CIV5000Z: DISSERTATION FOR THE DEGREE OF A MASTER OF SCIENCE IN CIVIL ENGINEERING

Managing the Water Quality of the Zandvlei Estuary using Sustainable Drainage Systems in the Diep Catchment

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

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Abstract

The Zandvlei Estuary is the only functioning estuary-wetland river system along the False Bay coastline and is therefore of extreme ecological importance. The estuary has and continues to face threats from excessive amounts of sediments and nutrients that can destroy its functionality. Historically, Zandvlei’s most significant problems are eutrophication and siltation, which have occurred in the estuary due to elevated nutrient and sediment levels. Increased Total Inorganic Nitrogen (TIN) and Soluble Ready Phosphorus (SRP) are the primary causes of eutrophication in receiving water bodies. The excessive amounts of nutrients and sediments deposited into the estuary are a result of urbanisation and the subsequent change in anthropogenic activities in and around the Zandvlei’s catchments. Additionally, the increased impervious surface area associated with urbanisation has caused a significant rise in runoff volumes and runoff rates in the stormwater drainage systems.

In South Africa, stormwater drainage systems conventionally channel everything they collect into receiving water bodies without significant treatment or intervention to remove harmful substances. Sustainable Drainage Systems (SuDS) provide an alternative approach to managing stormwater runoff. Unlike the conventionally used stormwater systems designed with the singular goal of removing runoff, SuDS can provide both stormwater quantity and quality management while also allowing for the development of biodiversity and amenity.

This project investigated the viability of improving Zandvlei Estuary’s water quality by implementing SuDS in Zandvlei’s Diep Catchment. PCSWMM, a modelling software developed by Computational Hydraulics International (CHI), was used to develop seven models. Included was an As-is model, developed, calibrated and verified to represent the Diep Catchment in its current state, a Pre-development model that provided an estimate of the Diep Catchment’s runoff volumes and stormwater constituent loads before urban development altered the catchment, and five SuDS scenarios to test various treatment train designs. Pollutant indicators that were modelled included SRP, TIN, Total Phosphorus (TP) and Total Suspended Solids (TSS). SRP and TIN were included as they cause eutrophication, while TP and TSS were modelled as they are good measures of pollution.

Scenario 1 utilised Source Control SuDS to capture and treat runoff as close to its source as possible. Scenario 2 reintroduced four wetlands and two retention ponds into the main river network. The stormwater network currently only uses these wetlands and ponds as attenuation storage during large rainfall events. Scenario 3 proposed a large, constructed wetland at the confluent of the two major stormwater systems in the Diep Catchment, Langevlei Canal and the Diep/Sand River. Scenarios 4 and 5 utilised combinations of SuDS controls from Scenarios 1, 2 and 3 to create more holistic treatment train systems. Scenario 4 employed the Source Controls from Scenario 1 and the large, developed wetland in Scenario 3. Scenario 5 utilised two wetlands and a retention pond from Scenario 2 and the large wetland from Scenario 3.

The SuDS scenario results were compared to those obtained from the As-is Scenario to provide percentage reductions of indicator loads and runoff volumes. Additionally, the Pre-development results, which indicated the likely natural indicator loads and runoff volumes and thus probably best represented sustainable conditions, served as a benchmark against which all the modelling results could be compared. Scenario 5 provided the most significant mean reduction in indicator loads (57.3%), while Scenario 4 provided the largest drop in runoff volume, approximately 52%. As the primary goal of this project was the reduction in indicator loads, Scenario 5 would provide the most significant improvement in Zandvlei Estuary's water quality.

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Abbreviations & Symbols

BMP	Best Management Practice	NSE	Nash-Sutcliffe Efficiency
CHI	Computational Hydraulics International	PCSWMM	Personal Computer Stormwater Management Model
CoCT	City of Cape Town	PES	Present Ecological State
CSIR	Council for Scientific and Industrial Research	RI	Return Interval
DEM	Digital Elevation Model	SAWS	South African Weather Service
DS	Design Storm	SDG	Sustainable Development Goal
DWS	Department of Water and Sanitation	SHWT	Seasonally High Water Table
EC	Electrical Conductivity	SRP	Soluble Ready Phosphorus
ECSA	Engineering Council of South Africa	SuDS	Sustainable Drainage Systems
EHI	Estuarine Health Index	TDS	Total Dissolved Solids
EMC	Event Mean Concentration	TIN	Total Inorganic Nitrogen
ESRI	Environmental Systems Research Institute	TN	Total Nitrogen
GIS	Geographical Information System	TP	Total Phosphorus
GZENR	Greater Zandvlei Estuary Nature Reserve	TSS	Total Suspended Solids
HLR	Hydraulic Loading Rate	UCT	University of Cape Town
HRT	Hydraulic Retention Time	UN	United Nations
ISE	Integral Square Error	USEPA	United States Environmental Protection Agency
LID	Low Impact Development	WDT	Watershed Delineation Tool
LPV	Little Princess Vlei	WQV	Water Quality Volume
MAP	Mean Annual Precipitation	ZENR	Zandvlei Estuary Nature Reserve
NH3	Ammonia	ZPAAC	Zandvlei Protected Areas Advisory Committee
NO3	Nitrate		

1. Introduction

The Zandvlei Estuary is the largest of the eight estuaries along the False Bay coastline. It is located in Cape Town, South Africa and borders Marina da Gama, Lakeside, Steenberg, and Muizenberg. The three main rivers that feed the estuary are the Westlake, Diep and Keysers rivers. Along with the Langevlei Canal, Sand River Canal, and many unnamed seasonal flows, these rivers drain the southern extension and eastern slopes of the Table Mountain chain (Zandvlei Trust, n.d.).

The Zandvlei Estuary Nature Reserve (ZENR) is the only functioning estuary-wetland river system along the False Bay coastline and one of two functioning systems in Cape Town (Day *et al.*, 2020); it is therefore of extreme ecological importance. The estuary is home to a diverse range of fauna and flora, including several endangered species (IUCN, 2020). The system continues to face many threats such as sewage spills (Spatial Planning and Environmental Management Department, 2019), litter, excess nutrients, sediments, and heavy metals that can all devastate it (Adams et al., 2020).

The Greater Zandvlei Estuary Nature Reserve (GZENR) hosts multiple recreational activities. The Sea Scouts and Zandvlei Sports Club extensively use the estuary and surrounding areas. The False Bay Rendezvous, along with the paths and walkways, picnic areas, bird hides and the environmental education centre, provides a source of attraction for various user groups. The public often judges the water quality based on its aesthetics; as the water quality declines and causes the estuary to lose its aesthetic value, the public desire to use the estuary and its surrounds for functional and recreational use diminishes, while public health concerns may completely reduce the use of the estuary.

1.1 Research problem

Historically, the Zandvlei Estuary has not been used or protected sustainably as pollutants (litter and heavy metals) and other contaminants (excess nutrients and sediments) associated with agriculture and urban development have been allowed to flow directly into the estuarine system. As the estuaries' catchments became urbanised, the nutrient and sediment loads received by the estuary increased significantly, resulting in the estuary experiencing eutrophication and sedimentation, both of which were to the detriment of the estuary's functionality (Thornton et al., 1995). Eutrophication is the increase in nutrients utilised by plants, resulting in excessive plant growth (Brown & Magoba, 2009). A Situation Assessment for the Zandvlei Estuary (Coastal & Environmental Consulting, 2010) reported that eutrophication has frequently occurred in the estuary since 1994. The occurrence of dredging, deepening, and the introduction of invasive alien species into the estuary has further degraded the estuary's condition (ZPAAC, n.d.-b).

Zandvlei has three catchment areas: the Westlake Catchment to the west, the Keysers Catchment to the north-east and the Diep Catchment to the north (Figure 3-2). Zandvlei's catchments support multiple land uses with the most urbanized areas, including commercial and industrial zones found in the Diep Catchment (Coastal & Environmental Consulting, 2010). This project investigates how implementing Sustainable Drainage Systems (SuDS) may improve Zandvlei Estuary's water quality. The scope of the work was split into two parts, with the focus of this project being Zandvlei's Diep Catchment (catchments discussed further in Section 3), while research into the use of SuDS in the Westlake and Keysers catchments was being conducted simultaneously with this project by someone else.

1.2 Research justification

A link between the economy, environment and social wellbeing has been observed around the globe that has shown itself to be particularly strong in the developing nations and regions (Mihelcic et al., 2017). As the population and economies worldwide have continued to grow, the strain on the environment has increased drastically, causing many of the planet's primary ecosystem goods and services to be destroyed, degraded and unsustainably used to breaking point (Millennium Ecosystem Assessment, 2005).

In South Africa, the conventionally used stormwater drainage systems contribute to the degradation and eventual destruction of rivers and receiving water bodies. These drainage systems focus on removing stormwater runoff as quickly as possible with little to no regard for the runoff quality. They then direct everything they collect into receiving water bodies without significant intervention to remove harmful substances (Armitage et al., 2013).

Sustainable Drainage Systems (SuDS) provide a different approach to stormwater drainage. They are designed to manage stormwater quality and quantity while potentially protecting biodiversity and offering amenity (Armitage et al., 2013). SuDS are not currently widely used in South Africa; however, there is a growing awareness of their potential (Nyawo & Tanyimboh, 2018). In this project, the potential for protecting the Zandvlei Estuary and its catchments from receiving poor quality water through the use of SuDS was investigated.

1.3 Research questions and objectives

The primary research question was '*Would the implementation of SuDS in the Diep Catchment make a significant improvement to the water quality in the estuary?'*

The following secondary research questions helped address the primary research question:

- What contaminants are present in the estuary requiring intervention?
- What are the sources of these contaminants?

- What Sustainable Drainage Systems (SuDS) may be appropriate for use as intervention measures, and where might they be implemented?
- What contaminant loading reductions are achievable using the proposed SuDS?

1.4 Overview of the method

The overall goal of this project was accomplished through:

i) A desktop study of Zandvlei Estuary, the challenges it faces, its catchment areas, and the Diep Catchment rivers and stormwater drainage network.

ii) The collection of site-specific data, including a digital elevation model (DEMs), land use, soil types, rainfall records, streamflow data, and water quality data.

iii) The collection of water samples along the river network within the Diep Catchment to determine the key problem areas to supplement CoCT water quality data.

iv) The development of a numerical hydrological, hydraulic and water quality model in PCSWMM, a propriety urban drainage software package, of the Diep Catchment and its major river networks – the Diep/Sand River network and the Langevlei Canal system.

v) The consideration of various SuDS and treatment train scenarios to investigate their likely effectiveness.

vi) Comparing the modelled nutrient, sediment wash-off loads, and runoff volumes resulting from each scenario.

1.5 Limitations

Stormwater flows are complicated to accurately model. A catchment’s physical layout is highly complex and continuously changing. The rainfall characteristics within a catchment are also highly variable and may be subject to climate change (Armitage et al., 2013).

Acquiring sufficiently detailed data proved challenging during previous investigations surrounding the Zandvlei feeder rivers (Rohrer, 2017), and this was not different during this project. Limited data introduced uncertainty into the modelling process. However, the hydrological model was calibrated and verified to mitigate the impact of some of the uncertainties. Unfortunately, the water quality model could not be calibrated fully as no long-term water quality data was available. In order to overcome this lack of water quality data, grab samples were used to conduct some level of calibration for the water quality model. This research project is entirely theoretical; SuDS should be trialled at a pilot scale before implementing any new systems into the river networks.

1.6 Project layout

This report details the research project's outcomes and consists of ten chapters.

- Chapter 1 (this one) introduces the project. It includes the background to the study, the research problem, justification for the research, research questions, objectives, and project limitations.
- Chapter 2 presents a literature review on critical issues encountered in this research, including the process of defining an estuary's health condition, followed by a review of SuDS terminology, philosophy, types and design, and selection criteria. Investigations into water quality standards in South Africa, SuDS treatment ability and various stormwater modelling software complete the chapter.
- Chapter 3 investigates the study area and its current condition.
- Chapter 4 presents the method followed during the project. The modelling software utilised is discussed along with the modelling process. Further, it presents the data collection, analysis and processing procedures employed.
- Chapter 5 discusses the rainfall data utilised during the project.
- Chapter 6 details the hydraulic and hydrological model development, including the calibration and verification procedures.
- Chapter 7 presents the water quality of the study area, including water quality sampling and the collection of data from the CoCT.
- Chapter 8 details the various scenarios created in the model.
- Chapter 9 presents and discusses the results and findings of the various scenarios.
- Chapter 10 draws conclusions based on the various scenarios' results and provides recommendations for future research.

2. Literature Review

In this chapter, relevant published work on topics related to the proposed research project is discussed to give background context to the investigation. The chapter includes an overview of establishing an estuary's health condition, followed by details of SuDS terminology, philosophy, types and design, and selection criteria. An investigation of the South African water quality standards, the treatment potential of SuDS, and how to model water quality are provided. Additionally, the chapter provides a discussion of various stormwater modelling software packages.

2.1 Estuarine health conditions

An estuary's health condition is often classed using a Present Ecological State (PES) rating. The health condition is classified according to how the current conditions differ from its theorised natural conditions. The theorised natural or pre-development conditions are built up for each estuary using expert knowledge and available information and is described by one of six PES categories (Van Niekerk *et al.*, 2018 & Van Niekerk & Turpie, 2012). These categories range from a natural system with an A rating to a critically modified system with an F rating (Table 2-1). The dynamic nature of the physical conditions of estuarine systems means that the degradation of an estuary could potentially involve a system shift from a dynamic to an unproductive system (DWAF, 2008). The loss of functionality within a system indicates that the estuary's health is declining.

Table 2-1: Ecological Management Categories (DWAF, 2008)

Health Condition	**Description**
A	Unmodified and natural
B	Only a few alterations, but mostly natural.
C	Moderately modified. The essential functions and processes performed by the ecosystem still occur, but a loss of natural habitat is observed
D	Largely modified. A loss of natural habitat and basic ecosystem processes and functions has transpired
E	Seriously modified. A severe loss of the natural habitats and ecosystem processes and functions has occurred
F	Critically/Extremely modified. The system has lost almost all its natural habitats and ecological functions due to excessive modifications to the system

The PES category is based on a percentage score from the Estuarine Health Index (EHI). The index rating includes biotic (biological) factors and abiotic (habitat) factors. For each variable, five biotic and four abiotic, a score is generated based on the variance between the current condition and the theorised pristine health condition. Table 2-2 shows the biotic and abiotic factors. Scores are weighted separately and aggregated, as shown in Figure 2-1. The final system's rating reflects the current estuarine health conditions as a percentage of the ideal state. Table 2-3 presents the relationship between the EHI score and PES rating (Van Niekerk & Turpie, 2012).

Table 2-2: EHI Biotic and Abiotic Factors (DWAF, 2008)

Biotic Factors	Abiotic Factors
Microalgae	Hydrology
Macrophytes	Hydrodynamics and mouth condition
Invertebrates	Water chemistry (salinity and combined score for other variables)
Fish	Sediment processes
Birds	

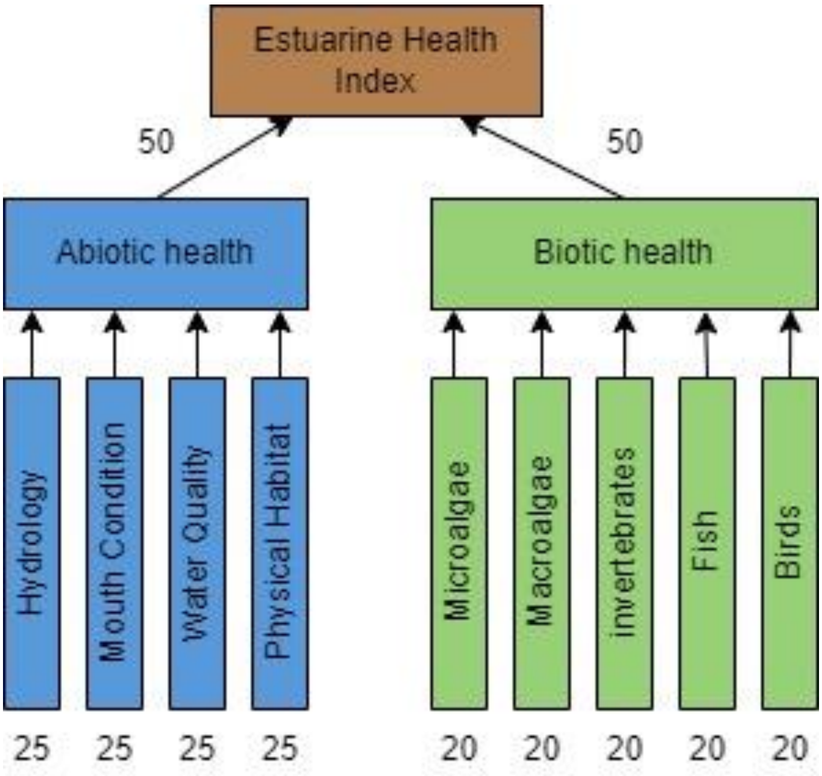


Figure 2-1: Weightings of Estuarine Health Index (DWAF, 2008)

Table 2-3: Relationship between EHI and PES (DWAF, 2008)

EHI Percentage Score		**≥ 91%**	**90-76**	**75-61**	**60-41**	**40-21**	**≤ 20**
PES	**Category**	A Natural	B Largely natural with few changes	C Moderately modified	D Largely modified	E Highly degraded	F Extremely degraded
	Rating	Excellent	Good	Fair		Poor	
Functionality		Retain Process & Pattern (representation)		Loss of Process or Pattern		No Process & Pattern	

2.2 Stormwater and Sustainable Drainage Systems

Stormwater runoff can be a significant concern for estuaries located within urban areas. As surface water runoff washes over urbanised areas it collects many pollutants that are in its path (Yang & Lusk, 2018). These pollutants range from nutrients, microbial contaminants, and organic matter to large amounts of suspended solids and toxic chemicals, such as hydrocarbons and trace metals. These contaminants originate in built-up areas such as roads, parks, industrial and commercial zones, and cultivated areas used for agriculture, golf courses, and gardens. Litter and other forms of solid waste are also significant components of the pollutants in stormwater (Van Niekerk & Turpie, 2012). ‘Diffuse pollution’ originates in various locations and is often collected by stormwater runoff. Direct sources of pollution, such as sewage pipe leaks or breaks, also pose a threat, but collectively diffuse pollution is often a more significant threat to ecosystems.

Conventional stormwater systems in South Africa focus primarily on the quick removal of runoff from urban areas to avoid damage to property or infrastructure. Runoff is directed towards rivers and other such surface water with little to no regard for the runoff quality. Very little thought goes into the amenity or biodiversity values of the system or the quality of the runoff it is channelling, and this frequently results in high levels of pollutants in the stormwater runoff. This runoff eventually flows into groundwaters, rivers, estuaries, and the ocean. It is becoming increasingly apparent that the conventional drainage methodology needs to be abandoned. A new approach that considers stormwater an integral part of the urban water cycle needs to be adopted (Armitage et al., 2014).

National and local governments around the globe are increasingly interested in sustainable development, including the management of stormwater and other surface water (Ellis et al., 2006). Sustainable Drainage Systems (SuDS) offer a fresh approach to the design of stormwater runoff drainage whereby the drainage components are designed to recreate holistic pre-development processes, in line with the principles of sustainable development (Armitage et al., 2013).

2.2.1 SuDS terminology

Stormwater drainage terminology has evolved due to the constant changes in urban drainage practices (Fletcher *et al*., 2015). The term SuDS began in the United Kingdom and has since been adopted in South Africa. Other terms for the same approach are used elsewhere. The term Low Impact Development (LID) is primarily used in New Zealand and North America. Best Management Practices (BMPs), principally used in the US and Canada, describe a system or practice to prevent pollution. In French-speaking countries, the term Alternative Techniques (AT) has been used to describe new techniques in the management of stormwater runoff since the 1980s. To avoid confusion, this project will consistently use the term SuDS for all similar approaches.

