that apricot kernels consist of about 1450 mg/kg of cyanide, approximately 0.5 mg/kernel as a result, animal poisoning due to the cyanide containing fruits and grasses is problematic for cattle. The complexity to understand the poor performance of the PPV and PP cells as carbon source to yield good performance in reduction of elevated nutrient concentration is discussed in a study by Loh *et al.*, (2021) which has shown that cellulose, hemicellulose, and lignin in some but not all organic materials, create a slower release of carbon that supports development of the denitrifiers and biofilm, since denitrification is triggered by presence of sufficient organic matter levels in biofilter system. Muduli *et al.*, (2022) attributes the poor treatment and reduction rates of the highly organic substrates such as PP and PPV cells to organic loading rates which plays a key role in concentrating biomass and developing biofilm. He noted that high organic load creates a competition between the organic matter and microbes to inhabit the adsorption site. This creates fewer adsorption sites which affects the performance of the biofilter.

Even though LSV was the best performing cell, NH_3-N was also significantly reduced in the SS and LS, and again these results are consistent with observations from a study by Liu *et al.*, (2021) which suggested that nitrification by microorganisms on larger surface area is responsible for conversion of ammonium (NH_{4+}-N) to nitrate (NO_3-N). These findings concur with the study by Kawan *et al.*, (2022) which demonstrated that a gradual decrease in NH_3-N concentration (as shown in the LSV, LS, SSV and SS) is correlated with an increase in NO_3-N concentration (as illustrated by the LSV, LS, SSV and SS cells).

4.3.2. Nitrate (NO_3-N)

The presence of higher NO_3-N concentrations in a constructed wetland setting was established in a study by Steidl *et al.*, (2019) which was attributed to seasonal variation, where colder weather conditions are likely to reduce the overall nitrogen retention capacity of constructed wetlands. However, in the current study, no seasonal influence of NO_3-N concentration was established in this study since the data collection period commenced on the 11th of August 2017 (late winter season) and ceased on 6th June 2018 midwinter season in the Western Cape Province of South Africa.

Poor NO_3-N reduction efficacy was observed with the median values in PP (2.2 mg/L), LS (2.2 mg/L), PPV (1.8 mg/L), LSV (2.5 mg/L) and SS (1.6 mg/L) biofilter cells in relation to influent (1.3 mg/L). The poor reduction efficiency and an increase in the concentration of NO_3-N shown in Figure 4.2 (B) compared to the influent concentration is an indication of effective biological conversion of NH_3-N to NO_2-N and NO_3-N. A study by Jacklin *et al.*, (2021) indicates that this causes minimal sorption to biofilter media as a result of oxidised nitrogen yielding NO_3-N.

The assimilative capacity of vegetation and biofilm development combined with tight pore spaces in SSV resulted in lowered NH_3-N concentration with a median value of 1.5 mg/L compared to the influent 1.3 mg/L. The lower NH_3-N concentration in the influent with an increase in the NO_3-N levels in the influent (which constitute of composite sample from an average of 8 days HRT of abstraction) was indicative of the nitrification process where NH_3-N converts to NO_2-N and subsequently oxidised to NO_3-N (Zinger *et al.*, 2021).

About 25.5 percent of incoming NH_3-N was removed in the SSV for the duration of the sampling period, within seven-day hydraulic residence time with 100 percent NH_3-N reduction rate on the 4th sampling event (25th August - 01st September 2017). The lower median value for SSV corresponds with the lowest and 95th percentile (4.8 mg/L) compared to LS (5.96 mg/L), LSV (6.14 mg/L), SS (8.06 mg/L), PPV (7.86 mg/L) and PP (6.84 mg/L). About 95 percent of the concentration removed in SSV is below 5.21 mg/L.

The outliers in the data set were prevalent in varying concentration as seen in Figures 4.2 (A–D). The possibility that the cause of outliers by equipment malfunction is low since the measuring equipment was routinely calibrated. The causes of the extreme values can be associated with the myriad catchment activities which was outside the scope of this thesis to investigate. A study by Chingombe, (2012) which assessed the impacts of land-use activity on water quality suggested that abnormally high values (outliers) can be associated with occasions where overflowing sewage systems are frequent.

4.3.3. Nitrite (NO_2-N)

LSV, SSV and SS cells had the highest NO_2-N removal efficacy, through a nitrification process by conversion of NO_2-N to NO_3-N as discussed in study by (Li *et al.*, 2018). The high nitrite reduction was presented by a median value of 0.02 mg/L in the LSV, SSV and SS followed by PP (0.05 mg/L), PPV (0.06 mg/L). Vegetation assimilation in the SSV and PPV can be associated with high nitrite removal efficacy. PPV and SSV had the lowest 95th percentile value of 0.18 mg/L and 0.3 mg/L denoting that 95 percent of nitrite concentration is below these concentration values. The 95th percentile values for PP, LSV, LS, and SS were below 0.54 mg/L. These concentrations were below the recommended < 5 mg/L by the South African Water Quality Guidelines for irrigation water quality and WHO guidelines for safe use of wastewater. About 55.8 percent of nitrite was removed in the SSV, followed by LSV with 50.5 percent confirming the efficacy of vegetation in the removal of NO_2-N. Under normal irrigation applications, NO_2-N concentration levels are low enough not to affect even sensitive crops such as grapes and most fruit trees.

Relatively higher NO_2-N concentrations presented as outliers were observed across the biofilter cell compared to NH_3-N, NO_3-N and PO_4^{3-}. This could first be attributed to the higher nitrite mobility state that could result into leaching of nitrite out of the system (Dlamini *et al.*, 2021). Secondly, nitrification process where NH_3-N /ammonium is oxidized to nitrites (NO_2), which are highly reactive before it could further be oxidized to nitrate under aerobic conditions (Nemani *et al.*, 2018). This indicates establishment of nitrification process which yielded nitrite across the cells. The stability of the NO_2-N afterwards and NO_3-N production indicate that the second step of nitrification (oxidation of nitrite to form nitrate) was established during the experiment (Milstein et al., 2018). The relationship between wet weather conditions and an increased in NO_2-N concentration was not established in this study, contrary to a study by (Dlamini *et al.*, (2021) which demonstrated elevated nitrite levels during wet weather conditions.

Relatively higher NO_2-N treatment and reduction efficacy was recorded after 3 sampling events over two months between 01st September 2017 and 27th October 2017 with an average reduction efficacy of above 90 percent. NO_2-N removal efficiency was 100 percent on consecutive sampling events from 08th September until 22nd September 2017 due to higher denitrification rates. Relatively poor NO_2-N removal efficacy was recorded between January and February 2018 with average reduction efficacy of about 16.8 percent due to loss of microbial capacity which decreased denitrification rates.

4.3.4. Orthophosphates (PO_4^{3-})

The best performing cells with the highest PO_4^{3-} reduction rates were recorded in LSV, SS, and LS with the following median values 0.26 mg/L; 0.42 mg/L and 0.53 mg/L respectively Figure 4.5. The corresponding 95th percentile values for LSV, SS and LS were 3.32 mg/L, 2.88 mg/L and 3.23 mg/L. The PO_4^{3-} concentration levels from the respective cells were low enough to be used for irrigation food crops as these concentration levels were below <2 mg/L recommended by FAO for agricultural use. Initial 100 percent PO_4^{3-} removal rates were recorded on the 15th and 22nd September 2017 (LSV), 19th January 2018 (SS) and 15th December 2017 (LS). The LSV was the first biofilter cell to show total removal of PO_4^{3-} followed by LS and SS biofilter cells. The surface area and vegetation are good substrates or natural media for effective treatment of PO_4^{3-} in biofilter cells.

This indicates that sorption onto absorptive surface area (LSV), (LS) and (SS) followed by vegetation uptake were the effective nature-based processes or treatment mechanisms for the removal of PO_4^{3-}. The significant phosphate reduction rates were found by Rasool *et al.*, (2018) to show that phosphate accumulating, nitrifying and denitrifying bacteria in the biofilm developed on LSV, LS and SS stone media compared to SSV, PPV and PP. A study by Shrestha *et al.*, (2018) confirms that phosphate treatment from soil solution through sorption reactions with metal cations (mainly Al, Fe, Ca) and chemical precipitation in soils. Thus, natural media targeting phosphate treatment must optimize on adsorption and assimilation properties of the substates.

The low average dissolved PO_4^{3-} concentration during June 2018 sampling period can be attributed to domination of mechanisms such as precipitation/dissolution or dilution were dominant. Secondly, the aftermath of the first flush effect, where high levels of pollutants and P rich sediments could be flushed by first high flows than the subsequent flows.

The high average PO_4^{3-} concentration of 5.47 mg/L during dry summer conditions with average rainfall of 0.07mm could be attributed to the high phosphorus adsorption capacity of sediments. This is supported by Blecken *et al.*, (2010) who have shown that a higher percentage of phosphorus in stormwater runoff exists as particle bound phosphorus. Therefore, due to its strong affinity to particles, its removal via passive sedimentation in the sedimentation tank could have significantly lowered its concentration levels. Numerous studies have demonstrated the effectiveness of sedimentation process which included constructing sedimentation basins for instance, prior to a constructed wetland inlet reported by Budd *et al.*, (2011) that was highly efficient at reducing TSS with a calculated reduction rate of about 28.5 mg L^{-1} (CW1) and 31.2 mg L^{-1} (CW2) which is tantamount to 68 percent of the total mass of trapped sediments. Meng *et al.*, (2014) has similarly demonstrated that the supply of phosphorus from external sources can be stored in sediments through adsorption of dissolved phosphorus, making sediments sinks for phosphorus in water column.

4.4. Physical parameters

4.4.1. Electrical Conductivity (EC) effluent

The influent water quality was characterised by elevated EC concentrations with mean and median values of 544.10 µS/cm and 347 µS/cm respectively, typical of sewage and soluble ions that are pollutants discharged into Stiebeuel River. The baseline mean EC concentration of 362.92 µS/cm at sampling site 2 (Figure 4.1 above), the stormwater discharge point from Langrug into Stiebeuel River was relatively lower compared to the mean 544.10 µS/cm EC concentrations at the influent of this study captured at the Water Hub. This suggests another importance source of salts in the lower reaches as the Stiebeuel River passes through vineyards before reaching the Water Hub coupled with irregular sewage overflows.

The highest EC values were found between January – April 2018, characterised by dry, summer weather conditions. The EC median values for influent (897.63 µS/cm) and LS (269.81 µS/cm) were 3 times higher in (January – April 2018) representative of dry summer weather conditions compared to August – November 2017 in influent (263.58 µS/cm) and LS (216.50

µS/cm) representative of the spring season. The EC values in the LSV biofilter cells were double during January – April 2018 (616.31 µS/m) compared to August – November 2017 (272.13 µS/cm). The high EC values during January – April 2018 concurred with findings in study by (van der Hoven *et al.*, 2017) where high EC values were observed during summer weather conditions with associated with higher evaporation rates.

The lowest median EC values were shown in the PP (216 µS/cm) and PPV (239 µS/cm), whilst the lowest mean EC concentrations were recorded in SS (309 µS/cm) and SSV (312 µS/cm). The highest median EC concentrations were shown in LSV (474 µS/cm), higher compared to influent median concentration (347 µS/cm). The high median EC concentration in the LSV cell than influent cannot be associated with summer, low flow weather conditions. Tomar and Suthar, (2011) attributes the high EC median concentrations to mineralization wastewater of organic waste through microbial activity. Furthermore, the study by Tomar and Suthar, (2011) argues that high EC is an indicator for the mineralized wastewater, since EC shows salinity of any material.

The EC median values for SS (235 µS/cm) and SSV (277 µS/cm) corresponded with the lowest 95th percentile values, 615.4 µS/cm and 552.2 µS/cm respectively. A study by Muvea *et al.*, (2019) has shown effectiveness of aquatic macrophytes in the reduction of EC conventions, which is contrary to the findings of this study. This study has shown that the EC concentration is not dependable on the absorption capacity of vegetation.

The concentrations of EC in the SS and SSV cells is a good measure for reusability the treated effluent for irrigation purposes. A study by Jeong *et al.*, (2016) has shown that EC values below 700 µS/cm are suitable for irrigation, whilst EC values above 3000 µS/cm causes damage to crop growth. Jeong et al, further indicated that the irrigation water quality guideline for wastewater reuse for food crops and processed food crop is set for 700 µs/cm and 200 µs/cm respectively in South Korea. According to the paper, EC values below the 700 µs/cm threshold does not affect a variety of crops. In South Africa, The EC of irrigation water is ideal if ≤30 mS m−1 (300 µs/cm), acceptable if >30 (300 µs/cm) and ≤50 mS m−1 (500 µs/cm), tolerable if >50 (500 µs/cm) and ≤85 mS m−1 (850 µs/cm), and unacceptable if >85 mS m−1 (850 µs/cm) (Mudaly and van der Laan, 2020). The EC acceptable guideline limits as per the South African Water Quality Guidelines for agricultural use: irrigation is categorised into good: 0 – 40 mS/m (400 µs/cm); fair: 40-90 mS/m (900 µs/cm) and unacceptable:270 mS/m (2 700 µs/cm).

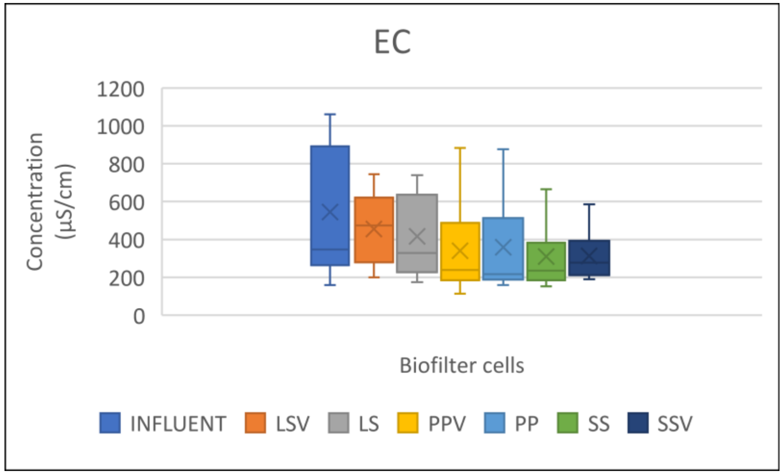


Figure 4.3(A): EC concentrations

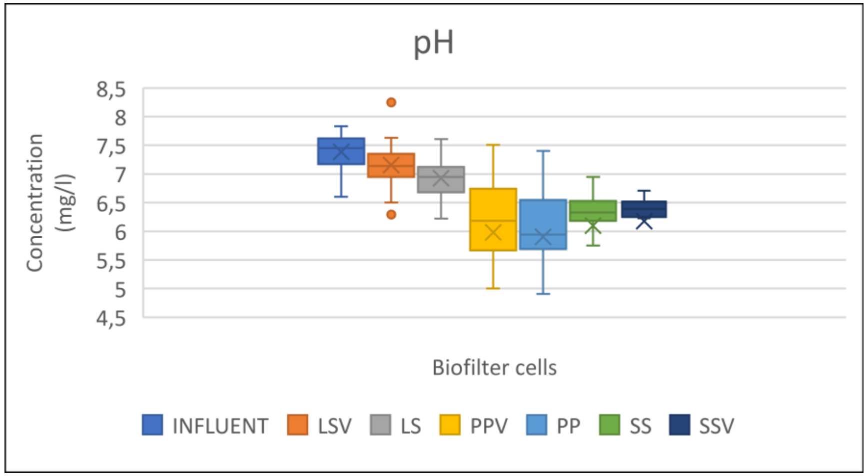


Figure 4.3(B): pH concentrations

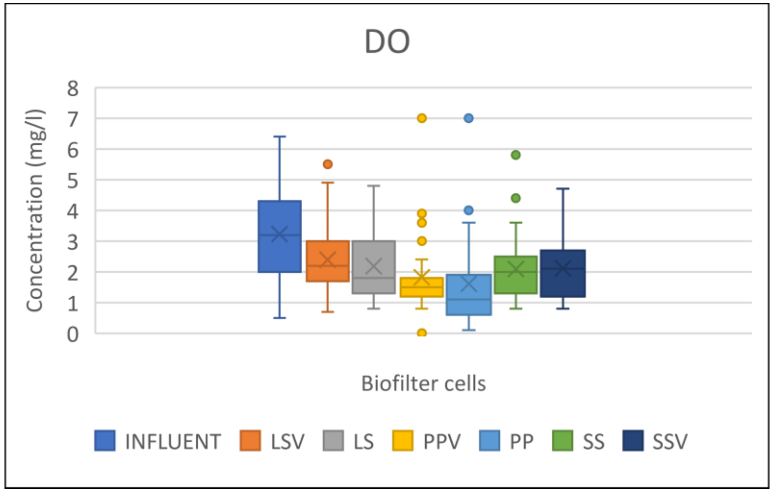


Figure 4.3 (C): DO concentrations

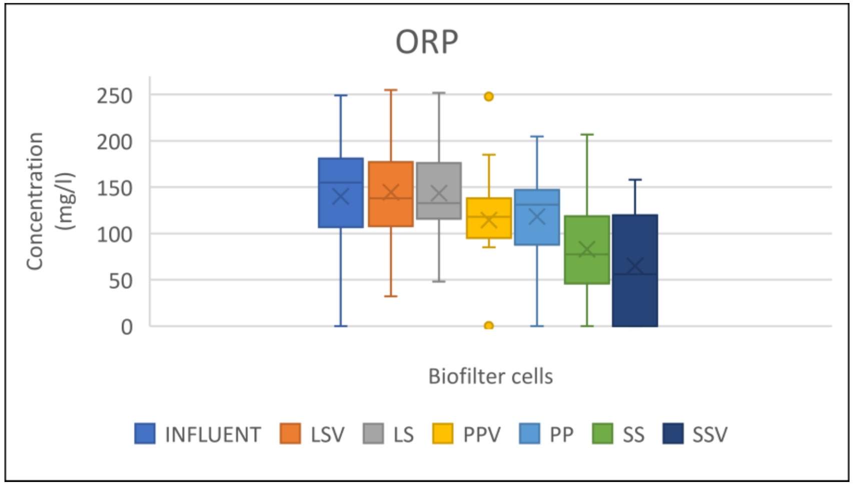


Figure 4.3 (D): ORP concentrations

Figure 4. 2: (A-D): Physical parameter concentrations in each cell against the influent concentrations

LSV: Large Stone Vegetated; LS: Large Stone; PPV: Peach Pips Vegetated; PP: Peach Pips; SSV: Small Stone Vegetated and SS: Small Stones

4.4.2. Potential of Hydrogen (pH)

The pH values throughout the sampling period in the influent were consistently above 7, showing an alkaline incoming (influent) runoff with a median pH value of 7.4. The minimum and maximum influent pH values were 6.6 and 7.8 respectively. The highest median pH values were recorded in the influent (7.4), followed by LSV (7.1). The pH values in this study were consistent with those reported by Li *et al.*, (2019) where water pH in the constructed wetland ranged from 7.35 to 7.58. The pH values for this study did not vary significantly between wet and dry weather conditions. This is inconsistent with results by Namaalwa *et al.*, (2020) where a slight seasonal effect was observed with a decrease of pH in the wet seasons as the result of increased discharge.

According to the study by Mudaly and van der Laan (2020), the average surface water pH value of 7.39 (indicated above) is within acceptable pH quality range for downstream users as per the ≥6.5 and ≤8.0 limit set out in the water quality guidelines by the South African Department of Water and Sanitation (DWS). Internationally accepted standard for pH of irrigation water ranges from 6.5 to 8.4. The pH below or above this limit is set to cause imbalance of nutrients or contain poisonous ions and can affect irrigation facilities through corrosion of agricultural infrastructure (Jeong *et al.*, 2016).

The LSV and LS cells were the only biofilter cells with median pH values within acceptable ranges at 7.1 and 6.9 respectively. The PPV, PP, SSV and SS had the following median pH values 6.1, 6, 6.4 and 6.3 which were acidic and unacceptable as per the study by Mudaly and van der Laan, 2020). The acidity concentrations in PPV (6.1) and PP (6) corresponded with the removal of PO_4^{3-} and NH_3-N concentrations as indicated in Figures 4.2 (A) and 4.2 (B) above. This concurred with the study by Kasak *et al.*, (2018b) which found that adsorption capacity of phosphorous is influenced by pH, including Fe, Al and Mg which means that reduced pH levels lowers the phosphorus adsorption capacity of the substrate therefore, alkaline waters increases the adsorption capacity of phosphorous. Due the high microbial activity in the PPV and PP cells, Gao *et al.*, (2017) attributes the low pH in both PP and PPV to the degradation of organic matter in the lease of organic acids and high nitrification rates, since NH_3-N is first oxidized to nitrite by NH_3-N oxidizing bacteria and then further oxidised to nitrate by nitrite-oxidising bacteria (Fell, 2017).

4.4.3. Dissolved Oxygen (DO)

The lowest median DO values were observed in the PP (1.10 mg/L) followed by PPV (1.50 mg/L), Figure 4.3 (C). Lower DO concentration is often associated with nutrient rich waterways due to elevated nutrient concentrations (Motitsoe *et al.*, 2020). The favourable DO concentrations from 3 to 5 mg/L are recorded by Yan *et al.*, (2019) to enhance denitrification compared to lower or higher DO levels. The influent had the highest median DO concentration of 3.20 mg/L compared to in the biofilter cells as it is largely consumed by microbial activity in the cells (Zhao *et al.*, 2019). Higher DO median values were recorded in the LSV (2.20 mg/L), SSV (210 mg/L), SS (2 mg/L), and LS (1.80 mg/L). The extreme outliers 7 mg/L for both (PP and PPV) can be indicative of instrument malfunction. The lowest DO values in PP and PPV correlates with lower pH values in the PP followed by PPV as indicated above. The correlation can be indicative of poor quality of treated effluent in the PP and PPV biofilter cells. This is because, PP which is a carbon source was indicated in a study by Duan *et al.*, (2019) to lower pH and dissolved oxygen (DO) and thereby affecting nitrogen (N) removal via microbial denitrification.