2.2.2 SuDS philosophy

SuDS attempt to maximise the positive impacts and benefits experienced from surface water runoff while minimising the negative impacts. Woods Ballard *et al*. (2015) discuss four elements associated with the SuDS philosophy: providing multiple benefits, mimicking natural hydrological processes, resilience to climate change and urbanisation, and enhancing development sustainability. These are further discussed below.

i) The provision of multiple benefits

To fully utilise SuDS and maximise the benefits experienced, they should be considered from the start of any development planning (Woods Ballard et al., 2015). The benefits provided by SuDS are site and layout dependent, and no two cases will be the same.

SuDS attempt to manage runoff as close to its source as possible. This reduces the risk of flooding downstream by lowering runoff volumes; however, SuDS also focuses on stormwater runoff quality and thus improves the quality of water received by rivers and water bodies (Jose et al., 2015). Additionally, SuDS allow for the development of blue and green corridors that link natural habitats and ecosystems.

Surface water in urban areas should be highly valued as it enhances the natural aesthetics and biodiversity, and people who use open spaces and local parks frequently perceive an improvement in their mental and physical health (Jose et al., 2015). Case studies show that an often experienced by-product of SuDS is increased property values (Ashley et al., 2018). The use of well-designed SuDS can develop resilience in urban areas in the face of an uncertain future (Ashley et al., 2018) by providing urban cooling and alternative sources of water supply.

ii) Natural hydrological process mimicking

Before humans began widespread urbanisation and the associated attempt to control the local environment, natural hydrological processes, such as infiltration and filtration, would have been extensive. However, when urbanisation began and land cover was altered, the natural hydrological processes were frequently diminished and destroyed (Butler & Davies, 2004). The increased impermeable land cover associated with urban development has decreased natural infiltration, groundwater recharge, filtration, storm peak attenuation, and transpiration. These are all essential factors in the water cycle balance (Woods Ballard et al., 2015).

The stormwater networks conventionally used in South Africa rely on a system of concrete pipes and channels to convey stormwater away from urban areas as quickly and efficiently as possible (Fisher-Jeffes & Armitage, 2011). The prioritisation of rapid runoff removal can create floods downstream as the water networks receive runoff flows and volumes larger than historically experienced. SuDS restore some balance by mimicking the natural hydrological cycle (Armitage et al., 2013). They remove some impermeable surfaces and aim to restore the critical elements of the hydrological cycle, including groundwater recharge and increased soil moisture (Woods Ballard et al., 2015). Runoff moves slower through SuDS than the conventional systems, making them effective storm peak attenuators. However, SuDS have a minimal impact on water quality during large, in-frequent storm events. SuDS are often integrated with conventional stormwater systems; this allows flows too large to be effectively managed by SuDS to be conveyed through conventional systems. Integrated systems can also reduce the risk of damage to SuDS from floods (Zhou, 2014).

iii) Climate change, severe rainfall, and urbanisation resilience

As rapid urbanisation and widespread climate change continue, cities worldwide are beginning to focus more and more on urban resilience. Resilience has been described in many ways, but the overall consensus is that it is the ability of a system to return to its natural stable state after a disturbance (Oladunjoye et al., 2019). For systems to be resilient in urban settings, they must maintain their functionality as temperatures rise and the risk of floods and droughts increase due to climate change (State of Green, 2015).

SuDS have the potential to enhance the resilience of the areas surrounding them. The storage of many SuDS provides flood protection through attenuation of runoff peaks and allows water harvesting to become a viable water source, enhancing the entire drainage network's resilience. The natural processes reintroduced by SuDS reduce stormwater volumes and improve quality while also reducing the heat island effect by blending water into the urban environment (Hong Kong - Drainage Services Department, 2018). Summer temperatures are expected to continue to rise in many parts of the world, and the urban cooling provided by SuDS could become increasingly important (Coutts et al., 2013). In areas serviced by combined sewer overflows (CSOs), systems that collect both stormwater and sewage, SuDS can reduce a city's energy requirements and carbon footprint. In 2005, some 70% of the urban sewer systems in

Europe were combined systems. However, in South Africa, most waterborne sewer systems are generally separate from the stormwater drainage systems (Stephenson & Barta, 2005).

iv) Enhance the sustainability of developments

Sustainable development promotes the improvement of quality of life for the current population while not compromising the quality of life for future generations. Developments need to be mindful of the limited nature of many natural resources and protect the natural processes of the environment while striving for economic growth (Woods Ballard et al., 2015).

Water is a finite element and must be preserved and reused as much as possible. SuDS allow developments to have a sustainable hydrological cycle in which water is not removed from a site but instead reintroduced into the cycle. In a water-scarce country, such as South Africa, this is an essential aspect of SuDS as rainfall patterns are highly variable. Using SuDS to manage runoff requires fewer resources and energy than conventional systems. It allows urban developers to create a holistic water management system that not only reduces runoff volumes but improves water quality, biodiversity and amenity while protecting the natural environment (Woods Ballard et al., 2015). For SuDS to effectively enhance urban development’s sustainability, they need to be integrated into the water management system throughout the development (Perales-Momparler et al., 2014).

2.2.3 SuDS design principles and objectives

SuDS offer a way to reduce many of the negative environmental impacts that stormwater has on receiving water bodies such as estuaries (Armitage *et al.*, 2013). The SuDS intervention components are designed in a multifaceted manner, with the critical objectives being the management of surface water runoff quantity and quality while maintaining biodiversity and improving the amenity of the runoff system. These objectives are achieved by attempting to mimic the natural hydrological cycle of the pre-development catchment. The objectives can be described as a hierarchy in which each additional layer enhances the sustainability of the system (Figure 2-2).

SuDS are generally arranged in a treatment train. A treatment train is a series of SuDS components set out along a watercourse. Each component incorporates a variety of unit processes (Section 2.2.4) designed to treat stormwater runoff. The use of a treatment train simulates the unit processes along a watercourse. Furthermore, if a single SuDS component were to fail, the entire system would not be compromised as the unit processes can be completed elsewhere (Armitage et al., 2013). Numerous international guidelines and manuals are available to guide the design of treatment trains. However, there have been no formalised rules regarding the level of treatment required from each SuDS sequence, thus, giving urban planners and designers flexibility in the choices made regarding treatment trains, and a large variety of designs have been used in various urban areas (Jefferies et al., 2008).

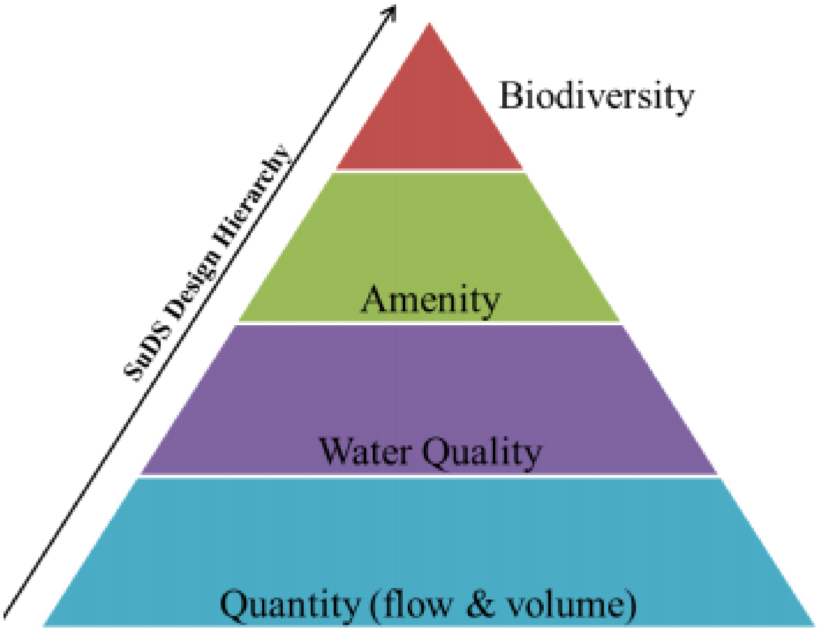


Figure 2-2: SuDS Design Hierarchy (Armitage et al., 2013)

Woods Ballard *et al*. (2015) suggest that the treatment trains should be designed in such a way as to prioritise either water quality control or water quantity control, depending on the flow volume. Water quality should be the focus for low flows, whilst for high flows, attenuation and volume control should be prioritised.

Various criteria have been proposed for effective SuDS design. The CSIR (2019) suggest that SuDS designs must satisfy the following criteria:

- Protection of the safety, welfare, and health of the public.
- Safely route and discharge all surface water runoff to protect property and developments.
- Improvement of the quality of life for all the communities affected.
- Conservation of water and allow access to the public.
- Preservation of the natural environment

These criteria can be achieved by designing SuDS interventions that are, as much as possible, based on the following principles (Woods Ballard *et al*. 2015):

- Utilise stormwater runoff as a resource
- Stormwater should be managed as close to its source as possible
- Stormwater should be managed on the surface

- Stormwater should be allowed to infiltrate the ground
- Evapotranspiration should be promoted
- Reduce contamination of stormwater through runoff source control and treatment
- Slow and store runoff

There are four key intervention stages along a treatment train, each of which is associated with various SuDS options (Armitage et al., 2013):

1. Good Housekeeping controls are measures employed at a site level to prevent or reduce the contact between runoff and pollutants. These should be included in site management plans (Woods-Ballard et al., 2007).
2. Source Controls manage stormwater runoff at or near the source (Section 2.3.1) (UCT UWM, 2013).
3. Local Controls manage the stormwater runoff in a local area or site, such as a neighbourhood or suburb (Section 2.3.2).
4. Regional Controls are responsible for the management of stormwater from multiple local areas. Regional Controls are the last interventions available before the stormwater enters receiving water bodies (Section 2.3.3) (Woods-Ballard et al., 2007).

The SuDS generally associated with each intervention stage are not limited to such and it is frequently possible to use them elsewhere (Armitage et al., 2013).

2.2.4 SuDS unit processes

Several unit processes may occur within each SuDS (Table 2-4 to Table 2-7). These unit processes promote various aspects of the natural hydrological cycle and are linked to one of the four fundamental design focuses of SuDS(Armitage *et al.*, 2013; Wilson *et al.*, 2004; Woods-Ballard *et al.*, 2007 & Woods Ballard *et al.*, 2015).

i) Water quantity processes

The runoff quantity from a site and the speed with which the runoff leaves a site are controlled to ensure that surface water runoff does not harm the environment, property, or people. Table 2-4 presents the processes utilised by SuDS to control the water quantity.

Table 2-4: Water Quantity Control Unit Processes
(Armitage *et al*., 2013; Woods-Ballard *et al*., 2007 & Woods Ballard *et al*., 2015)

Unit Process	Summary
Rainwater Harvesting	The capture of rainwater from where it falls. Often collected from rooftops and surrounding surfaces
Infiltration	The movement of surface water into the ground to reduce runoff and recharge groundwaters.
Detention	The temporary storage of runoff to reduce downstream flow rates
Conveyance	The transfer of stormwater runoff from one point to another
Long-term storage	The volumetric control of runoff during storm events to allow water to be released at the desired rate after the event
Extended attenuation storage	In the event of flooding, stormwater is retained to protect receiving watercourses. Necessary in events where no long-term storage is possible on site

ii) Water quality processes

Conventional stormwater drainage systems are designed to remove runoff from urban developments as quickly as possible. These systems do not treat the runoff for contaminants, and the high speed with which the water moves keeps sediments in suspension. SuDS are designed to control water quality and treat captured stormwater from urban areas. This protects receiving water bodies from the adverse effects of diffuse pollution. Table 2-5 describes the unit processes utilised by SuDS to control water quality.

Table 2-5: Water Quality Control Unit Processes
(Armitage *et al*., 2013; Woods-Ballard *et al*., 2007 & Woods Ballard *et al*., 2015)

Unit Process	Summary
Sedimentation	Reduction of flow velocity to allow sediment particles to settle and consolidate
Filtration and biofiltration	Removing contaminants and sediments from water by moving them through a filter. Often living materials (vegetation on a geotextile or soil matrix) are used as a filter
Adsorption	The adherence of stormwater pollutants to sediment particles
Biodegradation	The use of microorganisms to degrade organic contaminants in stormwater
Volatilisation	The conversion of stormwater runoff compounds to vapour or gas and subsequent transfer to the atmosphere
Precipitation	A chemical reaction between a control structure aggregate and a pollutant that causes suspensible insoluble precipitates to form
Plant-uptake	The use of plants to remove contaminants in runoff
Nitrification	The biological oxidation of ammonium and ammonia ions in stormwater runoff to form nitrite, often followed by the oxidation of nitrite into nitrate
Photosynthesis	The breakdown of organic substances within runoff due to extended exposure to sunlight

iii) Amenity Processes

Urban designs should deliver helpful, attractive, and liveable environments that improve local communities. SuDS manage surface water so that it is integrated into urban design. It becomes visible and audible as the water is managed above the ground. Areas where this occurs are often where stormwater is valued the most. Liveability also falls under amenity. Liveability concerns the local community's wellbeing and comprises education and safety, among other things. SuDS, designed to enhance amenity, can provide helpful, attractive, and liveable environments through the unit processes outlined in Table 2-6.

Table 2-6: Amenity Management Unit Processes

(Armitage *et al*., 2013; Woods-Ballard *et al*., 2007 & Woods Ballard *et al*., 2015)

Unit Process	Summary
Health and safety	Control measures implemented with SuDS to mitigate the possibility of injury or death caused by the SuDS
Environmental risk assessment and management	Assessment and management of the environmental aspects of a site that may reduce a SuDS lifespan and functionality
Recreation and aesthetics	Implementation of interactive and aesthetically pleasing facilities
Education and awareness	Sharing knowledge of stormwater management to interested and affected parties

iv) Biodiversity processes

Biodiversity incorporates all living things and their number, distribution, and abundance on earth. Around the world, biodiversity is being placed under extreme pressure due to human activities and species are dying out (State of Green, 2015).

It is possible to enhance an urban environment's value by utilising landscape features that promote healthy and stimulating environments with diverse habitats. SuDS can significantly enhance the biodiversity of a catchment or development. Although it is possible to provide biodiversity in small, isolated SuDS, the best results are achieved when SuDS are placed strategically to provide an interconnecting network. Table 2-7 summarises the unit processes utilised by SuDS to promote biodiversity.

Table 2-7: Biodiversity Management Unit Processes

(Armitage *et al*., 2013; Woods-Ballard *et al*., 2007 & Woods Ballard *et al*., 2015)

Unit Process	Summary
Protection	The identification and protection of indigenous fauna and flora
Maintenance of habitat	The removal of litter, contaminants and alien and invasive species
Monitoring	Early problem detection and intervention by observing fauna and flora

2.2.5 Selection criteria

Several important aspects must be considered before designing a stormwater system. SuDS are primarily selected based on the characteristics of a particular site. No two sites are identical, so no single solution works for each development. Additionally, it is improbable that all available SuDS components will be feasible on any given site; therefore, it is important to understand the limitations and advantages of each component before making a selection. The following aspects should be considered before designing a new stormwater system (Armitage *et al.*, 2013; Wilson *et al.*, 2004 & Woods Ballard *et al.*, 2015):

- Current and future land use characteristics
- Catchment characteristics, such as soil types, the hydrological cycle and the processes that may have been interrupted
- Stormwater runoff quantity (peak flow and flood volume) requirements
- Stormwater quality requirements
- Amenity and Biodiversity requirements
- The challenges associated with both retro-fitted, brown-field, and green-field developments. In developing countries, such as South Africa, the implementation of SuDS is most often in new developments

Woods Ballard *et al*. (2015) state that the size and number of SuDS utilised in a particular treatment train are dependent on:

- The sensitivity of receiving water bodies
- Contributing catchment size upstream of the treatment train
- The pollution levels to be expected in the stormwater runoff received by the treatment train

Ecosystem goods and services (EGS) also play a role in selecting SuDS. EGS are defined as '*all possible goods and services that benefit human livelihoods, produced by ecosystem processes involving the interaction of living environmental elements*'. These services may be used as performance indicators for SuDS that have been implemented as they encompass the very philosophy surrounding SuDS. Well-functioning SuDS and treatment trains should provide at least some of the following services (ASLA, 2009):

- Regulate the climate
- Purify the water and air
- Regulate water supply
- Control sediment and erosion

- Mitigate the hazards from extreme rainfall, storm surges and flash floods
- Preserve habitat
- Treat waste
- Benefit human health, well-being, and culture

As with every aspect of a development project, there are risks associated with using SuDS. For example, the creation of waterbodies could introduce a drowning risk. Therefore, a risk assessment should be carried out; SuDS should not introduce an additional source of risk into any community (Armitage et al., 2013).

Good treatment train designs utilise spaces to their maximum capacity. SuDS can be retrofitted into even the smallest of areas; thus, an apparent lack of space is not an excuse for not using them (Woods Ballard et al., 2015). In urban developments, where usable space is often an issue, the treatment train design becomes increasingly important and SuDS that can perform multiple functions should be utilised.

2.3 Types of SuDS

The South African Guidelines for Sustainable Drainage Systems (Armitage et al., 2013) present commonly used types of SuDS. Seven of the most used SuDS options are detailed here (Armitage *et al.*, 2013; Perrin *et al.*, 2009; Rossman & Huber, 2016 & Woods Ballard *et al.*, 2015); additional SuDS are described in Appendix A.

2.3.1 Commonly used Source Controls

Source Controls manage stormwater runoff as close to its source as possible. Source Controls are often the second link in a treatment train, implemented after ‘Good Housekeeping’.

i) Rooftop Disconnections

Rooftop disconnections (Figure 2-3) are a simple way to reduce runoff volumes. Runoff from rooftops generally flows directly into a conventional stormwater drainage system. Rooftop disconnection reconfigures the gutters and down water pipes to discharge the runoff onto pervious surfaces such as landscaped areas, lawns or planters. For a significant reduction in runoff volume, rooftop disconnections would have to be implemented on a large scale.

Figure 2-3: Rooftop Disconnection discharging onto a pervious lawn (CHI, 2019)

ii) Rain Gardens

Rain gardens (Figure 2-4) are landscaped depressions (Perrin et al., 2009). They can capture and treat stormwater runoff by passing the water through engineered soil that promotes filtration and biological uptake (Melbourne Water, 2013). Additionally, they can provide storage, evaporation, and infiltration. They are often found in residential areas/gardens but are also utilised in parks and other open areas.

Figure 2-4: Residential Rain Garden (CHI, 2019)

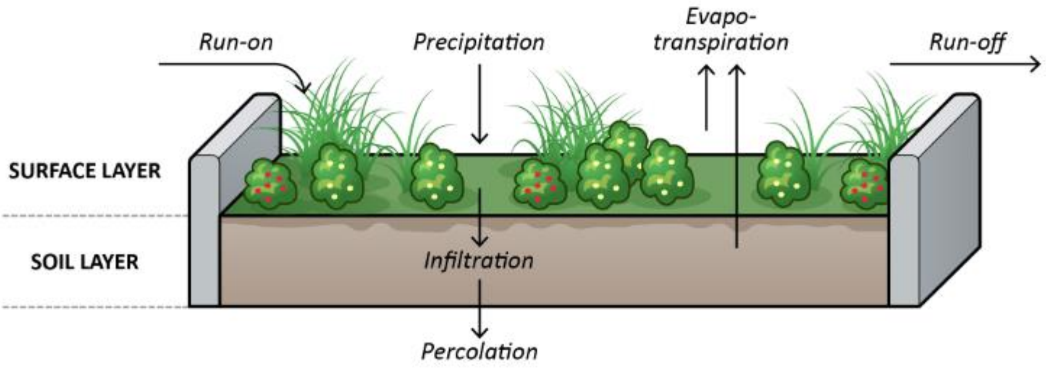


Figure 2-5: Rain Garden Conceptual Model (CHI, 2019)

2.3.2 Commonly used Local Controls

Local Controls are responsible for managing stormwater runoff in local areas such as neighbourhoods or suburbs. These controls often follow on from Source Controls in the treatment train.

i) Swales

Swales are shallow channels or depressed areas designed with trapezoidal or rectangular cross-sections, sloping sides and flat bottoms (Figures 2-6 & 2-7). They are lined with vegetation to slow runoff flow, grass being the primary vegetation used. Swales convey runoff and capture pollutants while providing biodiversity and aesthetic enhancements. They are often used to replace conventional stormwater network pipes to convey stormwater (Woods Ballard et al., 2015). Armitage *et al*. (2013) note that swales can be combined with other SuDS as a pre-treatment system. The treatment train design allows stormwater management to be more sustainable and efficient.