The lowest DO levels with median values of 1.50 mg/L and 1.10 mg/L for PPV and PP respectively are the result of high DO consumption by NH_3-N oxidizers and microorganisms. Other major contributors of DO reductions described by Gao *et al.*, (2017) which were demonstrated in the PP cells are the high microbial population colonisation on the spherical media (peach pips) in the PP cell. The microbial communities on large surface area contributed to the rapid oxygen consumption. The transportation of atmospheric oxygen into the rhizosphere is shown by higher median DO values in vegetated cell LSV (2.20 mg/L) compared to non-vegetated cell LS (1.80 mg/L).

A study by Kang *et al.*, 2018) established that the presence of DO is critical in P exchange between water and sediments. Similarly, this study demonstrated that DO remove P from water through adsorption to the sediment. This relation between DO and treatment of P is shown in Figure 4.2 (D) where relatively lower P concentration in the LSV, and LS is reduced in the presence of DO in Figures 4.3 (C). Furthermore, Kang *et al.*, 2018) indicated that DO concentration correlates with the Oxidation Reduction Potential (ORP). This is because, oxygen in a Biological Oxygen Demand (BOD) environment is consumed for decomposing organic matter to create anaerobic conditions, whilst oxides in the substrate (Fe^{3+}, Mn^{5+}, and SO_4^{2-}) consume oxygen to lower the oxygen reduction potential in the water (Jeong *et al.*, 2016).

4.4.4. Oxidation-Reduction Potential (ORP)

LSV reflected the highest ORP concentration with median concentration of 138 mV followed by LS with median value of 133 mV, while SSV and SS had the lowest median ORP values with 42 mV and 78 mV. This shows that the latter cells were limited in nitrifying bacteria, since ORP within the range of 100mV to 350mV is suitable for nitrifying bacteria to be established (Razzaghmanesh and Borst, 2019). The relatively high ORP values in LSV and LS corresponded with high PO_4^{3-} treatment as indicated in Figures 4.2 (D) and 4.3 (D). This reduction of phosphorous levels with an increase in ORP values is supported by Aimin *et al.*, (2005), which indicated that ORP increase will significantly influence phosphorus adsorption. There was no ORP correlation between vegetated and non-vegetated cells can be established due to the variation between vegetated and non-vegetated cells. No correlation between pH and ORP was established in this study in comparison to a study by (Qin *et al.*, 2019; Luca *et al.*, 2017) which reported an increase in pH values in constructed wetlands as the ORP decreases.

The concentration of ORP is also critical in the treatment of nutrients. An increase in ORP concentration was correlated with reduced phosphate levels. The highest median ORP concentrations in LSV (138 mV) followed by LS (133 mV), corresponded with the lowest median PO_4^{3-} concentrations in LSV (0.26 mg/L) and LS (0.53 mg/L). Similar findings were reported in a study by Gavrić *et al.*, (2019); Aimin *et al.*, (2005) where a higher phosphorus adsorption affinity caused by high ORP of particles is produced.

4.5. The effect of biofilter design features and operational conditions

To determine the effect of biofilter packed natural media from each cell and operating conditions on nutrient treatment for selected factors such as vegetation, substate type (surface area), water depth, water volume, and hydraulic residence times were examined. This was to determine the biofilter optimal operational conditions and characteristics to compare and assess effective treatment performance between the six biofilter cells over time (11 months period). This section intends to use statistical models to determine and compare performance of the design characteristics and selected operational conditions that enhances treatment performance.

4.5.1. Wilcoxon signed rank test

The Wilcoxon signed rank (non- nonparametric test) test was undertaken to determine the difference in the nutrient reduction against the influent and between vegetated and non-vegetated cells. Table 4.3 confirms the significant difference in the removal of incoming NH_3-N from all the biofilter cells (LSV, LS, PPV, PP, SSV and SS). Comparatively, there is no significant reduction efficacy of NO_3-N between the incoming nitrate and biofilter cells (LSV, LS, PPV, PP, SSV and SS). This is attributed to relatively lower incoming NO_3-N levels compared to NH_3-N with about 76 percent difference. The fluctuating levels between NH_3-N and NO_3-N was confirmed in a study by (Liu *et al.*, 2021). Where it was established that in the process of nutrient degradation, an increase in NH_3-N levels is accompanied by the decrease in NO_3-N levels. There was no significant difference between influent and biofilter cells (LSV, LS, PPV, PP and SS). This indicates that the concentration of NO_3-N increased in the biofilter cells as NH_3-N as oxidised to NO_3-N (Liu *et al.*, 2021).

A comparison between performance of vegetated and non-vegetated cells in the treatment of NH_3-N, NO_3-N, NO_2-N, and PO_4^{3-} was established in the table below using Wilcoxon signed rank test. Even though the presence of vegetation in the removal of these nutrients is evident in this study, other factors such as biofilm development on large and small surface area (LS & SS) showed significant PO_4^{3-} and NH_3-N removal. Vegetation type was recently established in a study by (Zhang *et al.*, 2021) as one of the major biofilter design feature for optimal nutrient removal. Biofilter features such as substrate selection, development of microbial activity, nitrification and denitrification processes and hydraulic residence time are important in the treatment of nutrients. Loh *et al.*, (2021) confirmed that a larger surface area, higher porosity, non-toxic, higher adsorption capacity and phenolic hydroxyls and carboxylic substrates) which can be contained in the organic filters.

Table 4. 3: Wilcoxon signed rank (non-nonparametric test) test scores for each biofilter cell

Biofilter cells	NH_3-N	NO_3-N	NO_2-N	PO_4^{3-}	EC	pH	DO	ORP
Influent vs LSV	0	217	197	27	194.5	74	97	347
Influent vs LS	8	217	186.5	21	67.5	23	85	348.5
Influent vs PPV	113	276.5	143	224	0	0	71	161
Influent vs PP	97.5	331.5	114	333	3	0	54.4	185
Influent vs SSV	9	130	47	218	107.5	0	157	24.5
Influent vs SS	16.5	224	93	6	12.5	0	81	87.5
Vegetated vs non-vegetated cells								
LSV vs LS	135	332	295	228.5	183.5	62	261.5	21
PPV vs PP (25 data set)	56	149	135.5	28	202.5	107.5	90.5	208
SSV vs SS (25 data set)	109	104.5	110	21	36	135	176.5	87
Key:	Significance at 0.005 probability level (Critical values of **168** and **60** for 39 and 25 data samples respectively as per the Wilcoxon Signed-Rank Table)							
>168/60(0.005)	There is no significant difference between the biofilter cells treatment and reduction efficacy							
< 168/60(0.005)	There is a significant difference between biofilter cells treatment and reduction efficacy							

4.5.2. Vegetated and non-vegetated cells nutrient degradation percentages

The role played by vegetation on the nutrient removal efficacy between LSV and LS, PPV and PP, SSV and SS was examined. This was to compare and statistically ascertain the degree removal between the vegetated and non-vegetated cells. The LSV cell had the highest >80 percent degradation percentage of NH_3-N and PO_4^{3-} compared to LS, SSV, SS, PPV and PP cells as indicated in Figure 4.4 (A-D) below. A significant reduction in the concentration of PO_4^{3-} from effluent discharged of between 80 percent – 95 percent was established in vegetated (*Agapanthus, Pennisetum, Stenotaphrum, Zantedeschia, Phragmites and Typha*) biofilter in a study by Milandri *et al.*, (2012).

4.5.2.1. LSV vs LS

The LSV was the best performing cell in the treatment of NH_3-N followed by PO_4^{3-} with 98 percent and 95 percent median percentages respectively. LS as the second-best performing cell in the reduction of NH_3-N followed by PO_4^{3-} with the following median percentages, 75 percent and 80 percent respectively (Figure 4.4 (A). A significant difference in the NH_3-N removal was observed between LSV and LS, whilst there were no significant removal percentages between LSV and LS in the concentration of PO_4^{3-} (Table 4.3). This concurs with the general findings by Zhang et al., (2021) and Lee *et al.*, (2009) which observed that vegetation type(s) were found amongst various other biofilter characteristics to significantly influence nutrient treatment performance compared to non-vegetated systems. However, since non-vegetated cells (LS) do not absorb nutrients, the major treatment pathway was through provision of surface area for the growth of biofilms which contributes to reduction of nutrients.

The helophyte emergent vegetation (mixture of *Phragmites australis and Typha spp*) planted in the LSV cell increased NH_3-N and by PO_4^{3-} reduction performance through absorption, adsorption and microorganism activity such as biofilm growth around the root zone together on surface area of the large stone. Yan *et al.*, (2018) found that the helophytes provide nutrients and oxygen to biofilms through absorption. The supply of oxygen in the vegetated cells (LSV, PPV and SSV) from the atmosphere through stomatal opening into the root zone-maintained biodegradation of NH_3-N and PO_4^{3-} The importance of dissolved oxygen in the biodegradation of pollutants in a biofilter was established in a study by Loh *et al.*, (2021). The study noted that aerobic microorganisms require adequate supply of dissolved oxygen (2–3 mg/L) for growth of nitrifying biofilms and to enhance biodegradation NH_3-N and PO_4^{3-}

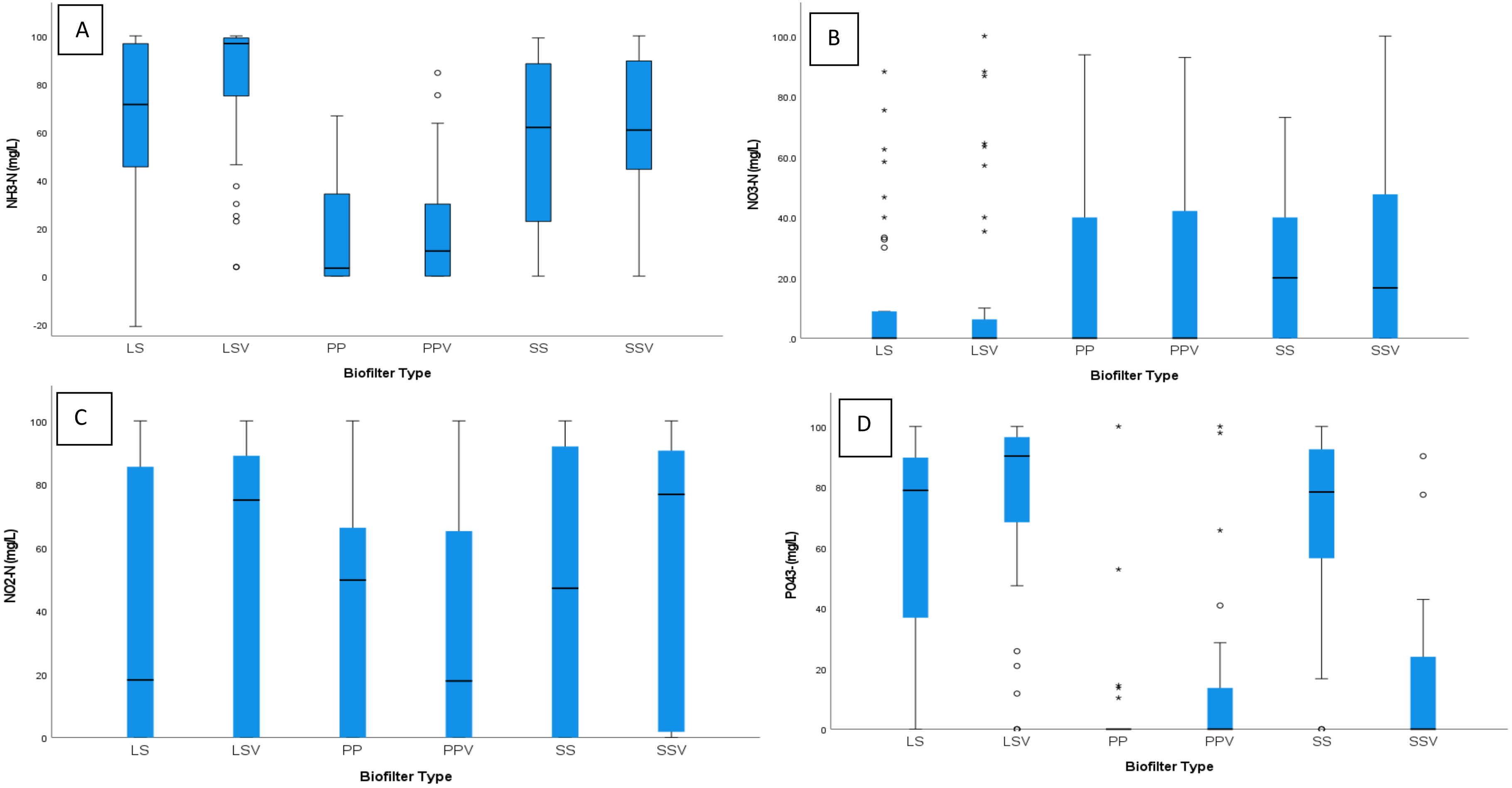


Figure 4. 3: (A-D) Differences in the reduction efficiency (percent) of the six purpose-built biofilter cells. Boxplot shows median, min and max, 25 percent and 75 percent interquartile range as bars.

LSV: Large Stone Vegetated; LS: Large Stone; PPV: Peach Pips Vegetated; PP: Peach Pips; SSV: Small Stone Vegetated and SS: Small Stones

4.5.2.2. PPV vs PP

PPV and PP were the best performing cells in the treatment and reduction of NH_3-N followed by PO_4^3. As a result, there was a significant difference in the reduction rates of NH_3-N and PO_4^{3-} between PPV and PP reduction efficacy (Significance at 0.005 probability level, critical values of 168 and 60 for 39 and 25 data samples respectively as per the Wilcoxon Signed-Rank Table 4.3 above). The PPV and PP cells had the lowest reduction percentages of NH_3-N and PO_4^{3-} compared to LSV, LS, SSV and SS. The lowest reduction efficacy in the PPV and PP cells coincided with the lowest median DO levels of 1.86 mg/L and 1.61 mg/L Figure 4.4 (A) above. A study by Loh *et al.*, (2021) described the low levels on dissolved oxygen to cause lower nitrification efficiency and higher denitrification rates which occurs in biofilters with high organic carbon sources and low oxygen concentration promoting growth of heterotrophic denitrifies. The study by Loh *et al.*, (2021) confirmed that high carbon source zones and microbial activity enhances denitrification rates.

4.5.2.3 SSV vs SS

The performance of SSV compared SS in the treatment of NH_3-N, NO_3-N, NO_2-N and PO_4^3 was variable throughout the study period. A median percentage of > 60 percent in the reduction of NH_3-N was achieved in both the SSV and SS cells. A higher median percentage of over 80 percent was achieved for the treatment of NO_2-N and PO_4^{3-} in the SSV and SS respectively. There was a significant difference in the reduction of PO_4^{3-} between SSV and SS (Significance at 0.005 probability level, critical values of 168 and 60 for 39 and 25 data samples respectively as per the Wilcoxon Signed-Rank Table 4.3 above with the highest removal in the SS (> 80 percent median percentage) compared to SSV (<20 percent median percentage). Vegetation played a lesser role in the treatment of PO_4^{3-} in the SSV cell. This could be because PO_4^{3-} removal pathway is through surface adsorption and that the sparsely distributed vegetation in the SSV cell that made little contribution.

A study by Zhang *et al.*, (2021) has shown that macropores formation due to long dry periods or the use of coarse-rooted vegetation can also lead to poor performance due to the lower residence time. The results show that the surface area adsorption of PO_4^{3-} was the major removal mechanism in the SS cell. A study by Loh *et al.*, (2021) observed that smaller sized sand properties in biofilter enhance effective contact between PO_4^{3-} and biofilm. The SS cell was effective in the treatment of PO_4^{3-} compared to SSV biofilter cell. Alam *et al.*, (2022) has shown that non-vegetated filters using recycled concrete aggregates were significant through surface precipitation followed by adsorption removal mechanisms.

4.6. Hydraulic residence time and biofilter cells treatment efficacy

Different HRT were applied in this study to ascertain the nutrient reduction efficacy in percentages over selected intervals. The HRT was divided into 4 broad HRT categories, < 5 days; 6 – 10 days; 11 – 15 days and >15 days for the duration of the sampling period of each category presented below. The application of HRT is discussed in the literature to influence pollutant removal. Lower HRT was reported in a study by Zhang *et al.*, (2021) to result in decreased adsorption of soluble pollutants such as phosphorus onto substrates. The PP and PPV cells can be considered ineffective in the treatment of excess nutrient inputs against the influent since they show similar concentration of the nutrients relative to the influent over time, except for the PO_4^{3-} where the concentration in PPV is lower, Figure 4.5 (a- d). Boxplots below shows the variation in the excess nutrient treatment by six purpose-built biofilter cells across the HRT days: (a) Ammonium, (b) Nitrate, (c) Nitrite and (d) PO_4^{3-}. The variation is demonstrated in the box and whisker plots using median, min and max in error bars, 25th and 75th percentile as shown in bars.

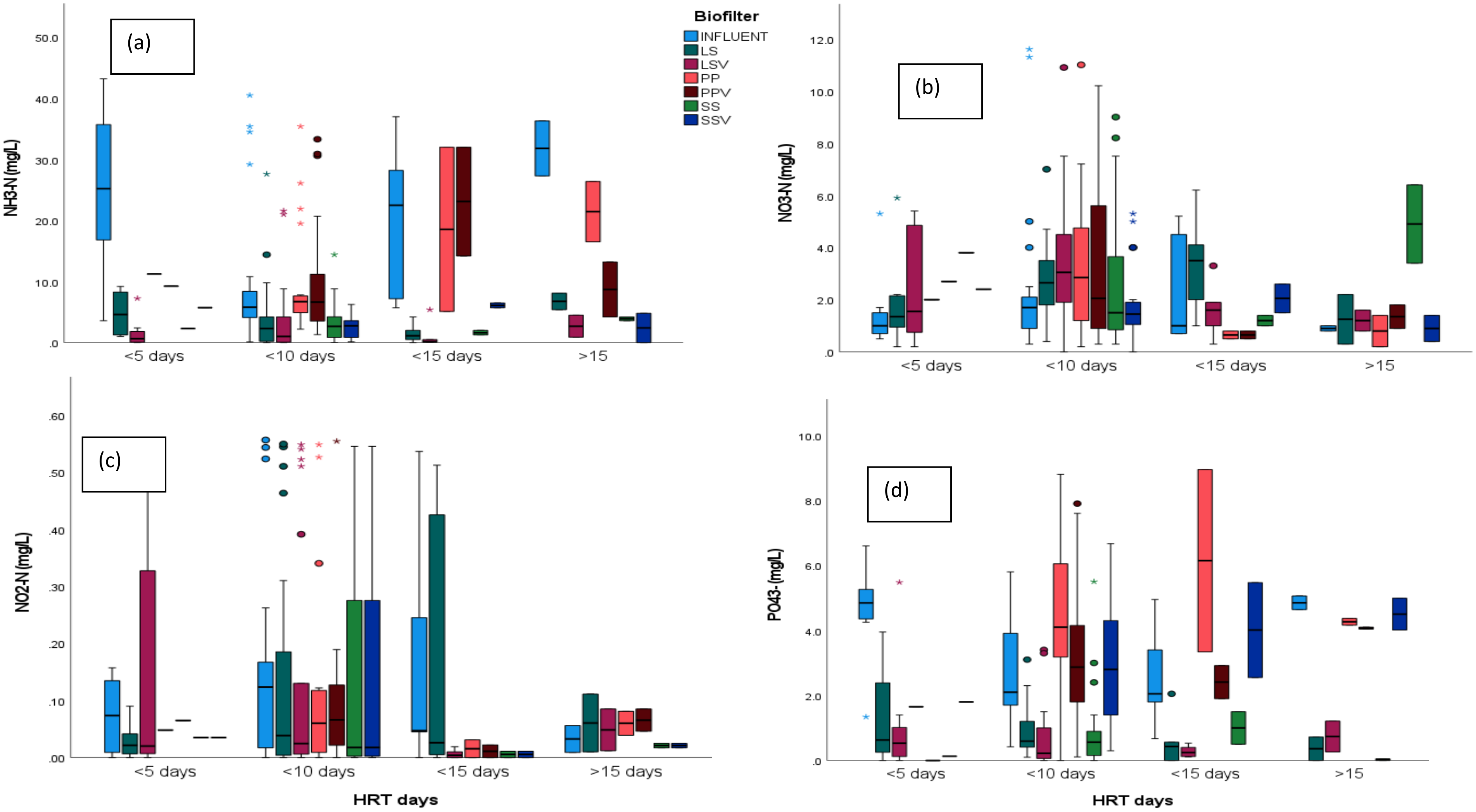


Figure 4. 4: (A-D): shows the boxplots of nutrients concentrations (median, min and max in error bars, 25th and 75th percentile show in bars) over selected intervals of HRT days.

4.6.1. HRT VS NH_3-N TREATMENT

The highest NH_3-N treatment was recorded within < 5 days and >15 days in the LSV and SSV cells with 91 percent removal (Figure 4.5 above). The highest NH_3-N reduction percentages above 90 percent were noted in the later stages of the biofilter operation (26th January – 16th March 2018) which coincided with dry summer weather conditions compared to earlier stages of the biofilter operation. The highest NH_3-N removal, 100 percent efficacy with 21 days of HRT was observed on the 16th of March 2018 in the SSV cell whilst 99.1 percent NH_3-N reduction efficacy was observed on the 24th of November 2017 with 7 days HRT due to high denitrification rate. Similar findings were observed in a study by (Gao *et al.*, 2017) where higher summer temperatures increased denitrification rate, leading to higher plant growth rate and increased nitrogen uptake. This study concurred with findings from Blecken, *et al.*, (2010) which indicates NH_3-N fixation and microbial nitrogen update are influenced by temperatures.

The highest (91 percent) NH_3-N reduction rate in the >15 days HRT is indicative that longer HRT is beneficial in biofilters for treatment of pollutants due to increased contact time, improving treatment and reduction performance (Sharaf *et al.*, 2020). However, the highest NH_3-N reduction was also established within < 5 days HRT, this was confirmed in the study by Raphael *et al.*, (2020) where HRT of 2.5 days was shown to be sufficient to yield high COD, TN and TSS reduction efficiencies (Raphael *et al.*, 2020). The varying residence time did not influence the NH_3-N treatment in the PPV and PP cells. Furthermore, the lowest NH_3-N removal occurred throughout the selected HRT days in the PP followed by PPV cells. A >15 HRT days are beneficial for treatment and reduction of NH_3-N in the biofilter cells.