Although swales are generally utilised as a conveyance structure, they may be combined with berms to increase temporary storage and retention time, allowing for more significant infiltration and pollutant capture. Variations of swales exist, the selection of which is dependent on the situation. Conveyance swales convey runoff from one section of a catchment to another and may direct runoff to a particular stage in a treatment train. Dry swales are the same as conveyance swales but include a filter bed with a prepared soil layer overlying an underdrain. The underdrain and soil bed allow for increased treatment and prevents the swale from becoming waterlogged. Wet swales are designed to ensure a wet marshy condition in the swale base. These are often utilised to increase an area’s biodiversity and amenity value (Woods Ballard et al., 2015). Wet swales may occur unintentionally if the seasonally high water table SHWT is allowed to intersect a swale base (Perrin et al., 2009).

Figure 2-6: Vegetated Swale (CHI, 2019)

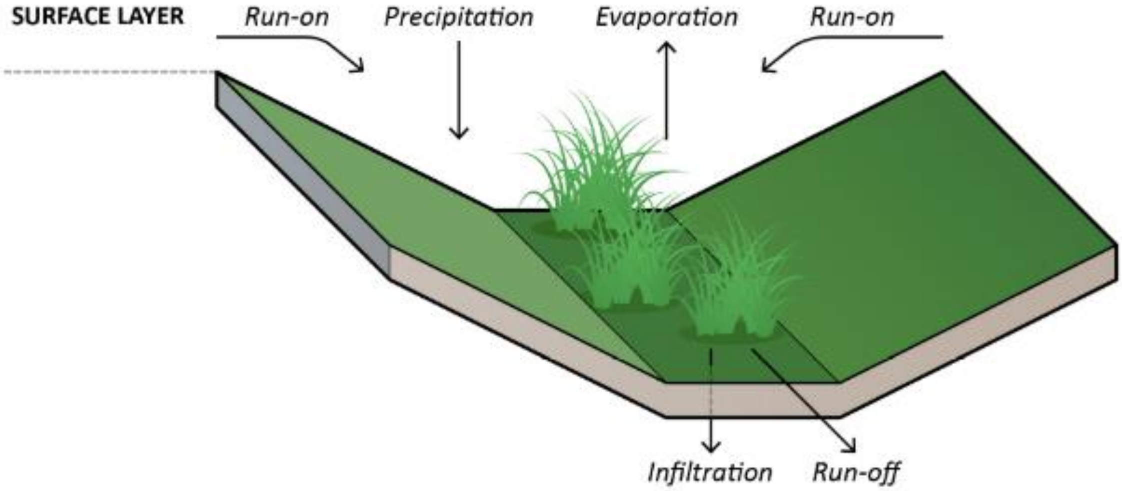


Figure 2-7: Vegetated Swale Computational Model (CHI, 2019)

ii) Infiltration Trench

These are linear, narrow ditches containing large granular material, such as rubble, gravel, or rock, that promotes voids' formation and provides temporary runoff storage before it can infiltrate into the surrounding soil (Figure 2-8). Infiltration trenches are linear in design, allowing infiltration to occur across various soils (Woods Ballard et al., 2015). A perforated drainage pipe may be included in the design if the surrounding soils are not conducive to infiltration. Large solids may clog the voids in the trench, and appropriate pre-treatment systems may be required (Hubert et al., 2013).

Figure 2-8: Infiltration Trench (CHI, 2019)

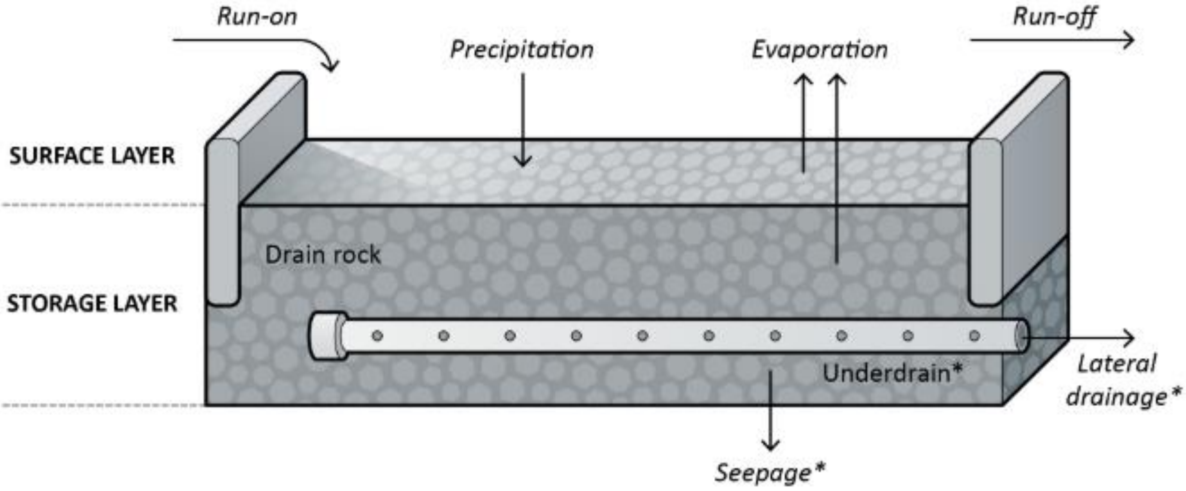


Figure 2-9: Infiltration Trench Computational Model (CHI, 2019)

2.3.3 Commonly used Regional Controls

Regional Controls are responsible for managing the runoff from several local areas. They typically follow on from Local Controls in a treatment train.

i) Detention Ponds

Detention ponds (Figure 2-10) are used to store runoff for short periods of time but are generally dry unless being utilised during or immediately after a storm event. They can be incorporated into a stormwater network in two different ways, either on-line or off-line. On-line basins are utilised for regular events where runoff is routed directly into the basin and allowed to infiltrate into the ground or released into the downstream system at a predetermined rate, thus making them effective flow regulators. Off-line basins are designed to receive and store runoff during very large storm events when a flow threshold has been reached (Woods Ballard et al., 2015).

Figure 2-10: Detention Pond (Woods Ballard et al., 2015)

The basin design is often governed by its use. On-line basins are often grass-lined and allow some infiltration, although most of the captured runoff is released downstream. Due to the regular use of these basins, upstream pre-treatment structures such as sediment forebays should be included (Woods Ballard et al., 2015). These prevent the basins from becoming clogged and reduce the need for dredging. Off-line basins are often designed as hard, concrete-lined areas and serve an alternative purpose when not in use.

Detention basins can require large areas. The treatment ability of these ponds depends on the water volume and surface area, with larger ponds performing better than smaller ones (Armitage et al., 2013). Additionally, detention basins are a primary source of sediment removal, including buoyant materials, but soluble contaminants, such as nutrients, are not captured significantly in these systems.

ii) Retention Ponds

Retention ponds or basins (Figure 2-11) are systems with a permanent pool of water and additional, temporary storage above that to provide attenuation. These systems treat and attenuate stormwater flows by mixing inflows with the permanent waterbody (Armitage et al., 2013). The attenuated stormwater may then be released at a lower, pre-determined rate. Retention ponds slow the runoff and allow a combination of biological uptake, filtration, infiltration, and sedimentation to capture and remove contaminants.

Figure 2-11: Retention Pond (susDrain, n.d.)

Retention ponds provide medium to high stormwater treatment (Armitage et al., 2013). Upstream pre-treatments prolong the lifespan of the system. If inflows are of very poor quality, public access should be limited. Vegetation is highly important in retention ponds as it enhances its treatment ability. The vegetation used should be native to the region. In water-scarce regions, such as South Africa, vegetation needs to be hardy to survive during periods of drought.

Retention ponds may serve additional purposes; the permanent water body presents the opportunity to be utilised as a non-potable water source while also providing an aesthetic appeal and an opportunity for environmental education. However, retention ponds may introduce health and safety issues, and measures must be taken to prevent drownings and mitigate pests such as mosquitoes.

iii) Constructed Wetlands

Constructed wetlands (Figure 2-12) are not natural systems but are instead developed to mimic the processes and functions found in natural wetlands. As with retention ponds, constructed wetlands are shallow vegetated water bodies (AECOM, 2013). They provide a permanent water body with additional, temporary storage space for attenuation. Wetlands differ fundamentally from retention ponds in that the surface area is mostly covered in vegetation (Woods Ballard *et al.*, 2015). The water body and extensive vegetation area provide a haven for many animals, often including rare or endangered species.

Figure 2-12: Constructed Wetland (Armitage et al., 2013)

Wetlands are considered to be highly effective treatment systems. They employ a combination of biological uptake, filtration, pathogen removal and sedimentation to reduce nutrient and sediment concentrations. Wetlands should be designed to include a pre-treatment system upstream as this enhances the treatment ability of the wetlands while protecting the system from excessive sediments and other buoyant substances. (Armitage *et al.*, 2013; & Woods Ballard *et al.*, 2015).

The wetlands design generally includes four main zones (Armitage *et al.*, 2013). This includes the inlet (including a sediment forebay), a macrophyte zone (a shallow, heavily vegetated area that promotes biofiltration and nutrient uptake), the macrophyte outlet zone (channels partially treated stormwater to downstream zones and structures) and the high flow bypass channel zone (protects the inlet, macrophyte zones and outlet from vegetation damage).

Wetlands may be designed as holistic systems to enhance multiple aspects. As the public perception and acceptance of any new system are highly dependent on the aesthetic appeal, it is important to design wetlands to enhance biodiversity and amenity while also providing stormwater attenuation and treatment (Woods Ballard et al., 2015).

2.4 Water quality standards

Historically eutrophication has been deemed a consequence of excessive phosphorus (P) concentrations (Mcgarrigle, 1993). However, due to changing activities in the catchment areas of receiving water bodies, imbalances have come about in the nitrogen (N) and P loading. Thus, both N and P need to be managed to create a long-term eutrophication management plan (Paerl, 2009).

The South African Water Quality Guidelines for Aquatic Ecosystems (DWAF, 1996) describe Soluble Reactive Phosphate (SRP) as the phosphorus form available immediately in the aquatic biota and should thus be the primary phosphorus targeted for intervention. Further, the guidelines state that an N:P evaluation must accompany any SRP assessment. The ratio observed in unimpacted streams has a range greater than 25-40:1, while streams that anthropogenic activities have impacted have a range less than 10:1.

Table 2-8: TIN & SRP Target Water Quality Ranges (TWQR) (DWAF, 1996)

Mean Summer Concentrations (mg/L)		**Trophic State**
Inorganic Nitrogen (TIN)	**Inorganic Phosphorus (SRP)**	
< 0.5	< 0.005	Oligotrophic
0.5 – 2.5	0.005 – 0.025	Mesotrophic
2.5 – 10	0.025 – 0.25	Eutrophic
> 10	> 0.25	Hypertrophic

Total Inorganic Nitrogen (TIN) has a stimulatory effect on plant and algae growth and is thus a primary concern. TIN includes all inorganic nitrogen constituents in water bodies, including ammonia and ammonium (NH_3-N) and nitrites and nitrates (No_x-N). For TIN and SRP, the guidelines suggest using mean concentrations as a basis for assessment. Various mean concentrations for both TIN and SRP are provided in Table 2-8. The various ranges indicate varying degrees of the trophic state that may be experienced.

2.5 SuDS treatment ability

Water quality is fast becoming a significant problem due to urbanisation. An increase in nutrients, heavy metals, and emerging contaminants, such as pharmaceuticals, have been observed in runoff. The rise is often due to an increasing urban population (Salerno et al., 2018). Research has shown that diffuse source pollution presents a significant risk to receiving water bodies

(Butler & Davies, 2011). As the runoff quality received by water bodies has decreased, an increase in periods of eutrophication has been observed in many receiving water bodies. This is primarily due to excess nutrients, such as nitrogen and phosphorus (Salerno *et al.*, 2018 & Yang & Lusk, 2018).

One of the objectives of SuDS is to improve water quality by capturing and treating runoff contaminants (Allen et al., 2017). Urban pollution and non-point sources of contamination can be managed by reducing the contaminate build-up at each source and by controlling the quantities of contaminants in runoff (Yang & Lusk, 2018. Once it is in the runoff, however, treatment is required. Therefore, it is important to understand how different SuDS react to and treat various contaminants as this will further aid in the SuDS selection process. Table 2-9 provides estimated contaminant removal abilities of several SuDS utilised in developed countries.

Table 2-9: Estimated Contaminant Removal Abilities of Selected SuDS

(Debo & Reese, 2003; Minton, 2002; North Carolina Division of Water Quality Stormwater (NCDWQ), 2007; Wilson et al., 2004; Woods-Ballard et al., 2007)

Option / Technology	**Pollutant Removal (%)**		
	TSS	**TP**	**TN**
Source Controls			
Green roofs	60-95	-	-
Sand filters	80-90	50-80	25-40
Filter drains	50-85	-	-
Local Controls			
Bioretention areas	50-80	50-60	40-50
Filter strips	50-85	10-20	10-20
Infiltration trenches	70-80	60-80	25-60
Permeable pavements	60-95	50-80	65-80
Swales	60-90	25-80	30-90
Regional Controls			
Constructed wetlands	80-90	30-40	30-60
Detention ponds *	45-90	20-70	20-60
Retention ponds	75-90	30-50	30-50
TSS – Total Suspended Sold; TP – Total Phosphorus; TN – Total Nitrogen			

The performance of SuDS is dependent on several site-specific and design variables such as the soil and rainfall types, climate, and pollution concentrations. SuDS treatment abilities are often lower than expected during the ‘start-up’ period. Perales-Momparler *et al.* (2014) report that the biological processes utilised by many SuDS are still being established during this period, resulting in treatment abilities less than what is expected in the long term. The design, layout and maintenance of each SuDS further affect its treatment ability, with well-designed and maintained SuDS performing to a higher standard than those with poor designs and maintenance. Therefore, the values presented in Table 2-9 should act only as a guide for planning purposes.

Constructed wetlands are often used as part of SuDS treatment trains in urban areas. They utilise a range of unit processes such as filtration and biological uptake that make them particularly effective in removing sediments and nutrients. However, the performance of constructed wetlands is highly variable and is affected by several aspects, including rainfall characteristics, hydraulic conditions, and the targeted stormwater constituent (Mangangka et al., 2013). The knowledge of how each variable affects each stormwater constituent is unfortunately limited. Toet *et al.* (2005) state that the treatment abilities of ponds and wetlands depend on specific key hydrological parameters. These include hydraulic loading rate (HLR) and hydraulic retention time (HRT). Both variables affect the length of contact time between the treatment system and the stormwater. Abbassi *et al.* (2011); Akratos & Tsihrintzis (2007); Kabenge *et al.* (2018); Lee *et al.* (2014) and Toet *et al.* (2005) found that an increasing HRT results in increasing removals of total nitrogen (TN), total inorganic nitrogen (TIN) and total suspended solids (TSS). However, the removal increases were not directly proportional to the HRT increases but levelled off as the HRT increased. Increased HRTs had various effects on phosphorus removal. Messer *et al.* (2021) investigated 71 papers to provide a comprehensive review of the performance of wetlands for nutrient and sediment removals. The review corroborated the relationship between HRT and nitrogen species removals; however, different relationships between HRT and phosphorus species were reported. Some authors had observed a negative correlation, while others had a positive one. Messer *et al.* (2021) speculate that the longer HRTs may allow the release of sorbed phosphorus. Sorbed phosphorus is the inorganic phosphorus temporarily stored and later released from soil (Messer et al., 2021). Additionally, a negative correlation between HRT and phosphorus may be observed if plant die-off and decomposition occur in a wetland as this can release more phosphorus into the system (Menon & Holland, 2014).

2.6 Water quality modelling

There are several methods to estimate and generate stormwater runoff constituents in stormwater modelling (Charbeneau & Barrett, 1998). The two most common approaches are pollutant build-up and wash-off equations and Event Mean Concentrations (EMC).

Build-up and wash-off relationships are based on land-use types’ environmental and physical properties and describe the accumulation of constituents during antecedent dry periods and the wash-off during wet periods. However, Charbeneau & Barrett (1998) evaluated methods of estimating stormwater pollutant loads and concluded that they could not be readily utilised for large catchments as they are usually based on highly site-specific and climatic data. Other studies have also criticised the use of build-up and wash-off equations at a catchment scale as the same equations tend to be utilised across the entire catchment without accounting for different land-use types (Tuomela et al., 2019). Since one site's data cannot be used for another site of the same land use, build-up and wash-off data are not readily available in literature.

On the other hand, EMC values are widely used to simulate stormwater contamination. They require significantly less data than other process-based approaches and are readily available in literature (Rossman & Huber, 2016). Developing models with EMC values generates important results as they guide the design and placement of cost-effective SuDS and allow practitioners to determine the relative improvements from various SuDS designs (Tuomela et al., 2019).

The use of EMCs assumes that the stormwater constituent concentrations are consistent during the entire simulation and do not consider the effect of antecedent dry days and the build-up of constituents. The results obtained from EMC modelling can be highly variable unless measurements within the catchment are available for calibration and verification (Rossman & Huber, 2016). The use of EMCs represents a simplified reality; however, the uncertainty of the associated results decreases as the simulation period becomes longer. Tuomela *et al.* (2019) reported that the simulated loads from using EMCs were often overestimated compared to monitored loads as the EMCs used did not represent the local conditions.

2.7 Stormwater modelling software

Stormwater modelling software first began appearing in the 1970s (Zoppou, 1999). Since then, numerous different software packages have been developed as they simplify model creation and the highly variable natural processes of large-scale hydrological systems. Most software use 1D models based on mass, momentum and energy conservation principles (Rangari et al., 2018).

A brief description of nine models is provided in Table 2-10, while Table 2-11 summarises the model characteristics and components.

Table 2-10a: Stormwater Modelling Software Descriptions
(Bach *et al*., 2014; Haris *et al*., 2016; and Rangari *et al*., 2018)

Software	**Brief Description**
DRAINS	DRAINS can design and analyse stormwater runoff drainage systems and catchments and model systems up to 10 km^2 in area. It can simulate rainfall patterns and convert them into runoff hydrographs. The software models hydrological systems using ILSAX, the Rational Method and storage routing modes while integrating with the hydraulic modelling of open channels, pipes, and surface flow (O'loughlin et al., 2018).
MOUSE	MOUSE is used to analyse urban drainage and sewer systems. Additionally, it simulates spatial variations in water flows and levels and pollution and sediment transfers through stormwater systems. The software can model both single and continuous storm events. The software is also not limited by catchment size or the number of elements (River Systems & Meteorology Group, 1999).