4.6.2. HRT VS NO_3-N TREATMENT

Poor nitrate treatment over the predetermined HRT days compared to NH_3-N was established as the reduction percentages were below 70 percent for all the cells. The highest nitrate reduction percentage was observed within the 11 – 15 HRT Day period in the PPV and PPV (67 percent reduction percentage) due to highest organic matter and biological activity in the cells. The lowest nitrate reduction percentages were recorded in the LSV (>15 HRT days) with 0 percent, LS (6-10 HRT days and 11 – 15 days) with 8 percent, PPV (<5 HRT days) with 0 percent, PP (< 5HRT days) with 0 percent, SSV (< 5 HRT days) with 0 percent and SS (<5 HRT days and >15 HRT days) with 0 percent.

A 100 percent nitrate removal occurred between 6 – 10 days of HRT days in the SSV took place in the 4th sampling event from the 25th of August – 01 September 2017 batch sample. The poor nitrate treatment in biofilters was similarly found in a study by Koryto *et al.*, (2018) to be an attribute of its solubility state and limited capacity for sorption. HRT between 11 – 15 days could be sufficient for biofilters to activate denitrification of nitrogen. This is because, Sharaf *et al.*, (2020); Yang Yun-ya and Lusk, (2018) has established a positive relationship between increased residence time in biofilters for interaction with microbes and anaerobic zones to increased denitrification potential to improve treatment of nitrogen and improved biofilter performance.

4.6.3. HRT VS NO_2-N TREATMENT

The highest nitrite treatment in percentage was observed in 11 – 15 HRT days in the LSV cell compared to any other HRT Day and biofilter. The second highest nitrite reduction concentration was observed in < 5 HRT days with average of 69 percent reduction efficacy in SS biofilter cell. A 100 percent nitrite removal efficacy was recorded on two consecutive days, fifth and sixth sampling event taken on 08th and 15th September 2017. This was the initial phase of the biofilter operation. The rapid uptake of nutrients during the initial phase of the biofilter system was also confirmed in a study by Lin *et al.*, (2019) where nitrogen and phosphorus reduction efficiency increased rapidly during the initial phase of the biofilter operation but gradually slowed down and became stable.

The relationship between vegetated and non-vegetated could not be stablished in this study, contrary to the findings by Steidl *et al.*, (2019) which established high nitrate retention in presence of emergent vegetation. The highest average cumulative percentage of denitrified nitrate -levels showed 72 percent of nitrate removed for LSV followed by 69 percent nitrate removed for SS. This denotes the highest average nitrate denitrification to have taken place in the LSV cell followed by SS cell. The highest nitrate reduction percentages for LSV and SS are supported 90th and 95th percentiles 0.54 mg/L and 0.52 mg/L respectively which are below the <5 mg/L recommended by South African Water Quality Guidelines: agricultural use, irrigation water use and WHO guidelines for safe use of wastewater.

4.6.4. HRT VS $PO_4{}^{3-}$ TREATMENT

A variation in the treatment of phosphorus across HRT and biofilter was observed. A 100 percent average phosphorus removal percentage was established in PPV and SS with HRT < 5 days and >15 days as illustrated in Table 11 and Figure 4.5 (d) above. An average 90 percent, 93 percent and 85 percent were observed in HRT days < 5 days, > 15 days and > 15 days in the SS, LS and LSV biofilter cells respectively. This observation indicates that both < 5 days and > 15 HRT days is sufficient in the reduction of phosphorus. Kumar and Dutta, (2019) established macrophyte contribution in the reduction of phosphates in biofilter systems to range from 4.8 percent to 74.8 percent. The treatment and reduction percentage of phosphate in vegetated biofilter in this study ranged from 20 to 100 percent efficacy which was consistent and even higher than phosphate treatment and reduction efficacy reported by Kumar and Dutta, (2019).

A correlation can be established which confirmed the highest phosphorus treatment and reduction concentrations in LSV and SS between 19th January – 27 April 2018, indicative of low flow. The correlation between high phosphorus reduction and high temperature was also established in a study by Blecken, *et al.*, (2010) where phosphorus sorption in soils increased with rising temperature. The adsorption of phosphorus onto surface area material, followed by uptake by vegetation are confirmed in a study by Raphael *et al.*, (2020) as key mechanisms for treatment and reduction of phosphorus concentrations in wetlands/ biofilter systems which can be influenced by presence of metals such as Ca and Fe. This is because PO_4^{3-} which are dissolved state are taken up by macrophytes or adhere to the substrate when these metals are present (Kumar and Dutta, 2019). A study by Rehman *et al.*, (2021) has shown an increased phosphate reduction with an increase in HRT in biofilter. This is confirmed > 15 HRT days and < 5 HRT days are effective in the treatment and reduction of phosphorus concentration depending on the physical parameters and operating conditions. This is because of increase in contact time between substrate and water for development of microorganisms which are key for removal and uptake of phosphates.

4.7. Relationship between nutrient reduction efficacy with physical parameters and HRT days

Non-parametric approaches were used to ascertain differences in treatment and reduction of excess nutrients and changes in the physical parameter of the water in the biofilter cells. A generalised linear mixed model was used to compare the differences in chemical and physical parameters such as pH, DO, ORP and EC of the biofilters against the biofilter type, HRT days and change in volume as predictors. Statistical significance was accepted at P<0.05, the model has built in Bonferroni correction to adjust for multiple pairwise comparisons and to eliminate chance of making type ii errors. The data was analysed using Rstudio.

Table 4. 4: Results of the generalised linear mixed model showing the differences in the reduction rates of chemical parameters in the biofilter cells.

Variables	**NH_3-N**			**NO_3-N**			**NO_2-N**			**PO_4^{3-}**		
	F	df	P	F	df	P	F	df	P	F	df	P
HRT days	**3.23**	**3**	**0.02**	**3.24**	**3**	**0.02**	5.22	3	0.00	1.23	3	0.30
Biofilter cells	2.12	6	0.05	0.1	6	0.97	0.02	6	1	1.77	6	0.11
Biofilter X HRT days	2.45	18	0.00	0.78	18	0.72	0.72	37	0.79	1.19	18	0.28
EC	**44,88**	**1**	**0,00**	**16,17**	**1**	**0,00**	**50,77**	**1**	**0,00**	**9,03**	**1**	**0,00**
DO	1.64	1	0.20	0.32	1	0.57	0.02	1	0.88	0.01	1	0.93
pH	0.84	1	0.36	**15.13**	**1**	**0.00**	2.51	1	0.12	0.78	1	0.38
ORP	0.02	1	0.88	2.60	1	0.11	0.00	1	0.96	1.34	1	0.25

*Note: green colour represents the significance in the relationship between the two or more parameters

The reduced EC concentration significantly influenced the treatment and reduction of NH_3-N, NO_3-N, NO_2-N whilst no effect was found for the PO_4^{3-} (Table 4.4) above. NO_3-N was significantly influenced by the pH variation in the biofilter cells.

Table 4. 5: Differences in the reduction efficiency of nutrient inputs by the biofilter cells and influence of physical parameters.

Variables	**NH_3-N**			**NO_3-N**			**NO_2-N**			**PO_4^{3-}**		
	F	df	Sig.	F	df	Sig.	F	df	Sig.	F	df	Sig.
Corrected Model	15.01	11	0.00	1.93	11	0.04	3.03	11	0.00	16.71	11	0.00
Biofilter	**12.78**	**5**	**0.00**	1.81	5	0.11	1.10	5	0.36	**23.86**	**5**	**0.00**
ECµSm	0.83	1	0.36	0.01	1	0.93	**21.58**	**1**	**0.00**	**19.77**	**1**	**0.00**
pH	0.99	1	0.32	**5.74**	**1**	**0.02**	**7.10**	**1**	**0.01**	**5.70**	**1**	**0.02**
DO (mg/L)	**7.44**	**1**	**0.01**	0.05	1	0.83	3.96	1	0.05	0.91	1	0.34
ORP (mV)	**10.30**	**1**	**0.00**	0.10	1	0.76	1.51	1	0.22	0.03	1	0.85
Vol	0.15	1	0.70	**6.38**	**1**	**0.01**	0.38	1	0.54	0.20	1	0.66
Height	**8.64**	**1**	**0.00**	0.04	1	0.84	2.76	1	0.10	0.03	1	0.86

A positive correlation between change in water height and reduction of NH_3-N was established. A study by Kumar and Dutta, (2019) has also established that higher water depth with reduced flow velocity advances the nutrient removal rate. No positive correlation between the change in volume with the concentration of NH_3-N, nitrite and phosphate with exception of nitrate. The treatment and reduction rate of NH_3-N varied significantly across the biofilters over the HRT days (Biofilter x HRT days, F (18. 179) = 2.45 $P<0.001$, Table 4.5, Figure 4.5 (a-d), and was significantly influenced by EC F (1. 179) = 44.9 $P<0.001$). At <5 HRT days, the concentration of the NH_3-N in the LS (1.72±5.24, t=2.28 df=179 $p<0.05$) and the LSV (1.93±5.29 t=2.79 df=179 $P<0.001$) was significantly lower than the concentration in the influent (18.65±5.37), indicative of higher NH_3-N removal. No differences in the reduction of excess NH_3-N were detected between the biofilters at <10 HRT days. At <15 HRT days, the concentration of the NH_3-N in the LS (1.72±5.59, t= 2.20 df = 179 $p< 0.05$) and the LSV (-0.19±5.59, t= 2.45 df = 179 $p< 0.05$) was significantly lower than the influent (18.87±5.58), showing significant treatment and reduction of excess NH_3-N.

The concentration of NH_3-N in the LS and the LSV were also significantly lower than in the PP (22.26±6.59, t= -2.34 df = 179 $p< 0.05$); PPV (27.11±6.60, t= -2.94 df = 179 $p< 0.05$); PP (22.26±6.59, t= -2.59 df = 179 $p< 0.01$) and PPV (27.11±6.60, t= -3.16 df = 179 $p< 0.05$) respectively for the LSV. At >15 HRT days, the LS (4.10±6.56, t= 2.06 df = 179 $p< 0.05$) and LSV (-0.24±6.57, t= 2.53 df = 179 $p< 0.01$) were the best performers compared to rest of the biofilters. A significantly lower concentration of NH_3-N compared to the Influent (23.20±66) was established. The SS (2.28±6.57, t= 2.25 df = 179 $p< 0.05$) and SSV (2.19±6.61, t= 2.24df =

179 $p < 0.05$) were also significantly lower than the Influent; while the concentration in the LSV was also significantly lower than that in the PP (20.45±6.59, t= 2.82 df = 179 $p < 0.05$).

4.7.1 The application of NbS to improve water quality

It is clear from the literature and from this study that the quality of surface runoff coming from informal settlements contains elevated nutrient concentrations and other pollutants that are detrimental to the health of the freshwater resources. The need to improve water quality discharged from informal settlements is evident from several studies as discussed in the previous chapters in studies by (Omulo *et al.*, 2021; Amoah *et al.*, 2020; Leuta *et al.*, 2020; Fell, 2017; van der Hoven *et al.*, 2017; Nyenje *et al.*, 2014; Winter and Mgese, 2011). This study builds on the existing knowledge by these and several other researchers by demonstrating the highest influent median concentrations of 8.1 mg/L, and 2.86 for NH_3-N and PO_4^{3-} respectively collected form the surface runoff at the Water Hub. These concentrations are relatively high compared to the 2.5 mg/L and 1.5 mg/L for NH_3-N and PO_4^{3-}-P respectively which were high in urban nutrient concentrations for synthetic stormwater prepared from analytical grade compounds as reported by (Jacklin *et al.*, 2022). However, the NH_3-N and PO_4^{3-} concentrations in this study fall within similar ranges as presented in Table 2.2 (chapter 2 of this thesis) for expected pollutant concentration ranges for categories of residential catchments in South Africa (Asante, 2008b).

This study has contributed to new knowledge and filled gaps in application and understanding of a field scale NbS in a form of a biofilter to treat and reduce nutrient rich surface runoff generated from an informal settlement to reuse the treated effluent as a resource such as, irrigation of food crops in a food insecure and water scare South Africa. The lack of evidence-based research that would examine the effectiveness of NbS interventions to improve water quality coming from informal settlements is an indication that this study is novel. The novelty of this study experimental design also stems from its unique location of the biofilter cells which provided an opportunity to capture pollution coming from the informal settlement upstream, with the Stiebeuel River being the major carrier of polluted surface runoff downstream.

This study has reported one of the highest nutrient treatment and reduction values for a field scale biofilter with an average HRT of 8 days. This 11 months-based research has shown that LSV and SSV were the best biofilter cells in the overall treatment and reduction of elevated NH_3-N, PO_4^{3-} and NO_2-N with 98 percent, 90 percent and 78 percent reduction in the LSV, LSV and SSV cells respectively. A study by Fitchett, (2017a) does not provide evidence-based water quality data on the effectiveness of the selected SuDS interventions (permeable channels and soakaways) to improve water quality by treating and reducing elevated nutrient concentrations coming from an informal settlement, as the study consisted of limited number of samples (two sets of data). The recent study by Jacklin *et al.*, (2022) in South Africa compares the performance of six column plant biofilter designs receiving low, typically observed and high urban nutrient synthetic stormwater pollution for five months.

However, this synthetic stormwater runoff does not contain characteristics of the surface runoff discarded from informal settlements. However, the study by Jacklin *et al.*, (2022) reported effective NH_3-N load treatment of 98 percent mean reduction in the following biofilter designs, Up-flow filtration, Plenum Aeration, and Saturated Zone column biofilters. Jacklin *et al.*, (2022) also reported effective mean PO_4^{3-} reduction of 81 percent, with Up-flow filtration, Plenum Aeration, and Saturated Zone column biofilters being the best performing biofilter cells.

4.8 Conclusion

Informal settlements are renown point and diffuse sources of nutrient pollution in the African continent. The degree of pollution varies between informal settlements depending on the presence or condition of municipal infrastructure being the first crucial step in managing the current state of surface runoff from informal settlements. South African informal settlements are built on land which is eighter privately owned or not suitable for infrastructural development and near watercourses thereby discharging wastewater into receiving water bodies without treatment (Huamán *et al.*, 2022).

Several South African informal settlements have varying degree of grey infrastructure which are ineffective in reducing the quantity and quality of polluted surface runoff before being discharged into receiving water bodies. The literature in conjunction with the results of this study has shown that selected NbS have emerged as a positive response towards degradation of elevated nutrient levels and other pollutants of concern.

More so because, the use of wastewater for irrigation of agricultural products is a common practice around the world (Abdallah and Mourad, 2021; Jeong *et al.*, 2016). About 20 million hectare of land is estimated to have been irrigated worldwide using wastewater (Abdallah and Mourad, 2021). Several techniques may have been used worldwide to treat wastewater for irrigation purposes. This study has demonstrated that performance of nature based biofiltration cells can effectively be used in the treatment and reduction of nutrients at varying degree of concentrations. The table below summaries the performance of the treated water from each of the biofilter cells.

The recent drought conditions (lack of rainfall to replenish the water reservoirs and dams) experienced in the Western Cape and Eastern Cape has put pressure on the respective municipalities on the ability to provide safe drinking water to household. More so for agriculture as it is the largest consumer of water mainly for irrigation purposes. The treatment and reuse of the polluted water using several context-specific NbS solutions (in this case a biofilter) is critical in a water-scarce and food-insecure South Africa. The effectiveness of the selected NbS to treat and reuse the polluted surface water runoff was demonstrated in this study. However, the effectiveness of the NbS to treat pathogens and reuse of the treated water that meets the target water quality ranges as per the South African and International irrigation guidelines for irrigation of food crops must be examined in subsequent research studies.

Table 4. 6: The median and 95th percentile concentrations of the treated water quality in the biofilter cells and influent against the SA and WHO irrigation limits

Biofilter cell	Determinant	Physical and Chemical Water Quality Constituents							
		NH_3-N	NO_3-N	NO_2-N	PO_4^{3-}	EC	pH	DO	ORP
	Unit	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(μs/cm)	pH unit	(mg/L)	
	SA irrigation limit	5	5	5	-	40 (400)	6.5 - 8.4	-	-
	Unacceptable	30	30	30	-	-		-	-
	WHO limit	5	5	5	-	<0.7dS/m (700μs/cm)	6.5 - 8	-	-
Influent	Median	8.1	1.30	0.10	2.86	347	7.4	3.20	155
	95th percentile	40.26	6.50	0.53	5.61	978	7.7	5.42	241
LSV	Median	0.88	2.50	0.02	0.26	474	7.1	2.20	138
	95th percentile	11.24	6.14	0.54	3.32	695	7.6	4.50	242
LS	Median	2.40	2.20	0.03	0.53	328	6.9	1.80	133
	95th percentile	10.72	5.96	0.51	3.23	704	7.4	4.26	240
PPV	Median	7.40	1.80	0.06	2.92	239	6.1	1.50	118
	95th percentile	31.78	7.86	0.18	7.19	865	7.4	3.84	181
PP	Median	7.20	2.20	0.05	4.16	216	6.0	1.10	131
	95th percentile	30.88	6.84	0.48	8.60	865	7.3	3.92	198
SSV	Median	3	1.50	0.02	3.10	277	6.4	2.10	42
	95th percentile	6.14	4.80	0.39	5.65	552	6.6	3.76	154
SS	Median	2.50	1.60	0.02	0.42	235	6.3	2	78
	95th percentile	8.12	8.06	0.53	2.88	615	6.7	4.24	152

Legend	
TN	Colour description
5_30	🟧
>30	🟥
pH	Colour description
< 6.5	🟥
PO_4^{3-} (mg/L) as per FAO guidelines	Colour description
>2	🟥
EC (μs/cm)	Colour description
> 400 (Exceeds SA water quality irrigation guidelines only)	🟦
>700 (Exceeds both SA irrigation and WHO guidelines for wastewater use in agriculture)	🟥

SA irrigation guideline limits and WHO guideline limits must be read in conjunction with crops nitrogen requirements. This is to prevent high concentrations which may cause lodging, delayed crop maturity, poor quality excess nitrogen and bioaccumulation in food crops that could pose a risk to human health.

The median and 95th percentile concentration of NH_3-N in the influent was the highest exceeding both the SA irrigation limit and WHO limit of 5 (mg/L) respectively. Similarly, the effluent NH_3-N median concentrations for electrical conductivity exceeded the SA irrigation limit. However, the 95th percentile of the incoming (influent) NH_3-N concentration was 40.77 mg/L which was unacceptable as per the S.A irrigation guideline limits. Excessive nitrogen application (above the recommended guidelines) may introduce extreme leaf growth and lodging, delayed or poor crop quality (Titshall, 2020). However, sensitivity of crops tend to vary with crop growth stage as high nitrogen concentrations for example can be valuable during the initial growth stage compared to the later stage (Lee, 2012).

The median values of the treated effluent from the SSV and SS cells for NH_3-N, NO_3-N, NO_2-N and EC were below the SA irrigation guideline limits and WHO guideline limits. The median concentration levels for NH_3-N, NO_3-N, NO_2-N in the LSV and LS were below the recommended 5 mg/L S.A irrigation guideline limits and WHO guideline limits. This broadly reflects that nitrogen concentration is low enough not to affect sensitive crops which includes grapes and most fruit crops under normal irrigation applications (Department of Water Affairs and Forestry, 1996b).

The median EC concentrations were slightly above the recommended 400 µs/cm as per the S.A irrigation guideline limits. Therefore, treated effluent from the SSV, SS, LSV and LS can be used with caution to irrigate sensitive crops such as grapes and most other fruit crops may be affected when total nitrogen concentrations in irrigation water exceed 5 mg/L. Several other crops are suitable to be irrigated with treated effluent from the biofilter cells were median and 95th percentile is below the 30 mg/L since many other crops will remain relatively unaffected. The South African water quality guidelines, volume 4: agricultural irrigation categorises the risk associated with nitrogen irrigation on crop yield based on the four broad concentration guidelines. However, these can be used as guidelines since they are generic and do no cover site specific conditions such as climate, crop type and irrigation management. The guidelines do not list number of crops with various tolerance levels in terms of nitrogen concentration. Instead, it provides a list of various crops sensitivity levels to EC (since crops have different salt tolerant levels) which are tabled in appendix 4 of this thesis. The guidelines do not include the various tolerance concentrations for the list of crops.

CHAPTER FIVE CONCLUSION AND RECOMMENDATIONS

5.1 INTRODUCTION

Informal settlements are well known source of surface runoff pollution as described and documented in several studies (Chen *et al.*, 2022; Abia *et al.*, 2017; Nyenje *et al.*, 2014; Winter *et al.*, 2010; Carden *et al.*, 2008). The polluted surface runoff is often discharged without any form of treatment to reduce pollution load before it is discharged into the receiving water bodies. This study aimed at contributing to the knowledge of understanding the efficacy of the field scale biofilter for treating and reducing elevated nutrient concentrations generated from an informal settlement. One measure of the ability of biofiltration treatment is to achieve a water quality standard that is safe for the irrigation of edible crops.

This chapter concludes on the key and significant findings of this study and an evaluation of the aim and objectives. The recommendations for further research are also discussed. The study aim was addressed by undertaking and establishing the following objectives:

- **Objective one**: Measure the nutrient concentrations in surface runoff coming from the informal settlement over the sampling period.
- **Objective two**: Examine the nutrient (PO_4^{3-} and Total Nitrogen (NH_3-N, NO_3-N and NO_2-N) reduction rates from the six biofilter cells (packed with various media) against the influent concentrations.
- **Objective three**: Assess the best performing biofilter cells and evaluate the risk of treated water reuse to acceptable water quality concentrations suitable for irrigation of edible crops in a water-scarce, food-insecure country like South Africa.
- **Objective four**: Determine the influence of nature-based processes, media type, HRT and flow regime on the performance of biofiltration cells in the treatment and reduction of excess nutrients.