Table 2-10b: Stormwater Modelling Software Descriptions
(Bach *et al*., 2014; Haris *et al*., 2016; and Rangari *et al*., 2018)

InfoWorks River Simulation (RS)	InfoWorks RS is a hydrodynamic modelling software. It can model open channels, hydraulic structures, embankments, and floodplains and provides complete flood mapping. The software utilises event-based and conceptual hydrological methods. Rainfall-runoff simulations can be displayed in plan view, sectional view, or longitudinal view. The software combines an advanced flow simulation engine with hydraulic and hydrological models and GIS functionalities (Salarpour et al., 2011).
HSPF	Hydrological Simulation Program–Fortran was developed to simulate the water hydrology and quality processes in natural and man-made systems. The model requires basic inputs to model stormwater flows, including rainfall data, land use and soil types (Rangari et al., 2018).
DR$_3$M	Distributed Routing Rainfall-Runoff Model was developed by the United States (US) Geological Survey for use in urban hydrology. The model does not allow for baseflows or interflows, and water quality is simulated using exponential build-up and wash-off functions for arbitrary parameters (Rangari et al., 2018).
SWMM	USEPA's SWMM has been used widely to develop detailed hydrological models. SWMM can simulate a single event or long continuous events. It allows for dynamic rainfall-runoff modelling. The model allows simulation of water quantity and quality of stormwater runoff through an urban area and has been deemed a *'detailed model for planning and preliminary design'* (Elliott & Trowsdale, 2007). Numerous proprietary derivatives of SWMM, including Mike SWMM, XP SWMM, PCSWMM and Hydro-SWMM, have been developed, each claiming superior performance to the basic USEPA SWMM software.
MUSIC	MUSIC is an Australian-based stormwater quality assessment tool used to analyse stormwater infrastructure conceptual designs, emphasising water quality objectives. It allows stormwater professionals to model the stormwater quantity and quality characteristics in stormwater systems of various sizes. Incorporated into the software are several treatment measures that can be developed as a single element or incorporated into a treatment train (Armitage et al., 2014)
SLAMM	SLAMM predicts the flow and discharge of contaminants from a wide range of urban environments and includes several different stormwater control combinations. The software can provide mass balances for various pollutants during multiple rainfall events. Unlike many other software, SLAMM is not based on purely theoretical concepts but rather on actual field observations. This means it includes unique processes that accurately predict flows and pollutant movements (Pitt & Voorhees, 2002).
SUSTAIN	SUSTAIN is a GIS-based decision support tool. It can perform comprehensive stormwater management strategy evaluation and aids in selecting structural Best Management Practices in a catchment area. This is done based on user-defined cost and effectiveness criteria. The location, cost and type of various BMPs are evaluated to reach specific water quality objectives (Armitage et al., 2014)

Additionally, Jayasooriya & Ng (2014) summarised the SuDS available in 20 modelling tools. Table 2-12 provides details of several of these tools.

Table 2-11: Model Characteristics and Components Summary (Haris et al., 2016)

Modelling Software		**DRAINS**	**MOUSE**	**Infoworks RS**	**HSPF**	**DR3M**	**SWMM**	**STORM**
Routing Level	**Simple Storage**	✓	✓		✓	✓	1	✓
	Hydrologic	✓	✓	✓	✓	✓	✓	
	Hydraulic	✓	✓	✓		✓	✓	
Time Modelling Scale	**Continuous**	✓	✓	✓	✓			
	Event	✓	✓	✓	✓	✓	✓	✓
Component Availability	**Pipes**	✓	✓		✓	✓	✓	
	Open Channel	✓	✓	✓	✓	✓	✓	
	Retarding Basin				2	✓	✓	
	Other						3	
	Natural Streams	✓	✓	✓	✓	✓		
	Rainfall-Runoff	✓	✓	✓	✓	✓	✓	

*1 = Flow balance only, 2 = reservoir module, 3 = gutter and pumps

Table 2-12: SuDS Available in Models (Jayasooriya & Ng, 2014)

Model	**SuDS Available**
SWMM	Bio-retention cells, green roofs, infiltration trenches, porous pavement, rain barrels, street planters, and vegetative swales
SUSTAIN	Bio-retention cells, cisterns, constructed wetlands, dry and wet ponds, green roofs, infiltration basins and trenches, permeable pavements, rain barrels, sand filters, vegetated filter strips and vegetated swales
MUSIC	Bio-retention cells, buffer strips, detention basins, gross pollutant traps, infiltration systems, media filtration systems, rainwater tanks, sedimentation basins, vegetated swales, wetlands
SLAMM	Detention ponds, infiltration and biofiltration basins, filter strips, permeable pavement, street cleaning, vegetated swales

2.8 Best practice criteria and guidelines

The City of Cape Town (CoCT) has set out the best practice criteria and guidelines for improving stormwater runoff quality, quantity and rate and natural groundwater recharge in the city (Table

2-13) (City of Cape Town, 2009). These criteria were designed to minimise the impact on receiving water bodies from the conventionally used urban drainage systems.

Table 2-13: Criteria for Achieving SuDS Objectives (after City of Cape Town, 2009)

SuDS Objective		**Criteria for Achieving SUDS Objectives**
Improve Stormwater Runoff Quality		Design Storm = 24 hour, 6-month return storm
		Pollutant removal target = Reduction of contaminant load expelled from catchment TSS and TP loads reduced to catchment's pre-development levels or reduced by 80 and 45%, respectively Whichever achieves the highest treatment level
		All developments are further required to capture oil, litter, and grease at the source
Control Stormwater Runoff Quantity and Runoff Rate	Protect downstream channel stability	24 hour, 1-year return interval (RI) storms have an extended detention period of 24 hours
	Protect downstream developments from minor floods	Peak flow of 10-year return interval design storm reduced to the pre-development level
	Protect floodplains and developments within flood planes from major floods	100-year return interval design storm effect on the stormwater drainage system must be evaluated and negative impacts mitigated/ controlled
Promote Natural Groundwater Recharge		Requirements are site-specific and must be decided upon with the Cape Town City Council

*TSS = Total Suspended Solids, TP = Total Phosphorus

2.9 Summary

This chapter reviewed key issues encountered in this research. SuDS provide an alternative to the conventionally used stormwater systems. They attempt to reinstate the natural hydrological cycle by managing stormwater as close to its source as possible. Well-designed and maintained SuDS can provide runoff treatment; however, the treatment depends on many site and environmental aspects. Several stormwater modelling software packages are available, many of which allow a range of SuDS to be modelled.

3. Study Area – Zandvlei Estuary

The Zandvlei Estuary, located in Cape Town, South Africa (Figure 3-1), provides 80% of the estuarine area in False Bay, making it the largest of the eight estuaries found along the False Bay coastline (Brown & Magoba, 2009). The estuary is in a densely populated suburban area bounded by Lakeside, Muizenberg, Marina da Gama and Steenberg. Most of the water received by the estuary is delivered by three main catchments, namely the Keysers, Westlake, and Diep Catchments, that drain the eastern slopes of the South Peninsula Mountain chain.

The Grootbosch, Prinkasteel and Spaanschemat rivers are the most significant streams in the Keysers Catchment and give rise to the Keysers River. The Westlake River and Lakeside Stream drain the Westlake Catchment. The source of the Westlake River is to be found on the slopes of Steenberg. The river moves through Steenberg Golf and Wine Estate, Pollsmoor Prison and Kirstenhof Wetlands before merging with the Keysers River and flowing into Zandvlei. The Diep River originates above Constantia before flowing through several greenbelts and public areas and into Little Princessvlei. Once it leaves Little Princessvlei, it becomes the Sand River and merges with the Langevlei Canal before flowing into Zandvlei. As with Zandvlei itself, all the streams and rivers have been modified due to urban development (Zandvlei Trust, n.d.). Figure 3-2 illustrates the Zandvlei Estuary Catchment and its major feeder rivers.

Zandvlei’s catchments have several land uses, with the Diep Catchment having the largest percentage of urbanized areas (Coastal & Environmental Consulting, 2010). The Diep Catchment consists primarily of residential areas; however, several commercial and industrial zones are present along the middle reaches of the river networks.

Brown & Magoba (2009) reported that, under natural conditions, Zandvlei would likely dry out entirely during certain periods of the year. However, at the time of this research, Zandvlei was a semi-estuarine system due to alterations of its catchments and mouth. A rubble weir and sand bar controlled the water level – the latter being periodically opened to allow the movement of water between the estuarine system and the Indian Ocean to maintain the ecological functions of the estuary. The estuary drains into False Bay adjacent to Muizenberg Beach.

The Zandvlei Estuary Nature Reserve (ZENR) is of extreme ecological importance as it protects the only wetland/estuary/river system combination along the False Bay coastline. The reserve serves many ecological functions such as fish hatchery and habitat and nursery for many animals, including various endangered species (Zandvlei Trust, n.d.). The surrounding wetland provides essential habitat for many fauna and flora, such as:

- 166 species of bird, six of which are Red Data Species (IUCN, 2020).
- Amphibians and reptiles, such as the endangered Western Leopard Toad, are commonly found in the reserve.
- Small mammals such as otters, porcupines, grysbok, and mongoose are occasionally spotted in and around the reserve.

- The estuary also acts as a crucial hatchery for fish, such as Leervis and Steenbras.
- Five hundred plant species have been recorded around Zandvlei, several being Red Data Species (IUCN, 2020).

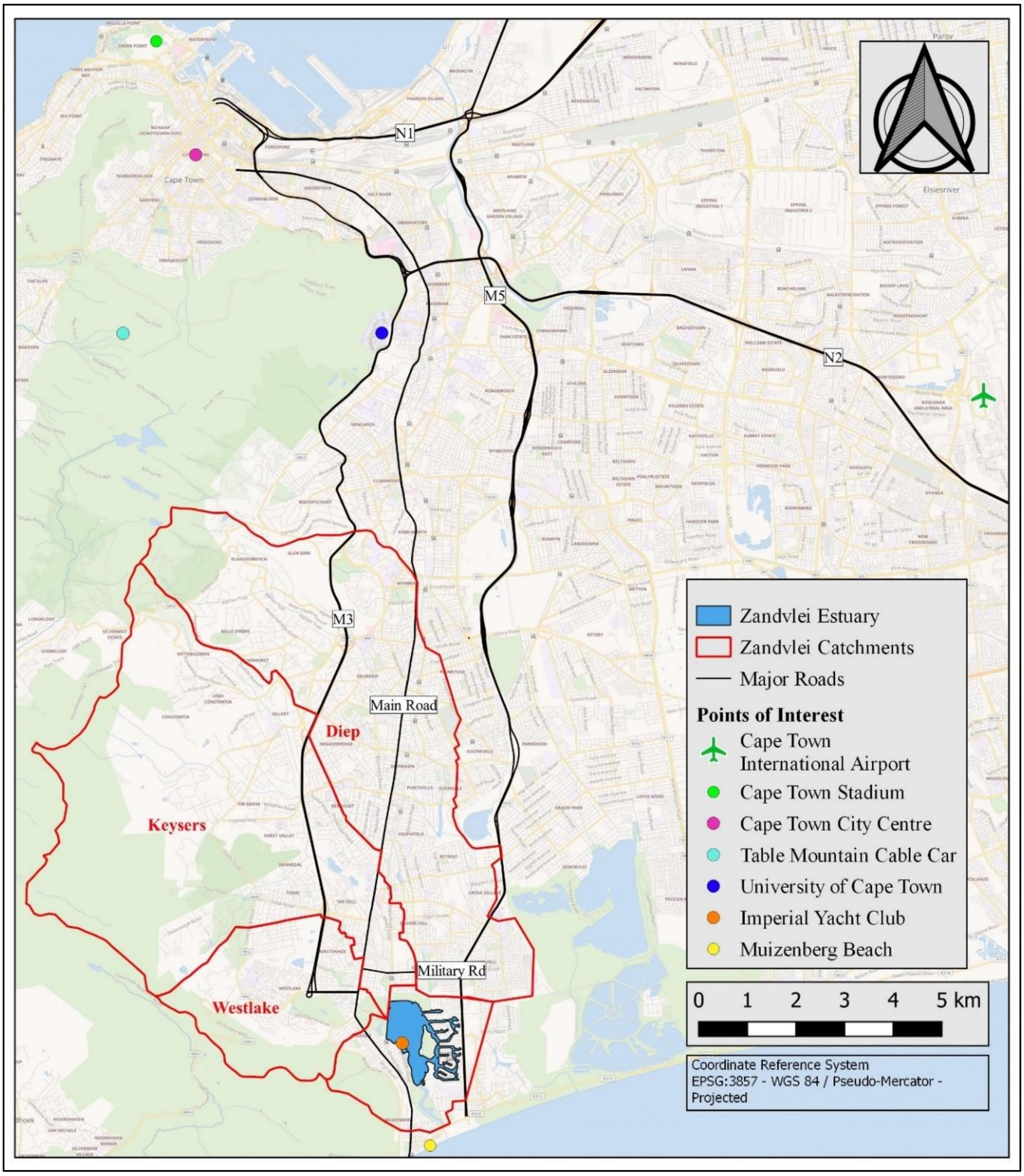


Figure 3-1: Zandvlei Estuary Locality Map – adapted from Wikimedia Maps (Wikimedia, n.d.)

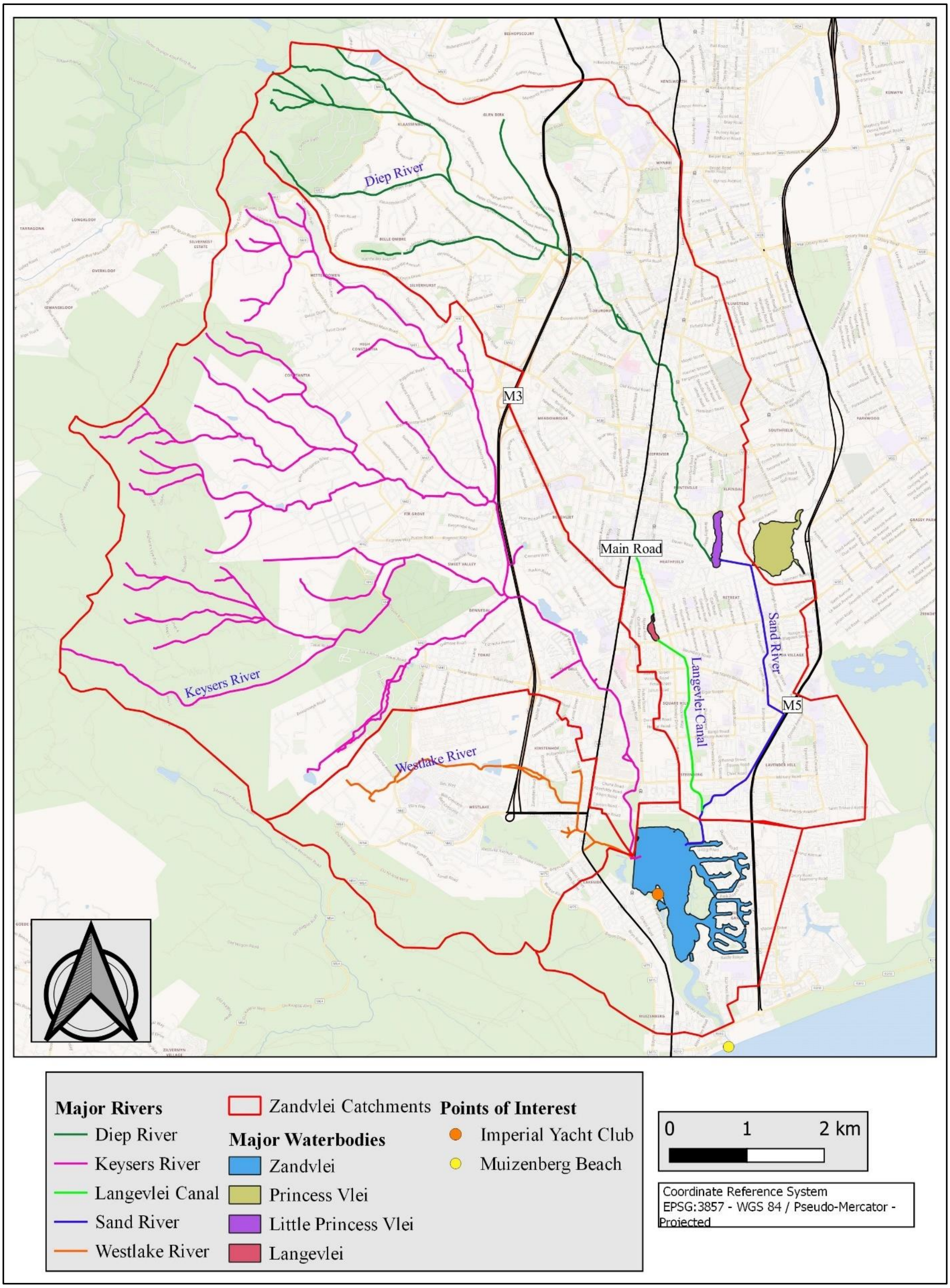


Figure 3-2: Zandvlei Estuary Catchment – adapted from Wikimedia Maps (Wikimedia, n.d.)

The Zandvlei Estuary has experienced many challenges, such as sewerage spills from faulty or vandalised pump stations, that have resulted in a decline of the water quality within the estuary and feeder rivers (Figure 3-3).

Figure 3-3: Polluted Water Sign near a children's park on the Diep River

Historically, the most significant problems experienced in Zandvlei are those caused by elevated nutrient and sediment levels, resulting in eutrophication (Figure 3-4) and siltation occurring in the estuary through the years.

Figure 3-4: Evidence of Eutrophication Occurring in Little Princessvlei

The Zandvlei Estuary Management Plan (CEC & Royal HaskoningDHV, 2018) reported increases in orthophosphate and total phosphorus in samples extracted in front of the Imperial Yacht Club between 1978 and 2012. The continuously high nutrient levels in the estuary promote excessive plant growth, creating eutrophic conditions in the water body. Such conditions frequently result in the overgrowth of invasive or pest species and cause a significant drop in biodiversity. The rapid growth of *Potamogeton pectinatus*, commonly known as pondweed, and the accompanying epiphytic algae, *Cladophora* / *Enteromorpha* sp., are also observable consequences of the excessive nutrient levels. The public often judges the water quality of a system on aesthetic criteria; hence the mass of pondweed gives rise to the understanding that the water quality has declined over the years (Thornton et al., 1995).

The National Biodiversity Assessment (Van Niekerk & Turpie, 2012) (Section 2.1) assigned Zandvlei a 'D' PES rating in 2011. This rating was re-established in 2018 (Van Niekerk et al., 2018). This rating indicates that the estuary health condition is 'fair'. Additionally, the 2018 National Biodiversity Assessment (Van Niekerk *et al.*, 2018) assigned Zandvlei an 'Important' Biodiversity Importance Rating (BIR). According to the assessments, Zandvlei's most significant threats are related to changes in flow due to dredging and mouth manipulation, loss of habitat and pollution. The biotic (biological) factors all received a 'fair' rating. Therefore, these biotic elements have a good recovery potential if the main threats are mitigated. The abiotic (habitat) components received the lowest ratings. The worst factors were those associated with the change of flow and estuary mouth breaching. Overall, it was recommended that Zandvlei Estuary be re-established to a more functional state; however, since it has been highly modified through urban development, it is unrealistic to assume that it could be restored entirely (Thornton et al., 1995). Nevertheless, reducing the sediment and nutrient inflows into the estuary should be possible, which should bring Zandvlei Estuary back to a more functional state.

4. Method

This research aimed to investigate the extent to which SuDS in the Diep Catchment may improve the water quality received by Zandvlei Estuary. Figure 4-1 presents the research framework adopted during this project, and this chapter presents the methods followed.