Despite the limited data of nutrient pollution concentration from sub–Saharan Africa informal settlements, the literature in chapter two of this study points out to informal settlements as the major cause of surface water pollution and nutrient enrichment through uncontrollable and untreated wastewater discharge into the receiving water bodies. Several studies examining water quality pollution from informal settlements have different sampling procedures, methods and objectives, making it difficult to undertake meaningful comparison. In this study, the mean (3.18 mg/L) and median (2.86 mg/L) PO_4^{3-} concentrations were higher compared to mean PO_4^{3-} (0.36 mg/L) base flow concentration reported in the Nsooba channel and within the PO_4^{3-} concentration range (2- 4.8 mg/L) recorded in the Bwaise slum Northwest of Kampala, in the capital city of Uganda as reported in a study by (Nyenje *et al.*, 2014). It is of utmost importance in a country with a water shortage and food insecurity to evaluate the efficacy of nature-based processes integrated into field scale biofiltration cells to treat and reduce nutrient-rich stormwater runoff from a South African informal community.

Over the years, a large body of literature has reported on the performance of NbS in the treatment and reduction excess nutrients in developed urban catchments around the world (Huamán *et al.*, 2022; D. H. Kim *et al.*, 2021; Dhadwal *et al.*, 2021; Di Capua *et al.*, 2020; Shen *et al.*, 2018; Milandri *et al.*, 2012). Biofiltration cells have been shown to have treatment efficiency of up to 70 percent, 80 percent, and over 95 percent for nitrogen, phosphorus, and suspended particles, respectively, in urban stormwater runoff (Zhang *et al.*, 2021; Aryal *et al.*, 2010; Blecken, Zinger, Deletic, *et al.*, 2010). Using several indigenous plant species, a biofilter setup was shown to lower PO_4^{3-}, ammonia, and nitrate by an average of 81 percent, 90 percent, and 69 percent, respectively (Milandri *et al.*, 2012). Phosphate and nitrogen levels in biofilters receiving domestic wastewater were reduced by 63 percent and 34 percent, respectively. The suspended solids removal efficiency was greater than 95 percent, confirming the findings of the study by Rasool *et al.*, (2018).

In comparison to non-vegetated biofilters that export significant amounts of nitrate and nitrite, Goh *et al.*, (2019) found that vegetated biofilters treat 59–79 percent of total nitrogen and 77–94 percent of total phosphorus. According to Morse *et al.*, (2018), vegetative uptake of nutrients accounts for 39-60 percent of total nutrient uptake through plant assimilation. On the other hand, Blecken *et al.*, (2010) reported a removal rate of 96 to 30 percent in vegetated biofilters. The treatment efficacies, he found, are dependent on the plant species used in CW'S or biofilters.

Blecken *et al.*, (2010) studied the effectiveness of a stormwater biofiltration system in removing nutrients and silt in cold temperatures. Seasonal fluctuations have a major impact on nutrient removal, according to the study. Temperature, for example, has been shown to have a major impact on ammonium fixation, microbial nitrogen, and phosphorus sorption to soils. The general consensus is that the effectiveness of NbS in South Africa, which is a semi-arid country with a variable climate and limited water resources due to longer periods of dry weather, will yield different results from those used in Europe or in a mesocosm study in other parts of the world with different climatic conditions. However, in the South African context, there is a paucity of evidence-based literature to support the idea that temperature effects nutrient treatment in nature-based systems such as wetlands and biofilters, to name a few.

As a result, key points that this and future research can help bridge the gap include producing evidence-based research that investigates the capabilities of biofilters or constructed wetlands in mitigating (through nutrient recovery and effluent reusability) stormwater runoff from informal settlements for a variety of non-portable water uses. Secondly, because South Africa is a semi-arid region with high density urban informal settlements and relatively high nutrient concentrations, the research focus should be on determining how seasonal fluctuations effect SuDS options nutrient reduction rates. Thirdly, to evaluate the performance and progress of present designs, resulting in recommended components (such as the use of a mulch layer or a submerged zone) and plant types for the effective treatment of nutrient-rich surface runoff.

This study makes a contribution to new knowledge, filling gaps in knowledge and build on existing biofilter knowledge as demonstrated in the framework in Figure 5.1 below.

New knowledge: The context of the study is unique from many the studies in urban catchment across the world because the study took place directly downstream of the informal settlement at an abandoned WWTW now called the Water Hub as shown in Figure 1.1 of chapter one of this thesis. The Water Hub research site and the Langrug informal settlement upstream share the same river system with 2 km between the informal settlement and the

Water Hub. It is clear from the diagram of the drainage network in chapter 3 (Figure 3.3) that the Stiebeuel River receives daily discharges from the informal settlement.

This is one of the first field scale biofilter cells to be applied and to produce long term results on the performance of biofilters in an informal settlement setting in South Africa. The study has introduced a unique methodology of comparison and understanding of the selected natural media performance under different HRT and flow volumes. The sampling method involved first discarding about 10 L of water that would have been stored in the PVC pipes before sampling was undertaken. This was to allow sampling of the water that been in contact natural media over the specified HRT. The advantage of introducing various HRT and flow volume method was that it was possible to establish the HRT and volumes in each cell associated with the best treatment and reduction efficacy.

Filling of gaps in knowledge: This is the one of the first study that has used off site biofiltration cells to treat nutrients to a water quality concentration fit for irrigation of food garden reuse. The use of the NbS in this study provides solution to the trending water scarcity issue by recovering and reusing polluted water for a crop irrigation as South Africa is water scarce and food insecure.

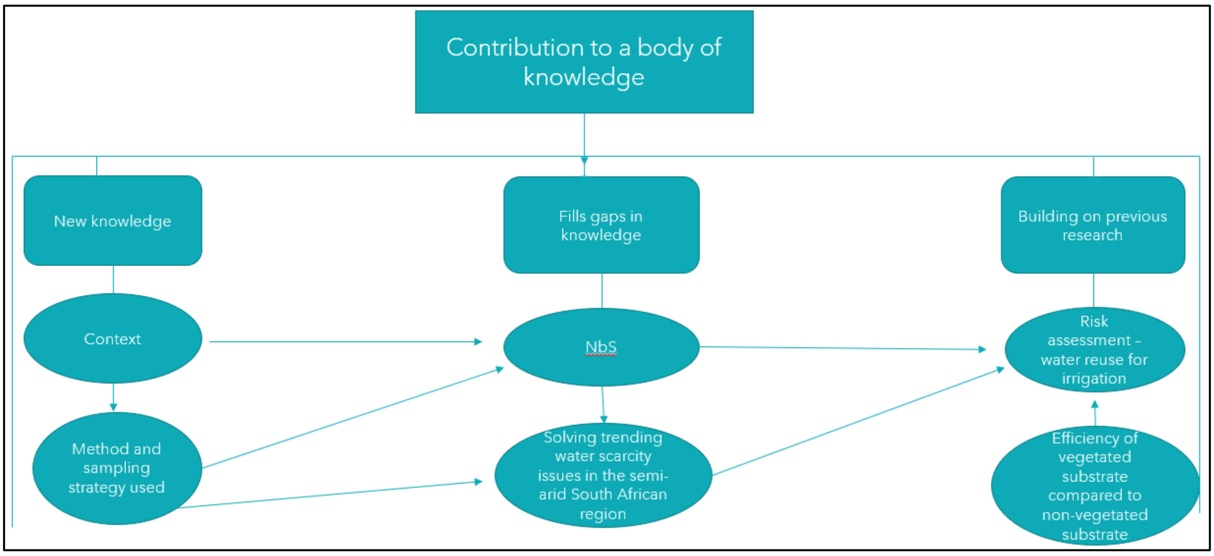


Figure 5. 1: Framework for this study contribution to knowledge

This study builds on the knowledge of several researchers such as Abdallah and Mourad, 2021; Delli Compagni *et al.*, 2020; Kgopa *et al.*, 2018; Rodda *et al.*, 2011) who have used different methods to treat and reuse wastewater for irrigation purposes. This study builds on existing knowledge in the international literature about the effectiveness of the biofilter (vegetated compared to non-vegetated) including the risk of reuse for crop irrigation. Wastewater use without treatment for irrigation of food crops such as lettuce, eggplant and onion is common and largely informal in several African cities such as Nairobi, Ghana and Dakar as these crops have a rapid growth rates (Abdallah and Mourad, 2021).

5.2. Key research findings

Nutrient concentration discharged from the informal settlements of South Africa which lack stormwater drainage and household drainage system connected to the municipal infrastructure discharge elevated nutrients and other pollutants into receiving water bodies without treatment. The highest incoming nutrient NH_3-N concentration with mean concentrations of 16.27 mg/L were above those reported in the literature by (Chen *et al.*, 2022). The median NH_3-N concentration and 95th percentile concentrations of 8.1 mg/L and 40.26 mg/L respectively. which exceeded the South African DWA irrigation limit and WHO guidelines for irrigation of <5 mg/L. The median concentration level of 8 mg/L would indicate that sensitive crops likely to be affected (depending on magnitude of irrigation application) as per guideline concentrations in chapter 3, Table 3.2.

The highest NH_3-N concertation in surface runoff contributes to nutrient enrichment or eutrophication with sewage discharge from the informal settlement upstream being the source. The highest median EC concentration 347 µs/cm above the recommended South African DWA irrigation limit but below the 700 (µs/cm) WHO guidelines for irrigation were also recorded. The combination of the increased EC, NH_3-N and the lowest DO levels were indicative of the nutrient rich, degraded water quality coming from the informal settlement upstream of the Water Hub.

This shows that the dilution downstream of the informal settlement was not significant factor as the impacts (highest nutrient concentrations) persist downstream of the informal settlement through to the Water Hub research centre which converges with the Franschhoek River downstream.

The effectiveness of a field scale biofilter in treating and reducing nutrient concentrations to an acceptable water quality level suited for irrigation of edible crops in a water-scarce, food-insecure, and climate-constrained country like South Africa: Table 5.1 and discussion below presents the best field scale biofilter cells in the order of effectiveness and their individual ability to reduce excessive levels of nutrients. It is in the authors view that the biofilter could have been implemented upstream and yield similar treated effluent results as at the current location, as the input and environmental conditions are the same.

Table 5. 1: Illustrates the best performing cells in the treatment and reduction of elevated nutrients

Nutrient	**VISUAL ANALYSES**						**REDUCTION EFFICIENCY (%)**		**STATISTICAL ANALYSES**	
	Best Performer			**2nd Best performer**			**Best Performer**	**2nd Best performer**	**Best Performer**	**2nd Best performer**
	Median	**Mean**	**95th Percentile**	**Median**	**Mean**	**95th Percentile**	**Median %**	**Median %**	**Wilcoxon signed rank (non-nonparametric test)**	**Wilcoxon signed rank (non-nonparametric test)**
NH_3-N (mg/L)	LSV 0,88	LSV 2,74	SSV 6.42	LS 2,40	SSV 2,88	SS 12.72	LSV 98%	LS 75%	LSV	LS
$PO_4$3-P (mg/L)	LSV 0,26	LSV 0,71	LSV 3.60	SS 0,42	LSV 0,71	LS 3.78	LSV 90%	LS 80%	SS	LS
NO_3-N (mg/L)	SSV 1,50	SSV 1,85	SSV 5,21	SS 1,60	INFL 2,2	LS 6.28	SS 20%	SSV 18%	SSV	NONE
NO_2-N (mg/L)	LSV 0,2	SSV 0,06	PPV 0.44	LS 0,03	PPV 0,09	SSV 0.51	SSV 78%	LSV 75%	SSV	SS

Best Performer	LSV Cell
Best Performer	SSV Cell
2nd Best Performer	LS Cell
3rd Best Performer	SS Cell

I. **LSV**: The LSV cell was one of the best performing cells for treatment and reduction of PO_4^{3-} levels with the lowest median (0,26 mg/L), mean (0,71 mg/L) and 95th percentile (3,60 mg/L). In addition, the LSV cell had the lowest NH_3-N median concentration (2.74 mg/L) which is below the 5 mg/L set guidelines as recommended by the South African Water Quality Guidelines for irrigation water quality and WHO guidelines for safe use of wastewater. The LSV cell has shown the highest median reduction rate by percentage of NH_3-N and PO_4^{3-} with 98 percent and 90 percent respectively.