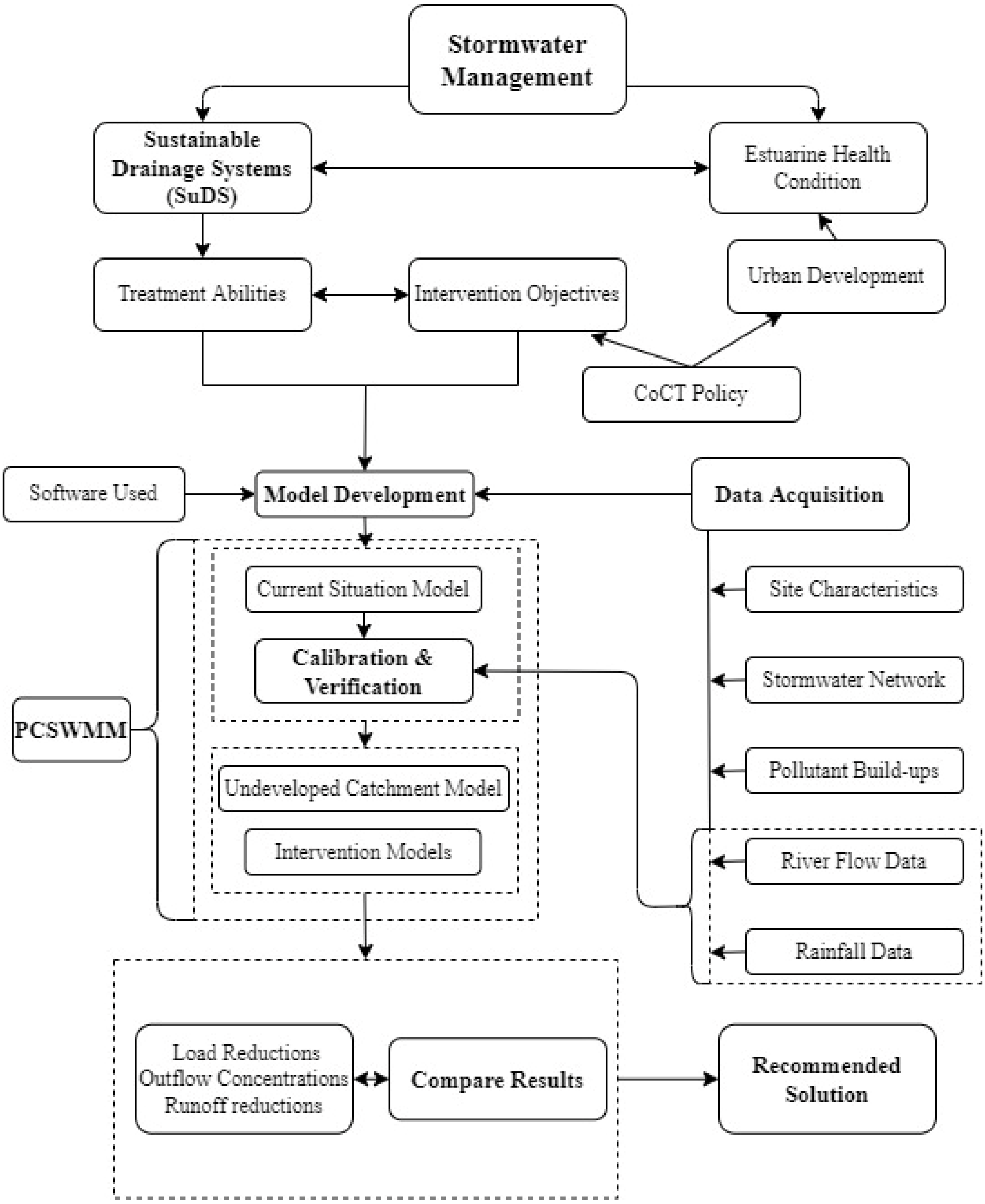


Figure 4-1: Research Framework

4.1 Stormwater modelling software

Various stormwater modelling software packages were researched (Section 2.7), and based on availability, functionality, and applicability, it was decided that PCSWMM would be utilised for the duration of this project. Similar investigations into Zandvlei's Westlake and Keysers catchments have been conducted using PCSWMM. PCSWMM '*is a dynamic rainfall-runoff simulation model*' (CHI, 2020) that uses the USEPA's SWMM 5 simulation engine. SWMM is widely used internationally and in South Africa by stormwater modelling professionals.

The SWMM engine can be used to simulate both long-term/continuous and single events/design storm models with both water quantity and quality parameters (Rossman, 2015). PCSWMM provides additional functionality to the SWMM engine that assists in the catchment area delineation and calibration. The software is primarily used to simulate stormwater runoff aspects from urban areas. PCSWMM's runoff component works by creating linked sub-catchments. The sub-catchments are areas that receive rainfall during events and generate surface water runoffs, infiltrations and indicator loads based on inputted data. This data includes but is not limited to soil type, land use and pollutant EMC values. Inlets, pipes, pumps, channels, regulators, weirs, and treatment/storage devices may all be utilised to transport runoff in PCSWMM's routing segment. Mass balances are created for each sub-catchment to track the runoff quantity and quality. During each simulation, the water quantity, flow depth and flow rate within each pipe/channel are also monitored for the entire simulation duration (Rossman, 2015). The PCSWMM modelling software was granted for free for the duration of this project. Figure 4-2 shows a simplified schematic of the PCSWMM processes.

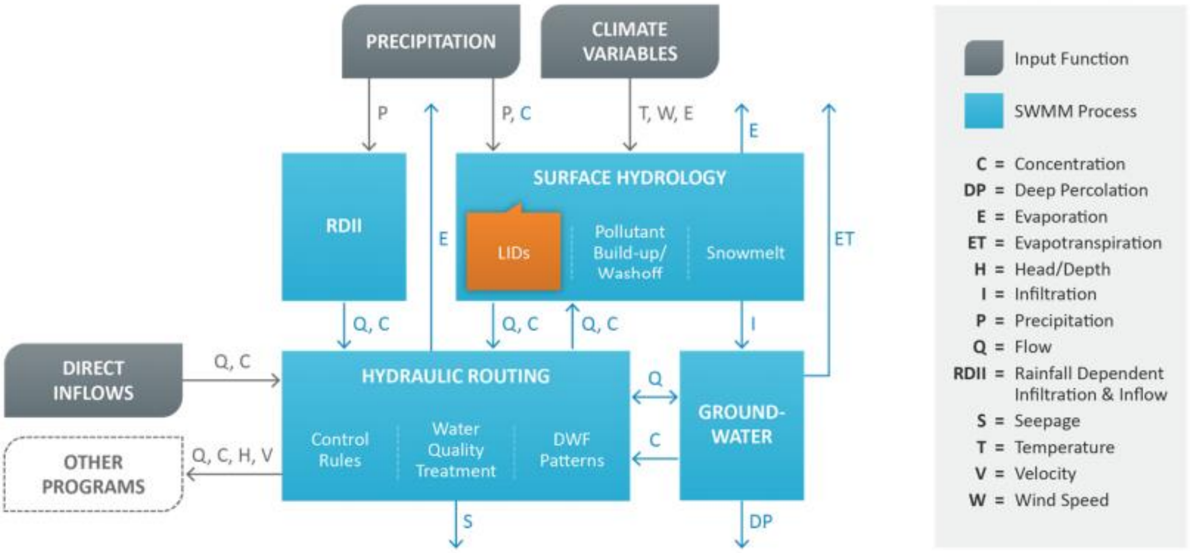


Figure 4-2: PCSWMM Process Schematic (CHI, 2019)

4.2 Method overview

A hydraulic and hydrological model was developed using PCSWMM to investigate the extent to which SuDS in the Diep Catchment may improve the water quality being received by Zandvlei Estuary. The model was initially set up to represent the Diep Catchment in its current state. Before the model development began, a desk study was required to investigate the project site, its current condition, and any threats it may currently face.

A data collection process began once the desk study had been completed. The model development required the input of considerable quantities of data (Section 4.3) that first needed to be collected, including:

- Catchment topography data
- Soil Type and infiltration parameters
- Land use and associated drainage properties
- Stormwater Conveyance Network
    - Open watercourses
    - Stormwater conduits
    - Stormwater bodies
- Rainfall data from multiple rainfall monitoring stations to adequately represent the rainfall variability in the catchment.
- Observed streamflow data to calibrate and verify the model.
- Water quality data. EMC values were used to simulate the build-up, wash-off, and transportation of various indicators within the model.

Many of the data sets obtained were not in suitable format or resolution to be utilised in the model and considerable data processing was required. The model development can be summarised in six steps:

1. The stormwater conveyance network was developed using shapefiles containing the open watercourses, stormwater pipes and conduits, manholes and catchpits, and stormwater bodies and ponds. The stormwater pipes and conduits had regular sections, while the open watercourse cross-sections had to be created using a Digital Elevation Model (DEM) and PCSWMM's built-in tools. Additionally, all the channels (both regular and irregular) required roughness coefficients before stormwater flow could be simulated.
2. Catchment topography data, in the form of a DEM, was used to model surface elevations. As PCSWMM works with sub-catchment areas, the DEM was further used to delineate the entire Diep Catchment into sub-catchments. Each sub-catchment required input parameters for the modelling of the rainfall-runoff relationships. These parameters pertain to the sub-

catchments land use, impervious area percentage, soil types and associated infiltration abilities, and overland roughness coefficients. PCSWMM's Area Weighting tool was used where sub-catchments had multiple land-use types or soil types to provide aggregated input parameters. Additionally, each sub-catchment required a rain gauge time series to be assigned.

3. Five rain gauges were developed in the PCSWMM model using the built-in 'Rain Gage editor' (Figure 6-1), each with a unique time series. The rainfall records collected were analysed to ensure they met several requirements, as detailed in Section 5. Those records suitable for use in the model were disaggregated to 15-minute intervals. The disaggregated rainfall records were then inputted into PCSWMM to create rain gauge time series. Sub-catchments were assigned a rain gauge time series based on their proximity to the rainfall monitoring stations.

4. Any modelling process requires calibration. The model was calibrated and verified using observed data from CoCT flow gauges. The calibration and verification processes focused on total flow, max flow, and comparison to the hydrograph. 26 storm events were used during these processes. The final calibrated and verified model included three stormwater bodies, 291 junctions, 294 channels (open watercourses, conduits, and pipes), five rain gauges, 229 sub-catchments and a single outfall at the end of the stormwater conveyance network.

5. As the objective of this research was to investigate the water quality improvements that may be achieved using SuDS, water quality had to be modelled. Water quality was modelled by simulating four indicators: Soluble Ready Phosphorus (SRP), Total Inorganic Nitrogen (TIN), Total Phosphorus (TP), and Total Suspended Solids (TSS). SRP and TIN were modelled as they are the primary causes of eutrophication in water bodies (Section 2.4), while TP and TSS were included as they are good indicators of pollution and the CoCT requires TP and TSS loads to be reduced when new SuDS developments are implemented (Section 2.8). The indicators were simulated using Event Mean Concentration (EMC) values as they are widely used to simulate stormwater constituents and are readily available in literature (Section 7.3). Four EMC values were developed for each land use to simulate each of the four indicators. Published values were used to provide preliminary EMC's which were later adjusted using water quality data from the CoCT for the Diep Catchment.

6. The calibrated and verified hydraulic and water quality model broadly represented the Diep Catchment in its current state and was used as the baseline for all the other model scenarios:

    - A pre-development model scenario was created to give an idea of the situation before urban development began. This scenario provides estimates of the runoff flow volumes and indicator loads entering into Zandvlei (Section 8.2).

    - Five SuDS scenarios were created to test various treatment train designs (Section 8.3).

4.3 Data acquisition and processing

The project required a substantial amount of data. The data were needed to develop and calibrate a hydraulic and hydrological model of the Diep Catchment and gain a deeper understanding of the sub-catchment area and possible sources of contamination. Table 4-1 summarises the data collected, the data sources, and the data type.

Table 4-1: Data Set Sources

Data Set	**Source**	**Data Type**
Digital Elevation Model (DEM)	University of Cape (UCT) GIS department	Raster
Conduits and Manholes	CoCT	Shapefile
Open watercourse	CoCT	Shapefile
Conduit and open channel roughness coefficients	Rossman, 2015	
Stormwater bodies	CoCT	Shapefile
Soil Types	CoCT	Shapefile
Soil infiltration properties	Maidment, 1993 Rawls *et al.*, 1983 & Rossman, 2015	
Land Use	CoCT	Shapefile
Land use drainage properties	Brabec *et al.*, 2002; Rossman, 2015	
Rainfall	CoCT Department of Water Affairs of South Africa South African Weather Service Department of Water and Sanitation UCT Climate System Analysis Group Private Citizens	Recorded data
Streamflow	CoCT	Recorded data
Water quality grab samples	CoCT Scientific Services Branch	Recorded data
Event Mean Concentrations	District Department of the Environment, 2014; Järveläinen *et al.*, 2017; Kayhanian *et al.*, 2007; Mitchell, 2005; Nordeidet *et al.*, 2004; Song *et al.*, 2019; Tuomela *et al.*, 2019; USEPA, 1983; Wicke *et al.*, 2021	

Several data sets were shapefiles (Table 4-1). These usually covered the entire city area of approximately 2500 km^2. Using QGIS, a free GIS software, these were clipped to include only the data within the Diep Catchment to minimise data sizes. All shapefiles were projected using the WGS 84 Pseudo Mercator projection system.

Site visits confirmed secondary data. The site visits brought about a greater understanding of the catchment’s physical features, allowing insights into local hydrology, hydraulics, possible contamination sources, and feasible SuDS intervention locations. The following sections discuss the methods used to prepare the obtained shapefiles and data sets to meet the requirements for a hydrological and hydraulic model.

4.3.1 Sub-catchment topography

Understanding and having a good representation of the catchment topography is crucial for the project. PCSWMM performs many functions, such as sub-catchment delineation, based on the topography data provided, so having a high-resolution Digital Elevation Model (DEM) was necessary. A 10 x 10 m resolution DEM was available from The City of Cape Town's (CoCT) open data portal (City of Cape Town, 2018). However, the terrain and slopes along river networks may change in elevation over short distances. As each pixel in a DEM is represented by a single elevation value, the 10 x 10 m DEM was not deemed satisfactory for model development during this project. The University of Cape (UCT) Geographic Information System (GIS) unit provided 1 x 1m and 0.5 x 0.5m resolution DEMs of the Diep Catchment. UCT develops these using Light Detection and Ranging (LiDAR) data obtained from the CoCT. '*LiDAR is an optical remote-sensing technique that uses laser light to densely sample a surface producing highly accurate x, y, z measurements'* (ArcGIS, 2019). Each pixel in a DEM is assigned a value of the LiDAR point with the lowest elevation within the pixel. It was thus decided to utilise the 1 x 1m resolution DEM as this would be more likely to have one point in each pixel at ground level allowing trees and cars to be ignored in the DEM but still accounting for buildings that alter natural flow paths. The two DEMs provided by UCT required considerable storage; it was, therefore, necessary to limit the DEMs to the Diep Catchment area.

4.3.2 Soil type and infiltration parameters

The CoCT Data Portal (City of Cape Town, 2018) provided a GIS shapefile of the upper soil types for the entire city. This shapefile made it possible to identify the soil types present within the Diep Catchment: sand, loam, and sandy loam (Figure 4-3). Soil identification is essential as it allows one to estimate infiltration parameters. As the stormwater runoff moves over pervious areas, there are infiltration losses, and thus the runoff volume decreases (Mitchell *et al*., 2007).

PCSWMM provides several infiltration methods such as Green-Ampt, Horton and SCS Curve Number. Green-Ampt was used for this research as the soil parameters required for this method are widely available in literature. To model the infiltration loss using the Green-Ampt method, PCSWMM requires the saturated hydraulic conductivity (K) in mm/hour, the suction head (Ψ) in mm, and the initial moisture deficit (Φ) in mm for each soil type. Rawls *et al.* (1983), Table A2 in the Handbook of Hydrology (Maidment, 1993), as well as the PCSWMM reference tables (Rossman, 2015) (Appendix B), were consulted to establish these variables. Table 4-2 presents the soil types and the infiltration parameters used. The initial moisture deficit provided is adapted by PCSWMM during the continuous simulations.

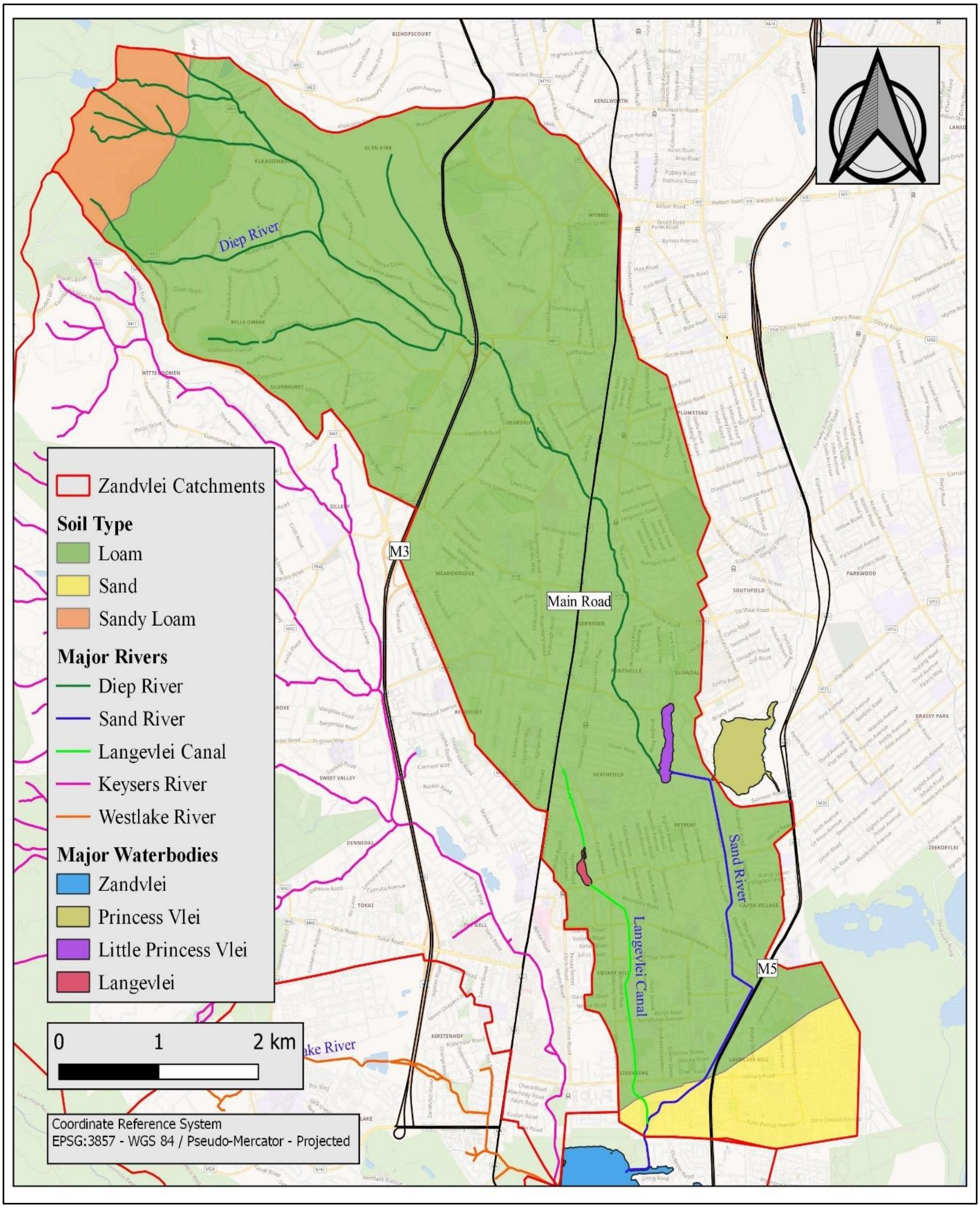


Figure 4-3: Diep Catchment Soil Map – adapted from Wikimedia Maps (Wikimedia, n.d.)

Table 4-2: Infiltration Parameters (Maidment, 1993; Rawls *et al.*, 1983 & Rossman, 2015)

Soil Type	**Saturated Hydraulic Conductivity (K) (mm/hr)**	**Suction Head (Ψ) (mm)**	**Initial Moisture Deficit (Φ) (fraction)**
Sandy Loam	10.92	109.98	0.37
Loam	3.30	88.90	0.347
Sand	120.34	49.02	0.413

4.3.3 Land use and drainage properties

Land use played a critical role in the development of the hydrological model. The various land-use types directly relate to runoff volumes, runoff rates, and indicator build-up and wash-off throughout the catchment.

The CoCT (2018) provided a GIS shapefile of the land use in the city and its surrounding areas. This very large shapefile had to be ‘cleaned’ before being usable. This included clipping the shapefile to solely represent the Diep Catchment, creating more specific land uses rather than the ‘blanket classifications’ used by the CoCT that incorporated multiple land uses and removing duplicate entries. The blanket classifications included land uses that presented noticeably different drainage attributes. In particular, public open spaces were regularly classified as residential areas. Public open places have a significantly lower impervious percentage than residential areas (Section 4.3.3.1), affecting the runoff volumes from each site, hence the need to separate the ‘blankets’. The land uses were then verified using site visits and satellite imagery, and the misclassified land uses were corrected. The land uses included during this project are listed in Table 4-3, while Figure 4-4 presents an adjusted land-use map.

Table 4-3: Land use categories used in this research

Land Use		
Agricultural	Public Open Space	Rural
Commercial	Residential – High	School Grounds
Environmental Conservation	Residential – Medium	Sports Fields
Industrial	Residential – Low	Roadways
Institutional	Residential – Very Low	Train Line

PCSWMM requires various attributes for each land use to simulate stormwater infiltration and runoff processes (Table 4-4). The collection and processing of these values are detailed in the following sections.

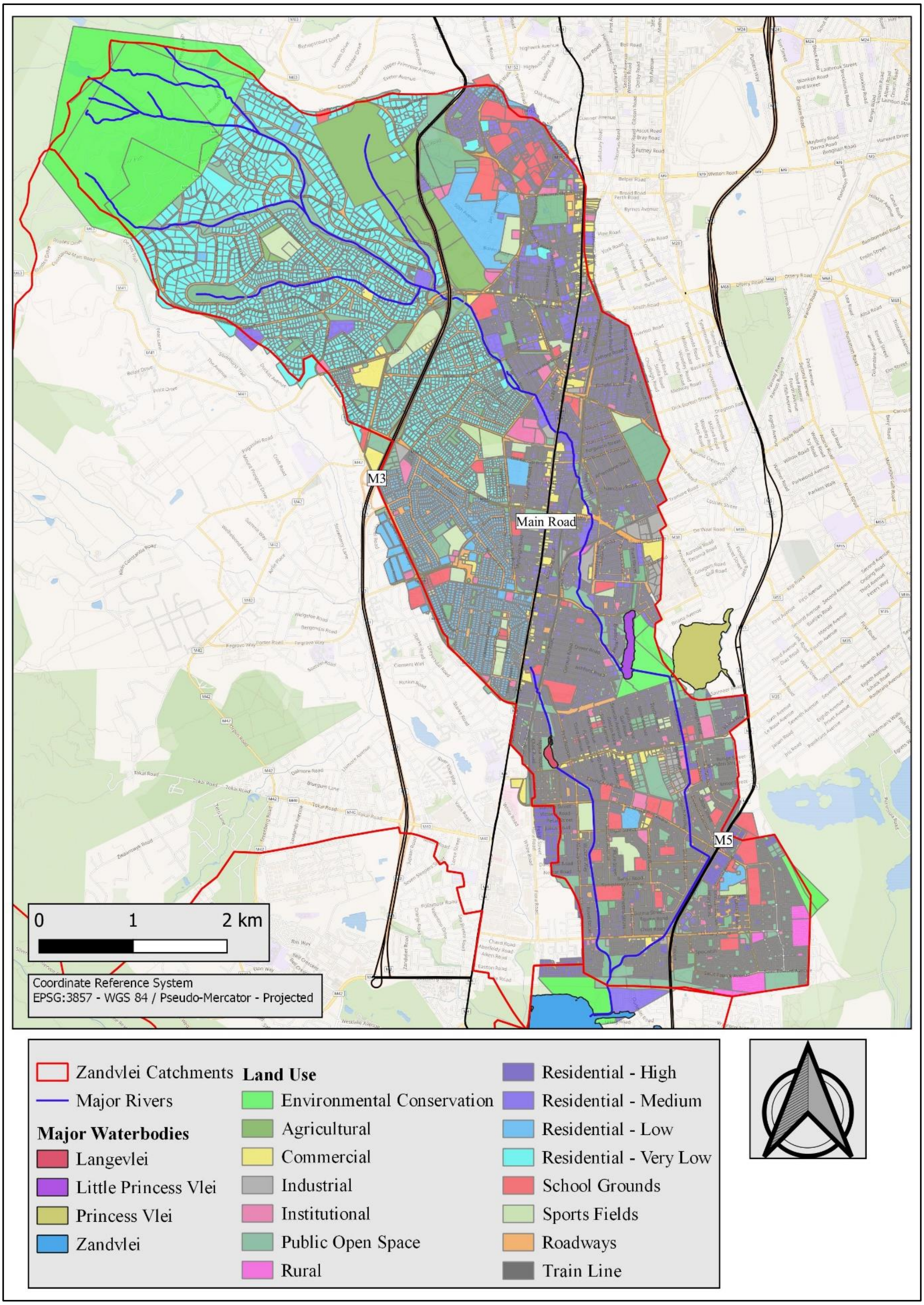


Figure 4-4: Adjusted Land Use Map

Table 4-4: Land Use Attributes required for modelling

Runoff Attribute	Description
Imperviousness (%)	Percentage area regarded as impervious
N Impervious	Manning’s roughness coefficient for impervious areas
N Pervious	Manning’s roughness coefficient for pervious areas
D Store Impervious	Depth of depression storage on the impervious ground (mm)
D Store Pervious	Depth of depression storage on the pervious ground (mm)

Table 4-5: Diep Catchment Land Uses and typical Attribute Values

Land Use	Imperv (%)	N Imper	N Perv	DS Imperv (mm)	DS Perv (mm)
Agricultural	10	0.024	0.17	2.5	5
Commercial	80	0.012	0.15	1.9	2.5
Environmental Conservation	5	0.05	0.13	2.5	5
Industrial	90	0.012	0.15	1.3	2.5
Institutional	70	0.013	0.15	1.9	2.5
Public Open Space	5	0.05	0.13	2.5	5
Residential – High	90	0.013	0.2	1.9	3.8
Residential – Medium	75	0.013	0.2	1.9	3.8
Residential – Low	50	0.013	0.15	1.9	3.8
Residential – Very Low	25	0.013	0.15	1.9	3.8
Rural	80	0.015	0.13	2.5	5
School Grounds	40	0.013	0.15	1.9	3.8
Sports Fields	5	0.012	0.15	2.5	3.8
Roadways	90	0.012	0.24	1.3	5
Train Line	50	0.013	0.24	1.3	5

4.3.3.1 Impervious Percentage

Impervious surfaces play an essential role in the hydrological cycle and its environment. The impervious percentage of an area affects the volume and speed of surface runoff. Generally, the more impervious surfaces there are in a catchment, the greater the runoff volume and runoff flow rate (Li *et al*., 2021). Impervious percentages were based on literature, satellite imagery and site visits. Brabec *et al*. (2002) reviewed impervious surface percentages from several literature sources; these were used as preliminary impervious percentages. The land use map overlaying satellite imagery of the Diep Catchment on QGIS was subsequently used to adjust the preliminary impervious percentages for the Diep Catchment context by investigating sample areas for each land use. The preliminary values were thus adjusted as necessary to represent the local sample areas. Table 4-5 provides the final impervious percentage values for each land use.

4.3.3.2 Manning's Roughness Coefficients

PCSWMM calculates the average velocity of overland flow using the Manning Equation. A Manning's roughness coefficient, *n*, was required for both pervious and impervious sections of each land use to calculate the mean runoff velocities. These were determined from the prevailing ground cover. PCSWMM support (CHI, 2021) provides reference tables with typical roughness coefficients for overland flow (Appendix B). Table 4-5 provides the values used for each land use.

4.3.4 Streamflow data

Continuous flow data was used to calibrate the hydrological model. The CoCT has several streamflow monitoring stations throughout the city, three of which are located within the Diep Catchment: DIEP05CS (Doordrift Road), LPVL05AS (Little Princess Vlei) and WYNB05BS (Maynardville Park), the locations of which are shown in Figure 4-5. These stations began recording continuous streamflow data in 2012, but all three sensors provided erroneous data due to an apparent lack of maintenance. The LPVL05AS and WYNB05BS stations were completely unusable as all data entries were the same since the sensors began operation. The DIEP05CS sensor recorded the same depth from its commencement date in 2012 to the middle of 2013. The data recorded after this period was thoroughly investigated and was deemed sufficient for this project as the data fluctuated in accordance with rainfall events. The calibration potential of the model was limited as the only functioning sensor, DIEP05CS, was in the upper reaches of the catchment area and could only be used to calibrate those sections of the catchment that were higher than it.

The CoCT streamflow sensors measure streamflow as water depth (m). The depth readings needed to be converted to flow rates (m^3/s) to use the data for the calibration process. Rohrer (2017) converted these by developing a rating curve for the DIEP05CS station based on a calibration table received from the CoCT. The following equation represents the rating curve for the flow rate for the DIEP05CS station, based on depth:

$$y = 2.091x^{1.315}$$ **Equation 4-1**

With:

y = flow rate (m^3/s)

x = flow depth (m)

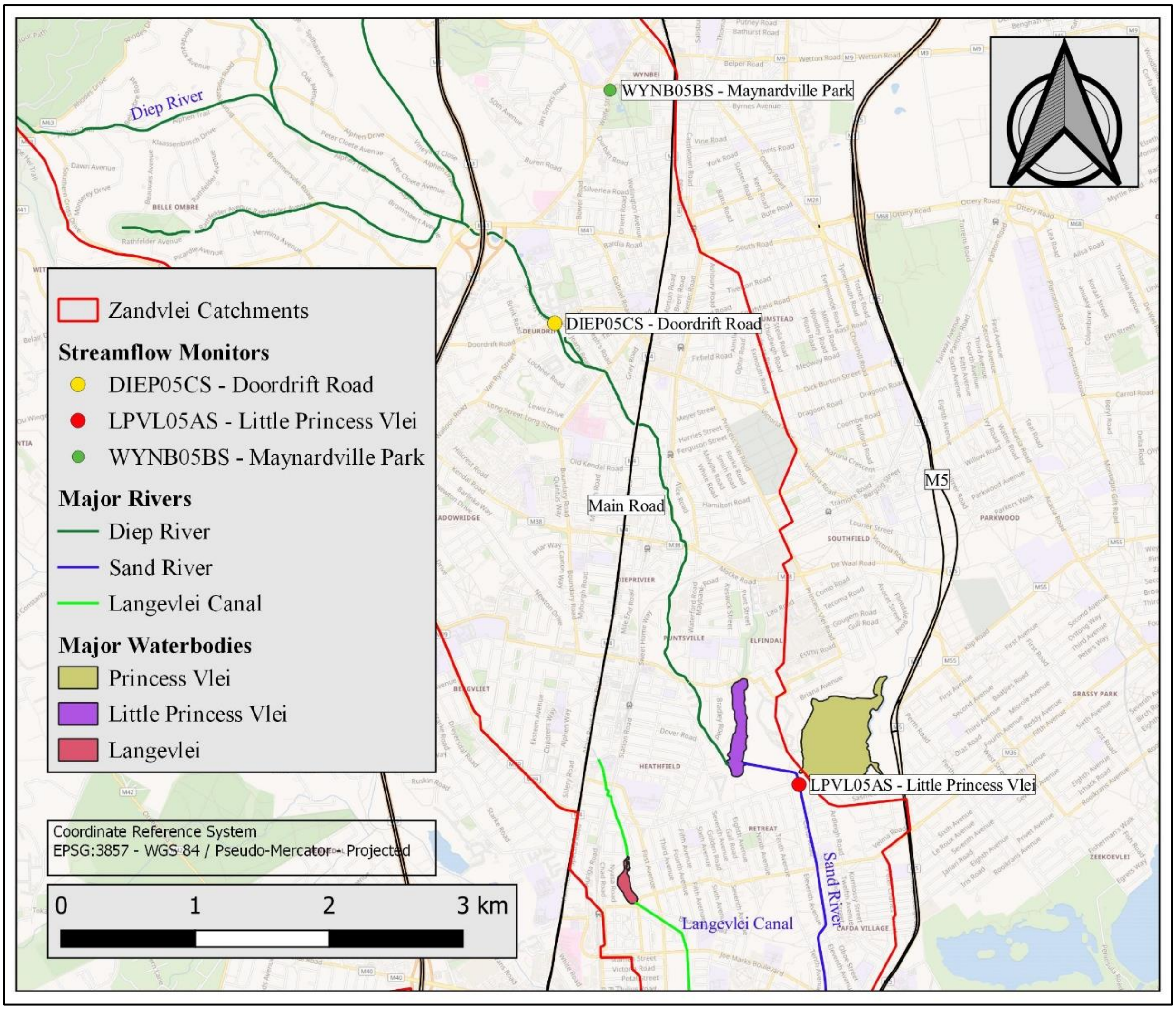


Figure 4-5: Streamflow Monitors

The equation converted all flow depth readings into usable flow rates. The equation has a coefficient of determination (R^2) of 0.9957, showing a high conversion accuracy. It was reported by Rohrer (2017) that the streamflow sensor did not pick up flow depths less than 0.02 m. A site visit was conducted during a ‘dry’ period and confirmed that erosion in the riverbed had occurred alongside the streamflow sensor, which allowed low flows to bypass the measuring point of the sensor. The lack of low flow readings caused limitations during the calibration and verification processes, however, the limitations were minimised during high flows that no longer bypassed the sensor measuring point.

4.4 Summary

This chapter describes the method used during this project. A hydraulic, hydrological and water quality model was developed using PCSWMM. The combined PCSWMM model required several data sets, including catchment topography data, soil types, land use, and observed streamflow data. The model was calibrated and verified using observed streamflow data from the CoCT. Additionally, rainfall data is required to simulate the model; the collection, analysis and processing of rainfall data are detailed in Chapter 5.

5. Rainfall Data

This chapter details and discusses the procedures followed during the collection, analysis and disaggregation of rainfall data adopted during this project.

Cape Town has a Mediterranean climate, which means it experiences mild, wet winters and warm, dry summers. However, due to the mountain range that surrounds the city, numerous micro-climates cause some areas to experience either much higher or lower rainfalls than others in the near vicinity (World Weather Online, 2020). The Diep Catchment, located at the foot of a mountain range, is one such area of considerable rainfall variation. The catchment experiences a rainfall variation from 800 to 1400 mm/year. To represent this variation, several sets of rainfall records for the catchment were collected from the CoCT, Department of Water Affairs of South Africa, South African Weather Service, Department of Water and Sanitation, UCT's Climate System Analysis Group and private citizens. In all, 21 rainfall data sets were obtained for this project, the details of which are provided in Table 5-1, while Figure 5-1 provides the locations of the rainfall gauges.

5.1 Rainfall record analysis

The rainfall records must meet certain criteria before they can be deemed acceptable for use in a hydrological model. They need to capture both intra- and interannual variation within a climate (Mitchell *et al*., 2008). Mitchell *et al*. (2008) further recommend that a rainfall time series should ideally be a minimum of 10 years if it is to be used in a continuous stormwater system simulation. More extended series will produce a better representation within the model, while shorter series could lead to a substandard model. The time step-step used in each rainfall record is also important. Daily time-step intervals were found to significantly underestimate stormwater runoff volumes (Coombes & Barry, 2007). The ideal time step for continuous rainfall model simulations is 5-minutes to account for the response time of small sub-catchments. Due to the lack of sufficient data sets with 5-minute intervals and the disaggregation abilities of PCSWMM (Section 5.2), 15-minute time steps were deemed acceptable.

The rainfall records gathered varied in resolution, from 5-minute intervals to daily records, and in record length, ranging from 5 years to 65 years in length. The 21 records obtained were checked for the duration, and those substantially less than the ten years recommended by Mitchell *et al*. (2008) were discounted.

The rainfall gauges operated by the CoCT were, for the most part, unusable despite having an ideal 5-minute interval, as there were very large data gaps in the records. Several of the gauges were missing data for up to 12 months over seven years. Others had record lengths of seven years and did not meet the recommended 10-year duration. Additionally, these gauges showed signs of poor record-keeping as impossibly large values were recorded over the 5-minute intervals. In the end, only two of the ten CoCT rain gauges were usable: the Newlands and Wynberg stations

Provided daily rainfall records over 39- and 20-year periods, respectively. The Newlands rain gauge was too far away from the catchment and was not included in the model directly. It was, however, utilised to patch other stations closer to the catchment, as described later.