II. **SSV**: The SSV cell was one of the best performing cell for treatment and reduction of the NO_3-N levels with the lowest median (1,50 mg/L), mean (1,85 mg/L), 90th (4.40 mg/L) and 95th (5.21 mg/L) percentiles concentration levels. The median, average and 90th percentile concentration values were below the 5 mg/L recommended concentration as per the South African Water Quality Guidelines for irrigation water quality and WHO guidelines for safe use of wastewater, whilst the 95th percentile was slightly above the South African Water Quality Guidelines for irrigation water quality and WHO guidelines. Therefore, the treated effluent from the SSV cell can be suitable to irrigate several sensitive such as grapes, most fruit crops (less sensitive) are unaffected until nitrogen concentration is higher than 30 mg/L (DWAF, 1996).

III. **LS**: The LS cell was the second-best cell to treat and reduce the NH_3-N and NO_2-N with the median values of 2.40 mg/L and 0.03 mg/L respectively. Because the median values were below the 5 mg/L recommended concentration as per the South African Water Quality Guidelines for irrigation water quality and WHO guidelines for safe use of wastewater, the effluent can be used to irrigate sensitive crops and several other less sensitive crops. The LS exhibited the second highest median percentages for reduction of NH_3-N (75 percent) and PO_4^{3-} (80 percent) respectively.

The optimal conditions for nature-based biofiltration processes to effectively treat and reduce elevated nutrient levels show that vegetation, surface area, hydraulic residence time and microbial activity played a major role in the treatment and reduction of elevated nutrients. LSV and SSV were the best in the treatment and reduction of the nutrients. The visual and descriptive analysis have shown that adsorption followed by vegetation uptake in the LSV cell was the major treatment and reduction mechanism for PO_4^{3-} whilst nitrogen transformation depended on nitrification and denitrification rates within the system. Therefore, maximization of these processes in the field scale biofilter cells would improve on treatment of water quality, taking into consideration the biofilter operating conditions. In addition, large surface area for development of microbial activity was also effective in the treatment and reduction of PO_4^{3-} levels in the LS and SS biofilter cells. The influence of hydraulic residence time on the reduction of nutrients was variable throughout the study period.

It was established during the study that the highest NH_3-N treatment was recorded within < 5 days and >15 days in the LSV and SSV cells with 91 percent removal. The effectiveness of the <5 and > 15 days HRT was supported by several local and international research literature as discussed in the results section. A variation in the treatment and reduction rates of phosphorus across HRT and biofiltration was observed. This is because, it was established in this study that average phosphate reduction rates of 90 percent, 93 percent and 85 percent were observed in HRT days < 5 days, > 15 days and > 15 days in the SS, LS and LSV biofilter cells respectively. This observation indicates that both < 5 days and > 15 HRT days was sufficient in the treatment and reduction of phosphorus levels.

5.3. Recommendations

Based on the results of this study, the following recommendations for further studies can be outlined:

I. Further research work should focus on the effectiveness of field scale biofilter cells not only on treatment and reduction of *E.coli and total coliforms* discharged from the non to partially-sewered informal settlements but also emerging pollutants of concern.

II. The influence of temperature, seasonal variation and microbial activity contribution responsible for the treatment and reduction of nutrients and *E.coli* pollutants needs further attention.

III. The role of vegetation on the treatment of pollutants is widely research in the literature, However, the contribution of specific and locally harvested vegetation types in the treatment of nutrients and *E.coli* is limited in the African context.

IV. Variable biofilter design configurations with different sizes, natural media and flow volumes are recommended to assess the ability of nature-based processes in the treatment and reduction of pollutants without the use of chemicals for fit for purpose reuse.

V. This study further recommends assessment of PPV and PP cells (carbon source) infectiveness in the treatment nitrogen and PO_4^{3-} levels. The study should examine the entire value chain of the commercial peach pips to ascertain its chemical composition that may have caused biofilm to poorly attach on to the surface.

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APPENDICES

Appendix 1: Statistical results of the nutrient concentrations in the six biofiltration cells

Water Quality Parameter	**Statistical results**	**IN**	**LSV**	**LS**	**PPV**	**PP**	**SSV**	**SS**
NH_3-N	**Maximum**	43.2	21.6	27.6	33.3	35.4	6.5	14.4

(mg/L)	**Minimum**	0.1	0	0	1.3	2.2	0	0.02
	Median	8.1	0.88	2.4	7.4	7.2	3	2.5
	Std Dev	13.9	5.04	5.25	10.25	9.74	1.98	0.07
	90th percentile	36.5	6,6	8.9	30,7	26,2	5.7	5.0
	95th percentile	40,2	11,2	10,7	31,7	30,8	6.1	8.1
PO_4^{3-} (mg/L)	**Maximum**	6.6	5.4	3.9	7.9	17.7	13.2	5.5
	Minimum	0.4	0	0	0	0	0.3	0
	Median	2.8	0.2	0.5	2.9	4.1	3.1	30.4
	Std Dev	1.7	0.9	2.0	3.5	3.5	2.6	1.2
	90th percentile	5.23	1.44	2.1	5.2	7.7	5.2	2.0
	95th percentile	5.6	3.3	3.2	7.1	8.6	5.6	2.8
NO_3-N (mg/L)	**Maximum**	11.6	10.9	14	10.2	11	5.3	9
	Minimum	0.3	0	0.2	0.3	0.2	0	0.3
	Median	1.3	2.5	2.2	1.8	2.2	1.5	1.6
	Std Dev	2.6	2.2	2.4	2.8	2.5	1.3	2.5
	90th percentile	5.0	5.3	4.6	7.5	5.2	4.0	7.0
	95th percentile	6.5	6.1	5.9	7.8	6.8	4.8	8.0
NO_2-N (mg/L)	**Maximum**	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Minimum	0	0	0	0	0	0	0
	Median	0.1	0.02	0.03	0.06	0.05	0.02	0.02
	Std Dev	0.17	0.20	0.18	0.11	0.15	0.14	0.20
	90th percentile	0.52	0.52	0.48	0.15	0.25	0.1	0.51

	95th percentile	0.53	0.54	0.51	0.18	0.48	0.3	0.53

Appendix 2: Statistical results of the physical water quality variables in the six biofiltration cells

Water Quality Parameter	**Statistical results**	**IN**	**LSV**	**LS**	**PPV**	**PP**	**SSV**	**SS**
EC (µS/m)	**Maximum**	1060	744	739	883	876	585	665
	Minimum	159	200	174	113	159	190	152
	Median	544.1	454.8	415.4	339.7	359.4	312.2	309.4

	Std Dev	322.8	179.2	206.8	236.5	254.2	120.	163.4
	90th percentile	961.2	664.4	686.8	751.8	815	484.6	575.8
	95th percentile	978.8	695.4	704.2	684.6	865	552.2	615.4
pH	**Maximum**	7.8	8.2	7.6	7.5	7.4	6.7	6.9
	Minimum	6.6	6.2	6.2	5	4.9	6.2	5.7
	Median	7.4	7.1	6.9	6.1	6.0	6.4	6.3
	Std Dev	0.3	0.3	0.3	0.6	0.6	0.15	0.28
	90th percentile	7.7	7.4	7.3	7.2	7.2	6.6	6.7
	95th percentile	7.7	7.6	7.4	7.4	7.3	6.6	6.7
DO (mg/L)	**Maximum**	6.4	5.5	4.8	8	7	4.7	5.8
	Minimum	0.5	0.7	0.8	0	0.1	0.8	0.8
	Median	3.2	2.2	1.8	1.5	1.1	2	2.1
	Std Dev	1.4	1.1	1.1	1.5	1.5	1.0	1.1
	90th percentile	4.9	3.8	4.2	3.3	3.5	3.4	3.2
	95th percentile	5.4	4.5	4.2	3.8	3.9	3.7	4.2
ORP (Mv)	**Maximum**	249	255	252	248	205	158	207
	Minimum	0	32	48	0	0	0	0
	Median	155	138	133	118	131	42	78
	Std Dev	66.9	58.3	53.4	55.1	55.1	59.6	51.2
	90th percentile	216.6	239	225	159.8	185.8	143	139.8
	95th percentile	241	241.6	239.8	180.6	198.7	154.2	152.6

Appendix 3: Biofiltration cells and components

The biofiltration cells at the Water Hub - Franschhoek, 33° 53’ 53.62’’S; 19° 05’ 38.82’’E

Biofiltration cell: LSV (left) and LS (right)

Biofiltration cells: PP (left) and PPV (right)

Biofiltration cells: SS (left) and SSV (right)

Treated water catch pit

vegetable garden

Spinach irrigated with the treated water from the biofilter cells

LSV cell: Initial stages of the biofilter: 29th September 2017

LSV cell: 5 months later: 16 February 2018 (5 months later)

Appendix 4: Commercial crops classified according to Salt Tolerance Classes as illustrated in the South African water quality guidelines: volume 4: agricultural irrigation.

A) **Fruit and nut crops** (DWAF, 1996)

Sensitive	Moderately Sensitive	Moderately Tolerant	Tolerant
Almond	Castorbean	Fig	Date palm
Apple	Grape	Jujube	Guayule
Apricot		Olive	Jojoba
Avocado		Papaya	
Blackberry		Pineapple	
Boysenberry		Pomegranate	
Cherimoya			
Cherry, sweet			
Cherry, sand			
Currant			
Gooseberry			
Grapefruit			
Lemon			
Lime			
Loquat			
Mango			
Orange			
Passion fruit			
Peach			
Pear			
Persimmon			
Plum/prune			
Pomelo			
Raspberry			
Rose apple			
Sapote, white			
Strawberry			
Tangerine			

B) Vegetables (DWAF, 1996)

Sensitive	Moderately Sensitive	Moderately Tolerant	Tolerant
Bean	Broccoli	Artichoke	Asparagus
Carrot	Brussels sprouts	Beet, red	
Okra	Cabbage	Squash, zucchini	
Onion	Cauliflower		
Parsnip	Celery		
Pea	Maize, sweet		
	Cucumber		
	Eggplant		
	Kale		
	Kohlrabi		
	Lettuce		
	Muskmelon		
	Pepper		
	Potato		
	Pumpkin		
	Radish		
	Spinach		
	Squash, scallop		
	Sweet potato		
	Tomato		
	Turnip		
	Watermelon		