Table 5-1: Rainfall Gauge Basic Information

Source	Gauge Name	Start	End	Years	Resolution
CoCT	Newlands	1981/01/01	2020/05/21	39	Daily
	Wynberg	2000/01/10	2020/05/28	20	Daily
	DIEP05CR – Wynberg Reservoir	2012/01/01	2019/04/01	7	5 minutes
	DIEP05BR – Southfield Road Depot		2019/04/30	7	5 minutes
	DIEP05DR – Cecilia Forest			7	5 minutes
	DIEP05ER – Table Mountain		2019/03/08	7	5 minutes
	KEYS05FR – Tokai Forest		2019/04/30	7	5 minutes
	LIES03FR – Newlands Reservoir			7	5 minutes
	DIEP05AR – Kendal Road Water Works Depot			7	5 minutes
	KEYS05DR – M3 Freeway		2017/03/01	5	5 minutes
DWS	Tafelberg	1980/10/03	2019/03/27	65	Monthly until 1980/10/3, then daily
	Tafelberg @ Newlands	1980/10/05	2019/04/01	60	Monthly until 1980/10/5, then daily
	Great Constantia	1980/10/05	1990/09/09	23	Monthly until 1980/10/4, then daily
	Seekoei Vlei Treatment works	1980/10/05	2003/01/22	37	Monthly until 1980/10/4, then daily
Dept of Agriculture	Constantia	2005/01/06	2015/07/25	10	Daily
SAWS	Kirstenbosch 1	2010/02/14	2020/01/31	10	Hourly
	Kirstenbosch 2	2010/02/16	2020/12/27	15	Daily until 2010/02/01, then hourly
	Kenilworth Racetrack	2012/03/25	2020/12/30	8	Hourly
Private	Versfeld Avenue	1995/06/04	2015/12/12	25	Daily
	Vineyard Road	2003/01/08	2015/11/26	12	Daily
	Corsair Crescent	2003/01/16	2015/12/06	12	Daily

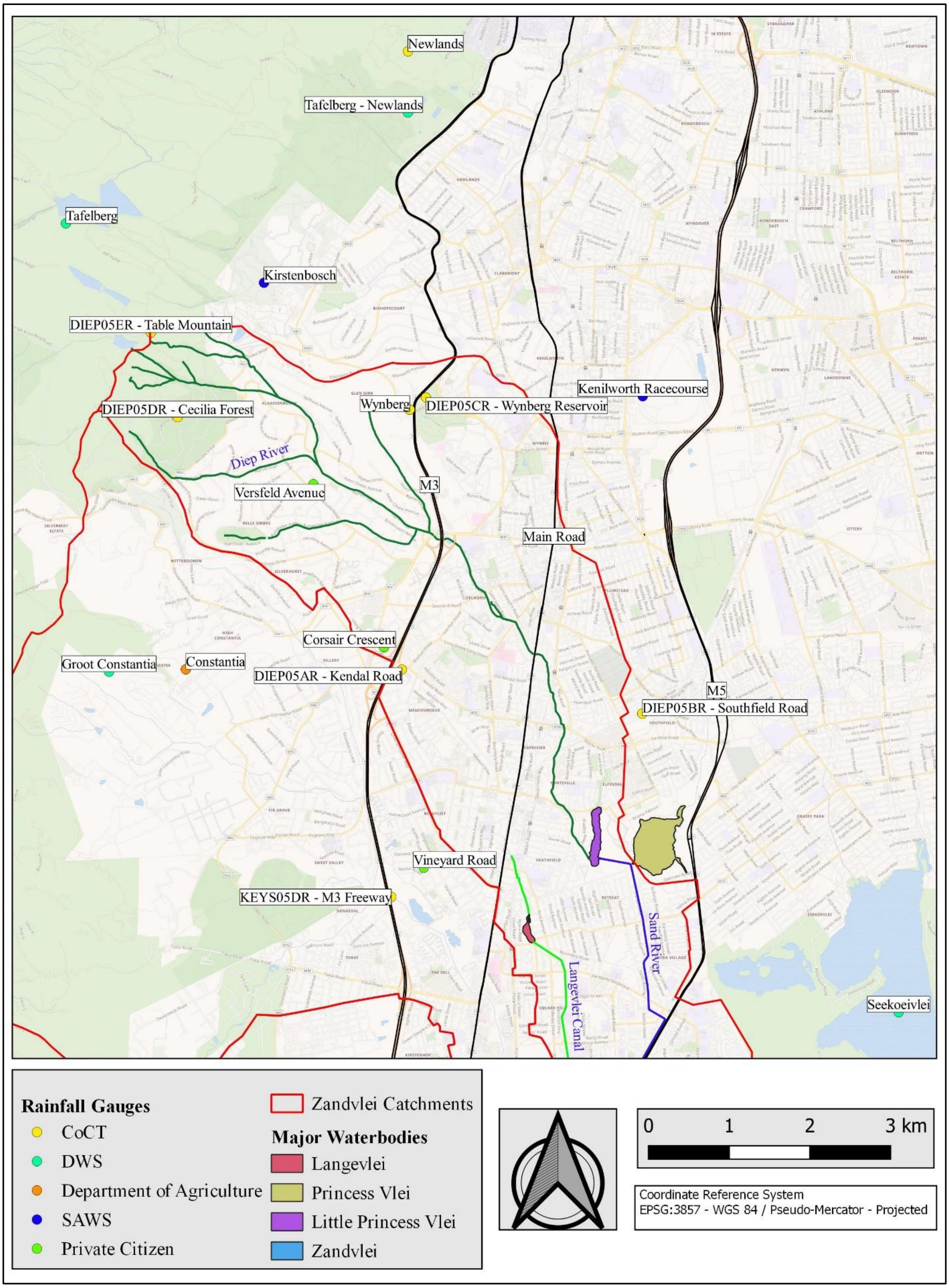


Figure 5-1: Rainfall Gauge Locations – adapted from Wikimedia Maps (Wikimedia, n.d.)

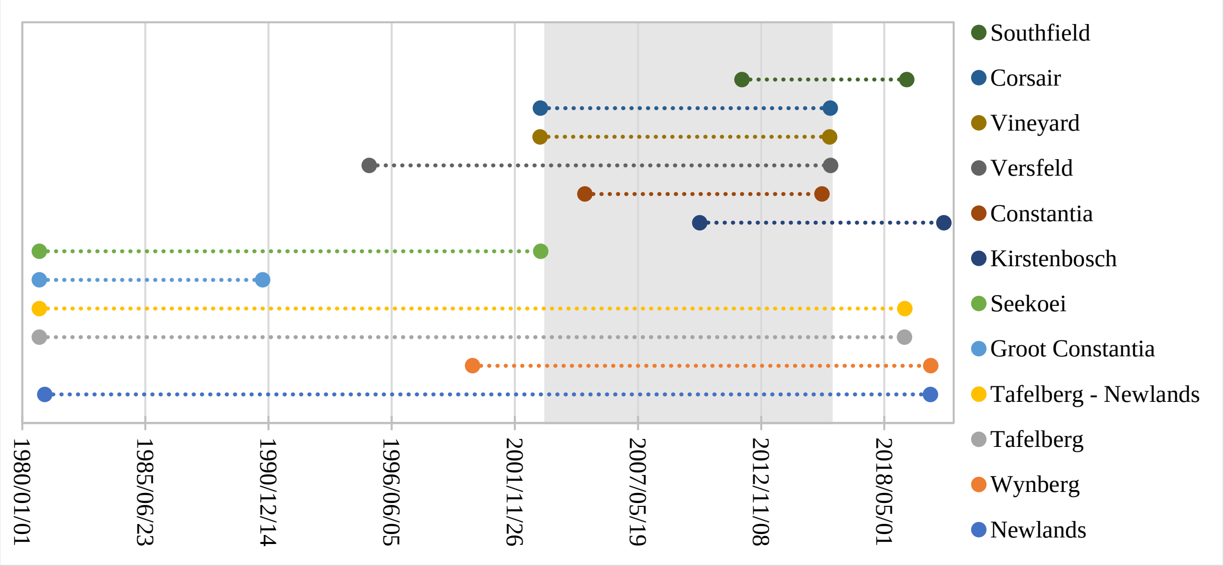
The Department of Water and Sanitation (DWS) has four rainfall monitoring stations in and around the Diep Catchment. These stations record daily rainfall levels ranging from 23 to 65 years in length. Although all four of the DWS gauges had records surpassing the minimum threshold of 10-years, the Groot Constantia and Seekoei Vlei gauges were not used due to the records ending in 1990 and 2003, respectively, and not overlapping with other usable rainfall gauges. With respect to the other two, there were several gaps in the records, however, the gaps only spanned a maximum one-month period, and even then, monthly totals for the station were provided. Linear scaling could therefore be used to fill in the data gaps. Reliable stations nearby were used to scale the monthly total over the entire month using the Normal Ratio method (Romman *et al*., 2021 & Chinasho *et al*., 2021). The length of the records and the way in which gaps were corrected provided records that could reasonably reproduce the rainfall patterns over the catchment.

The Department of Agriculture provided data for one rainfall gauge in Constantia, just outside the catchment boundary. This gauge had a 10-year record length with a daily interval. Slight data patching was required, but the recorded data’s overall quality met the level recommended by Mitchell *et al*. (2008).

The South African Weather Service (SAWS) has eight rainfall gauges in and around the Diep Catchment. Most of these were recorded at 5-minute intervals, although one gauge was reporting in hourly intervals and one with daily intervals. Unfortunately, seven of the eight gauges had records lasting less than the ideal 10-year period and were filled with inconsistencies. Values were reported as having surpassed the surrounding areas’ entire Mean Annual Precipitation (MAP) in a 5-minute period. Additionally, many of the data sets had large gaps of missing data resulting in the records being unusable. The remaining rainfall gauge, Kirstenbosch, had daily intervals, minimal gaps that were corrected with lin’ar scaling using nearby stations, and a 15-year record length. This gauge was therefore of a satisfactory standard for use in the model.

Three private citizens provided rainfall data for a previous study in the Diep Catchment. They were initially reached through advertisements in the *Constantia Bulletin,* a local newspaper, and by contacting the Zandvlei Trust (Rohrer, 2017). The records ranged from 12 to 25-years, with daily intervals. Two of the records, from Corsair Crescent and Versfeld Avenue, had data gaps rectified through linear scaling with nearby stations. The third private record, from Vineyard Road, was complete and did not require any data patching. Rohrer (2017) notes that Vineyard Road data was recorded with ‘*very stringent methods*’ to ensure the records were complete.

After analysing and assessing the viability and reliability of the rainfall gauges, 12 of the initial 21 gauges seemed acceptable in terms of record length, missing data, and data reliability. A time frame for the hydrological model simulations was determined by finding a period exceeding 10-years that encompassed the largest number of rainfall station records. Eventually, the time frame used was the period from 16 January 2003 to 6 December 2015, illustrated in Figure 5-2. This period allowed seven of the remaining 12 stations to be incorporated into the model. Figure 5-2 shows the record span of the gauges that met the requirements for modelling.



*Grey band = simulation period

Figure 5-2: Rainfall Gauge Record Lengths and Modelling Period

5.2 Rainfall disaggregation

The usable rainfall gauges all recorded data at daily intervals. The records needed to be disaggregated to ensure the usable rainfall records had sub-hourly rainfall data, as Coombes & Barry (2007) and Mitchell *et al*. (2008) recommended.

NetSTORM, a freely accessible software (DynSystem, 2008), was used to disaggregate the daily records into hourly records. The software comprises functions that disaggregate time series, analyse rainfall intensity-duration-frequency curves, and allow for runoff, storage, and overflow interactions to be investigated. NetSTORM uses stochastic disaggregation to disaggregate daily records into hourly records. To do this, the software requires rainfall data with hourly or sub-hourly intervals from a nearby station. Two rainfall stations were utilised for this, either DIEP05BR – Southfield Road Depot or DIEP05AR – Kendal Road Water Works Depot (Figure 5-1) as appropriate depending on the proximity of the station to be disaggregated. Both stations were adequate for use during the disaggregation process but were not adequate for use in the model due to the number of record gaps and short (7-year) record lengths.

PCSWMM offers a disaggregation tool to disaggregate the hourly data into 15-minute data. This, too, requires a separate rain gauge with sub-hourly data. DIEP05BR (Southfield Road Depot) and DIEP05AR (Kendal Road Water Works Depot) were again used. The PCSWMM disaggregation process is based on sampling event distributions from high-resolution rainfall records within the same climatic region (CHI, 2021). The disaggregation tool incorporates the Bartlett-Lewis Rectangular Pulses Rainfall Model (BLRPM). However, it is important to note that the disaggregation process does not recreate the actual rainfall events but instead generates rainfall data with the same underlying statistics as the records on which it is based. Nevertheless, the method preserves the general temporal nature and total daily rainfall to generate realistic data. The PCSWMM model is sensitive to the disaggregation method utilised as rainfall data is a primary input of the model, however, no sensitivity analysis was conducted during this study.

5.3 Summary

Rainfall data was essential in the development of the model. Records from 21 rainfall monitoring stations in and around the Diep Catchment were collected. These were analysed for erroneous data, consistency, and record length. Seven records were deemed satisfactory for use in the model. The processes of implementing the rainfall records in the PCSWMM model are detailed in Chapter 6.

6. PCSWMM Hydraulic and Hydrological Model

This chapter details the processes adopted to develop a hydraulic and hydrological model of Zandvlei’s Diep Catchment using PCSWMM.

All map backgrounds in this project were accessed via the Geographic Information System (GIS) software QGIS. Two map types were utilised, Bing Maps (Microsoft Bing, n.d.) and Wikimedia Maps (Wikimedia, n.d.).

6.1 Data for modelling

Sufficient and consistent data was essential in developing the hydraulic and hydrological model. The data required included information on catchment topography, land use data, soil types, rainfall, and streamflow. As detailed in Section 4.3, this data was acquired from several sources, analysed, and processed.

Calibration is an essential step in any modelling process. To do this, observed data is measured against the modelled outputs. The streamflow data obtained from the CoCT was used to calibrate the hydraulic and hydrological model in this project (Section 6.2.4).

6.2 Model development

This section details the steps and procedures taken to develop a hydrological model of the Diep Catchment. A calibrated and verified hydrological, hydraulic, and water quality model of the Diep Catchment was the primary tool used to investigate the viability of using SuDS to manage the water quality of the Zandvlei Estuary during this project. Once the model was calibrated and verified, it was used to create various SuDS scenarios (Section 8) that allowed the testing of various treatment train designs.

6.2.1 Sub-catchment delineation and development

Sub-catchments are the base of the hydrological processes in PCSWMM; their topography and drainage systems direct runoff to a single outlet point (Rossman, 2015). PCSWMM offers several tools to aid in model development. The Watershed Delineation Tool (WDT) allows users to delineate sub-catchments based on a DEM; the 1 x1 m DEM from the UCT GIS unit was utilised for this project. As the automated delineation process is based on a DEM that is not able to identify local deviations in surface level, small errors may be introduced into the model, however, these errors are accounted for during the calibration and verification processes (Section 6.2.4). The WDT incorporates the existing stormwater network (conduits, manholes and storage units) and introduces additional conduits and junctions; these were removed in the model as they were not present in the physical system (CHI, 2021). The WDT allows users to define a targeted sub-catchment size and determines the entire contributing area for specified drainage outlets (Jenson & Domingue, 1988 & Maidment, 2002).

PCSWMM deals with runoff and drainage at the sub-catchment level. Users must define various sub-catchment properties that affect the runoff and drainage. These can be manually entered or imported from background layers. The processed soil type (Section 4.3.2) and land use (Section 4.3.3) layers were imported and combined using PCSWMM’s Area Weighting Tool to create weighted means of each sub-catchments runoff and infiltration properties.

Each sub-catchment is defined by three subareas, pervious, impervious, and impervious with no depression storage. The default setting is for runoff to drain from all three areas to the sub-catchment outlet. However, PCSWMM allows users to route a percentage of runoff to a separate subarea to promote infiltration rather than allowing all runoff to be drained by the outlet. The sub-catchment outlet then drains any runoff routed from one subarea to another that is not infiltrated. The subarea routing was adjusted for agricultural, public open space, environmental conservation, and sports field land uses to direct runoff towards pervious areas instead of the sub-catchment outlets.

Sub-catchments also require a rain gauge to be assigned. Five rain gauges were assigned based on their proximity to the centroids of the various sub-catchments throughout the Diep Catchment (Figure 6-1).

6.2.2 Stormwater conveyance network

The Diep Catchment stormwater conveyance network (Figure 6-1) is a complex linear system that alternates between natural channels, closed conduits, open constructed channels and river systems. It was modelled in PCSWMM using GIS shapefiles from the CoCT open data portal (CoCT, 2018). The shapefiles provided the spatial positioning and geometric properties of pipes, channels, and manholes; Table 6-1 provides the quantities of each conveyance network element in the model.

Table 6-1: Conveyance Network Element Quantities

Element	Quantity	Total Length (km)
Pipe Network	135	13.12
Open Conduits	159	21.48
Junctions and Manholes	291	-

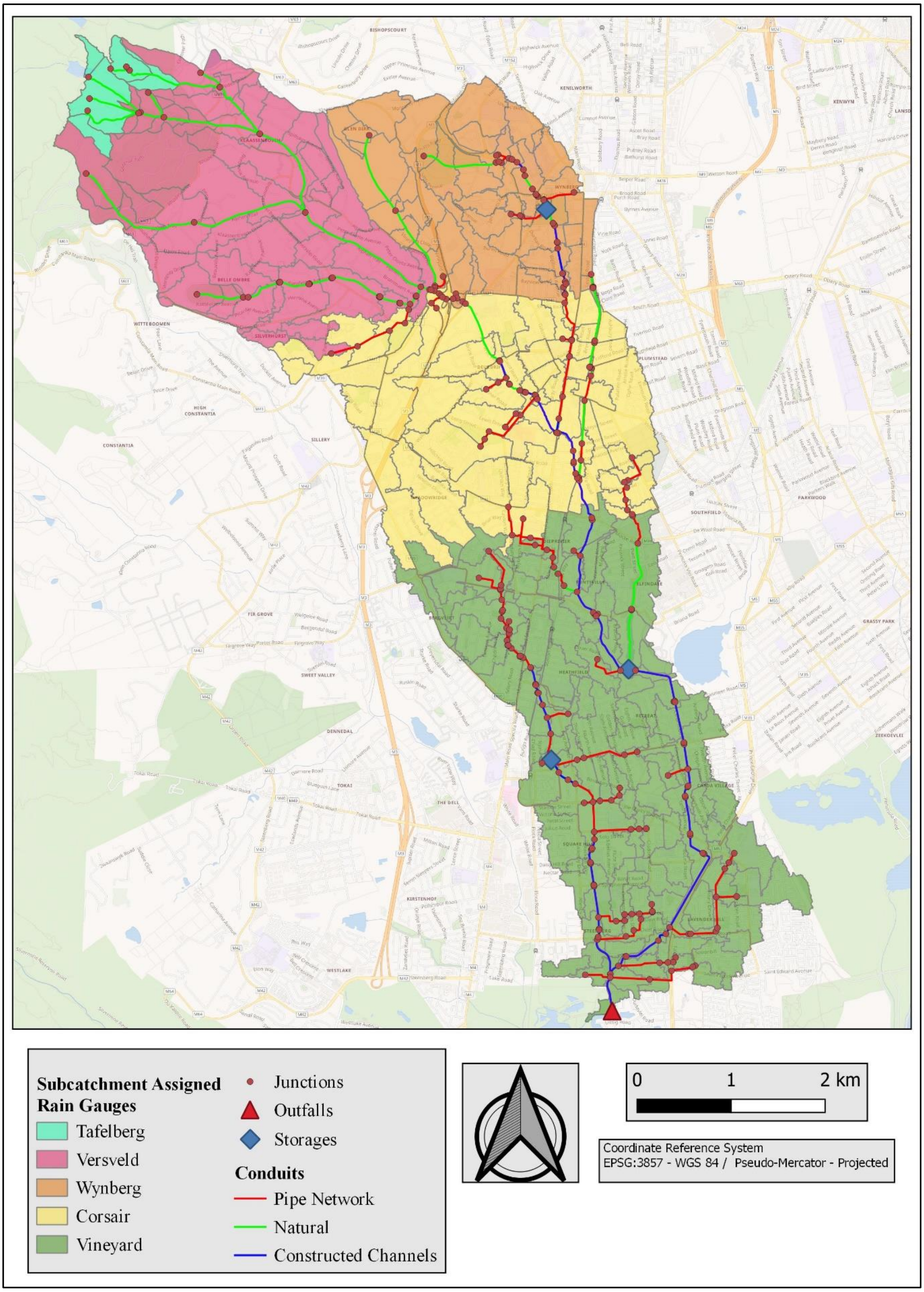


Figure 6-1: Model Network showing Sub-Catchment Rain Gauges, Conduits, Storages, and an Outfall – adapted from Wikimedia Maps (Wikimedia, n.d.)

6.2.2.1 Pipe network

The closed conduit pipe network was received from the CoCT. Due to the extent of the study site, it was decided to only model closed conduits with a diameter larger than 675 mm as the smaller diameter conduits were missing most of their data. Sub-catchments that would have been drained by the removed conduits, had their outlets assigned at the location where the excluded conduits (≤ 675 mm diameter) connected to the included conduits (> 675 mm diameter). However, in Figure 6-1 these sub-catchments do not appear to be connected to their outlets as the removed conduits are not indicated. Any uncertainties introduced during this process were accounted for by calibrating and verifying the model (Section 6.2.4). Unfortunately, a significant number of conduits were still missing diameter and slope data. The *Neighbourhood Planning and Design Guide* (CSIR, 2019) was used to estimate and patch the gaps based on the assumption that the original designers would have adopted a similar approach. Data gaps were patched by ensuring:

- All conduits flowed towards a single outlet.
- The conduit diameters were always equal to or greater, never smaller than those upstream.
- Conduit slopes were equal to or greater than the minimum slopes specified by CSIR (2019).

PCSWMM requires roughness coefficients for all conduits. The closed conduits were all considered to be concrete pipes and were provided with a roughness coefficient of 0.02 following the *User's Guide to SWMM5* (James et al., 2010).

6.2.2.2 Open channels

The CoCT open data portal contains a GIS shapefile of the open watercourses throughout the city (CoCT, 2018). This shapefile includes all the natural and altered waterways interconnecting the conveyance network. The shapefile provided the spatial location of the channels, but no geometric data was provided.

The channel sections were developed in one of two ways depending on the section type. Natural channel sections (Figure 6-2 left) were developed using PCSWMM's Transect Creator tool. The tool uses elevation data from a DEM to create transects along the natural sections of the river at specified points. Due to the highly variable geometries of natural channels, transects were created at 50 m intervals. Constructed channels with regular sections (Figure 6-2 right) were developed through site visits to measure selected channel sections. As the channel sections are extensive, there are many culverts present. These were not provided on the CoCT shapefile and had to be identified by satellite imagery and measured during site visits in order to include them in the PCSWMM model.

All open channels require a roughness coefficient, as with the closed pipe network. As the composition and lining of the open channels were not consistent, the different coefficients were estimated using the *User's Guide to SWMM5* (James et al., 2010) (Appendix B).

6.2.2.3 Manholes

As with the pipe network, the manhole GIS shapefile was missing a lot of data (invert and cover levels). PCSWMM's Elevation from DEM tool was used to estimate the missing cover levels. Once the cover levels were determined, the missing invert levels were initially estimated by deducting 2 m from the cover levels. The invert levels were adjusted in conjunction with the pipe slopes to meet the recommended minimums in an iterative process. The final manhole invert levels supported a network that reasonably represents the physical system.

Figure 6-2: Examples of Irregular (left) and Constructed Channels with Regular Sections (right)

6.2.3 Stormwater ponds

Three stormwater ponds were included in the model: the Little Princess Vlei, Langevlei, and Maynardville Park Pond, due to their size and location within the catchment area. Little Princess

Vlei and Langevlei improve the water quality of the system by removing nutrients, faecal bacteria and suspended solids (Brown & Magoba, 2009), additionally, all three ponds provide flood attenuation. These were modelled as ‘storages’ in PCSWMM. Storages store runoff according to specified storage curves. PCSWMM’s Storage Creator tool was utilised to develop curves for the three ponds. This tool uses a DEM to obtain elevation points to create an area-depth curve that PCSWMM then uses to determine storage unit volumes. The storage unit outflow controls were developed by measuring the selected channel sections that took stormwater away from the pond systems.

6.2.4 Calibration

Calibration is an essential step in developing a ‘useful’ model. As shown in the preceding sections, many input values had to be estimated to develop the base model of the Diep Catchment. The calibration and verification are undertaken to reduce the uncertainty of crucial estimated parameters within a model (James, 2005).

PCSWMM’s Sensitivity Radio Tuning Calibration (SRTC) tool was utilised to calibrate the model. Using a calibration tool allows users to remove error-prone processes that may lead to a poorly calibrated model as it ‘*reduces a virtually unmanageable task to a few mouse clicks and a couple sips of coffee*’ (James, 2005). The tool runs a sensitivity analysis on specified parameters based on uncertainty estimations (CHI, 2021). Each calibration parameter is provided with a user-defined uncertainty percentage. If a parameter was provided with an uncertainty of 5%, the calibration process would simulate the model twice, once with the parameter 5% higher than its original value and once with the parameter 5% lower than its original value. The calibration tool generates a sensitivity gradient for each calibrated parameter based on the two simulations and allows for linear interpolation between the two results. Uncertainties were assigned to each parameter based on suggestions from James (2005).

The parameters calibrated included the sub-catchment properties (width, slope, impervious percentage), Manning’s coefficients, and depression storage for both pervious and impervious areas, percentage of impervious area with no depression storage, percentage of runoff routed to pervious areas, and the Green & Ampt parameters (Section 4.3.2). The sub-catchment parameters were the focus of the calibration process as most of them were derived from other data sets and significantly altered the model’s outcomes. As PCSWMM’s automated SRTC tool was utilised for the calibration and verification process, the effect of each of the calibration parameters on the runoff hydrograph is not detailed.

PCSWMM calibrates models based on the created liner interpolations; thus, the calibrated parameters must be verified. 26 storm events were identified from the observed rainfall data and were used in the calibration and validation process. The identified storm events were split 2:1, with 17 events used to calibrate the model and the remaining nine used to verify calibrated parameters. This method follows those used in similar studies (Mancipe-Munoz et al., 2014).

The model was calibrated against the CoCT streamflow monitor DIEP05CS (Section 4.3.4). The calibration and verification process only considered the gauged section of the catchment (Figure 6-3); however, the calibrated parameters were adjusted equally in both the gauged and ungauged sections. At the end of the calibration and verification process, the model was deemed an acceptable representation of the physical catchment.

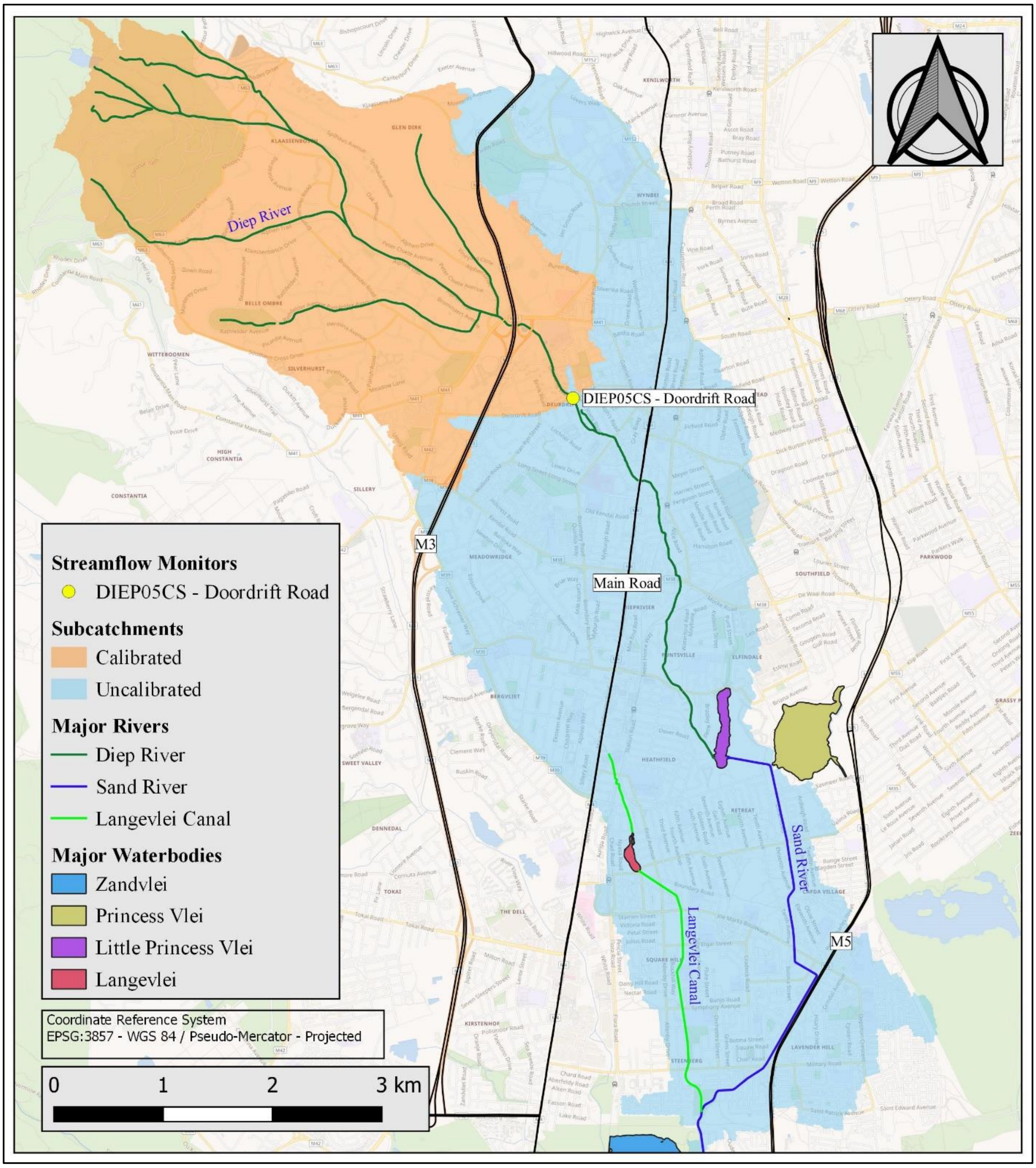


Figure 6-3: Gauged Section of the Diep Catchment

Table 6-2 presents the results of the calibration processes. The calibration focused on total flow, max flow, and comparison to the hydrograph. Three error measurements were used during the calibration:

1. Integral Square Error Rating (ISE) – rating from poor to excellent
2. Nash-Sutcliffe Efficiency (NSE) – possible range of -∞ to 1
3. Coefficient of Determination (R^2) – possible range from 0 to 1.

James (2005) notes that calibration and verification are of utmost importance during the modelling process; however, there is no standard for the accuracy of the calibration and verification process. Moriasi *et al*. (2007) and Golmohammadi *et al*. (2014) suggest that an NSE value between 0 and 1 and an R^2 of greater than 0.5 indicates an acceptable level of performance. Santhi *et al*. (2001) recommend an NSE value greater than 0.5 and an R^2 value greater than 0.6. The calibration was considered acceptable for this project when both NSE and R^2 were greater than 0.5.

Table 6-2: Calibration Error Functions

Parameter	**Error Function**	**Calibrated**	**Verified**
Total Flow	ISE Rating	Good	Fair
	NSE	0.883	0.842
	R^2	0.943	0.935
Max Flow	ISE Rating	Fair	Fair
	NSE	0.701	0.707
	R^2	0.748	0.747
Hydrograph	ISE Rating	Fair	Fair
	NSE	0.685	0.64
	R^2	0.724	0.721

Several factors limited the standard of the calibration process. These are discussed below:

- The rain gauges all provided daily data that had to be disaggregated (Section 5.2), limiting their calibration use. The disaggregated rainfall represents a statistically likely event and not the actual rainfall event.
- No rainfall gauges were of an acceptable standard in the lower reaches of the catchment (Chapter 5.). The rainfall variability within the lower reaches of the Diep Catchment was not adequately represented as only a single rain gauge, Vineyard Road, provided useable data for the area.

- The only acceptable CoCT streamflow sensor was in the upper middle region of the catchment, allowing only the section above the gauge to be calibrated. However, the gauge's inability to measure low flows negatively impacted the calibration process (Section 4.3.4).

Figure 6-4 provides storm event hydrographs of observed and modelled data after the completion of the calibration and verification processes on PCSWMM. The calibration error functions provided in Figure 6-4 indicate that the storm is calibrated to an acceptable standard as the NSE and R^2 values both exceed 0.5.

The calibration and verification processes focused on the total and maximum runoff flows before considering the comparison to the hydrograph. Additionally, as the rainfall data had to be disaggregated, the micro variations within the actual rainfall were not represented in the disaggregated data. This prevents the graph from presenting a well-fitting visual relationship between the observed and measured hydrographs. However, the overall calibration is suitable, as presented by Table 6-2.

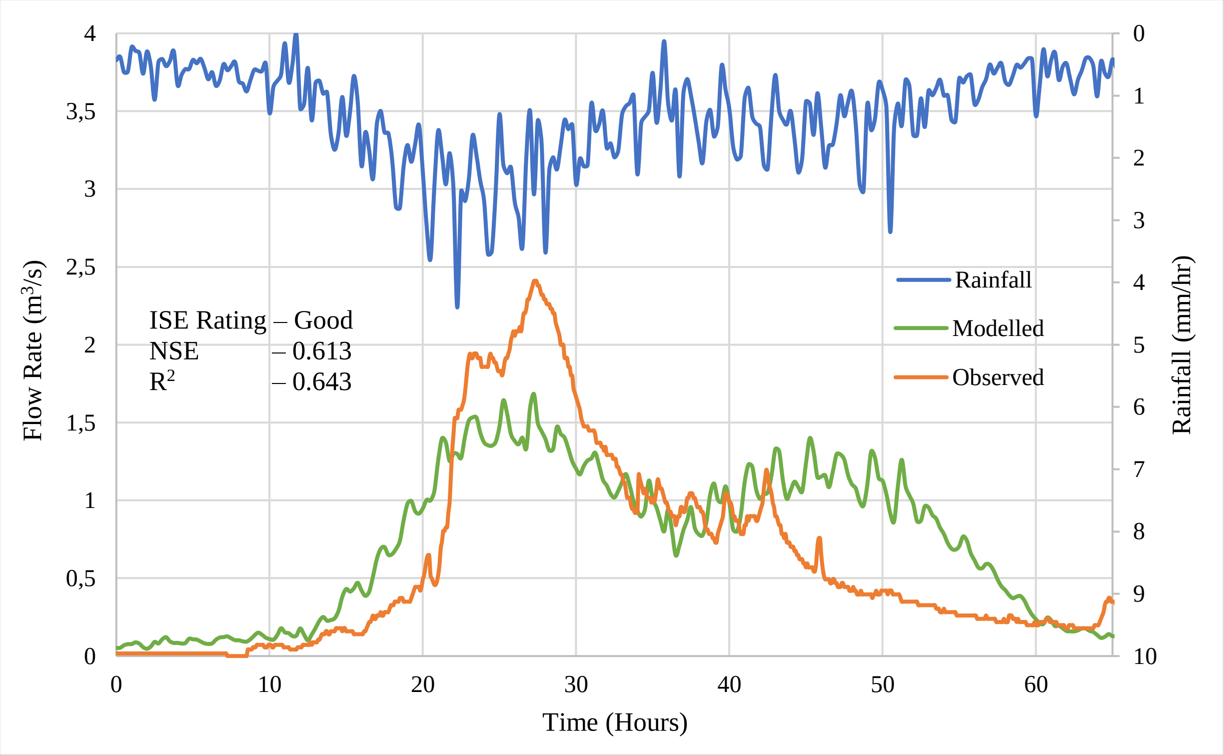


Figure 6-4: Modelled and Observed Hydrographs of a Typical Storm Event
(27-30 August 2013)

6.3 Summary

This chapter provides a detailed description of the processes employed to develop the hydraulic and hydrological model on PCSWMM. Several of PCSWMM's built-in tools were used to aid in the development. The model calibration and verification processes were also described. To develop a model capable of modelling the improvements achieved with SuDS, water quality had to be modelled as well and this is described in Chapter 7.

7. PCSWMM Water Quality Model

This section describes the procedures used to test various water quality parameters in the Diep River, Sand River and Langevlei Canal. Further, it details the development of Event Mean Concentration (EMC) values used within the hydrological model.

7.1 Testing

The testing phase of this project was intended to develop a greater understanding of the pollutant flows through the various rivers in the study area. Due to Covid-19 and the subsequent restrictions, access to water testing equipment and water quality labs was not feasible for most of 2020. To overcome this, water quality tests to measure Electrical Conductivity (EC), Total Dissolved Solids (TDS), pH and temperature were conducted at weekly intervals at several locations along the river network using three OHAUS pen meters: ST20 to test pH, ST20C-B to test EC and ST20T-A to test TDS (OHAUS, n.d.). Additionally, all three pen meters test temperature. The test locations (Figure 7-2) were selected based on points of interest along the main river networks and accessibility, such as at the convergence of rivers, upstream and downstream of major water bodies, and areas thought to contribute poor quality runoff to the river systems. The pen meters were calibrated before each round of testing and rinsed thoroughly after each test as directed by their instruction manuals. The pen meters were not placed directly into the river because the flowing rivers did not provide a stable reading. Therefore, plastic containers that had been previously rinsed with distilled water were dipped into the rivers and filled, and the pen meters were then used to measure the water in the containers (Figure 7-1).

Figure 7-1: Measuring a water sample with the pen meter

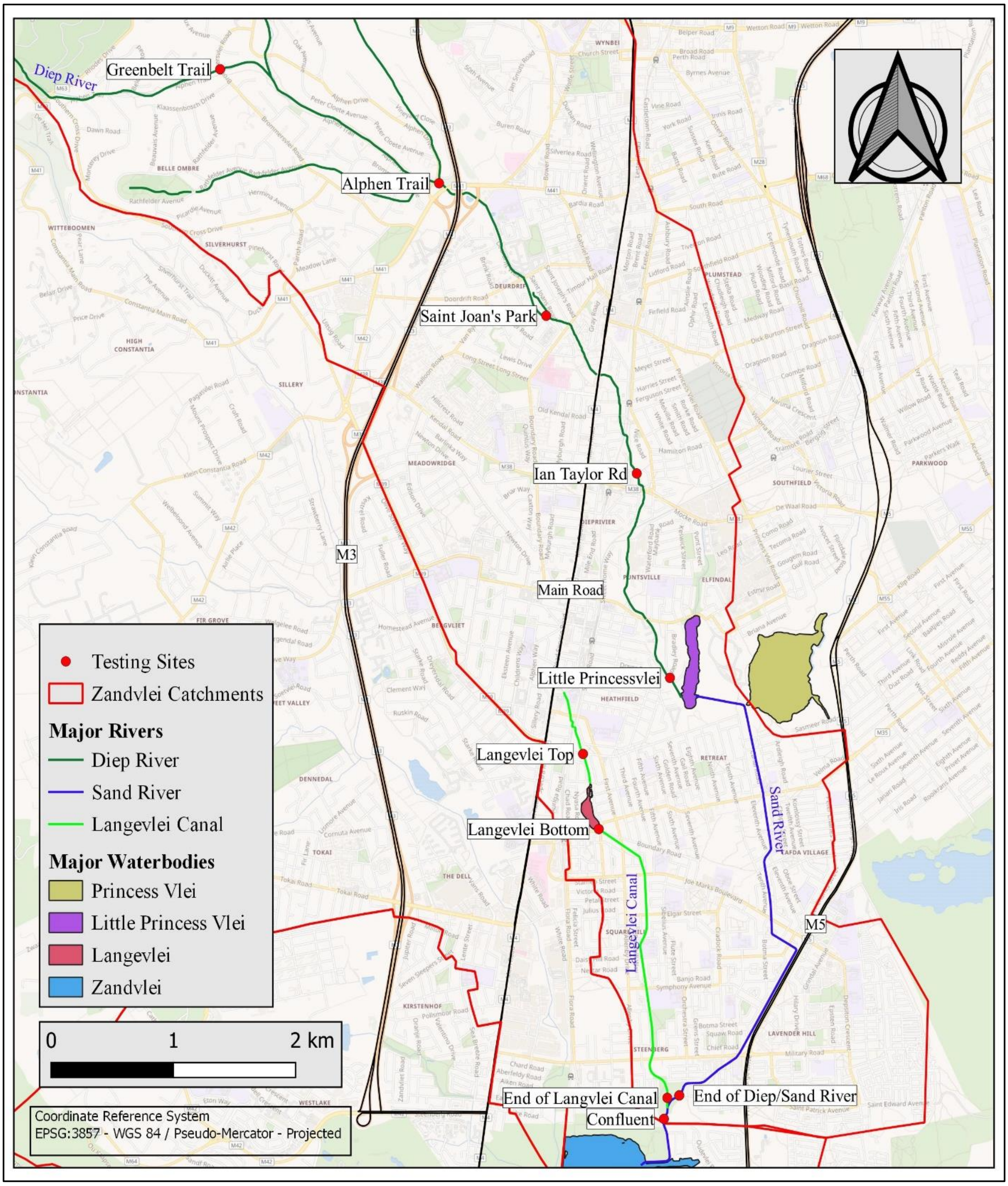


Figure 7-2: Water Quality Test Sites

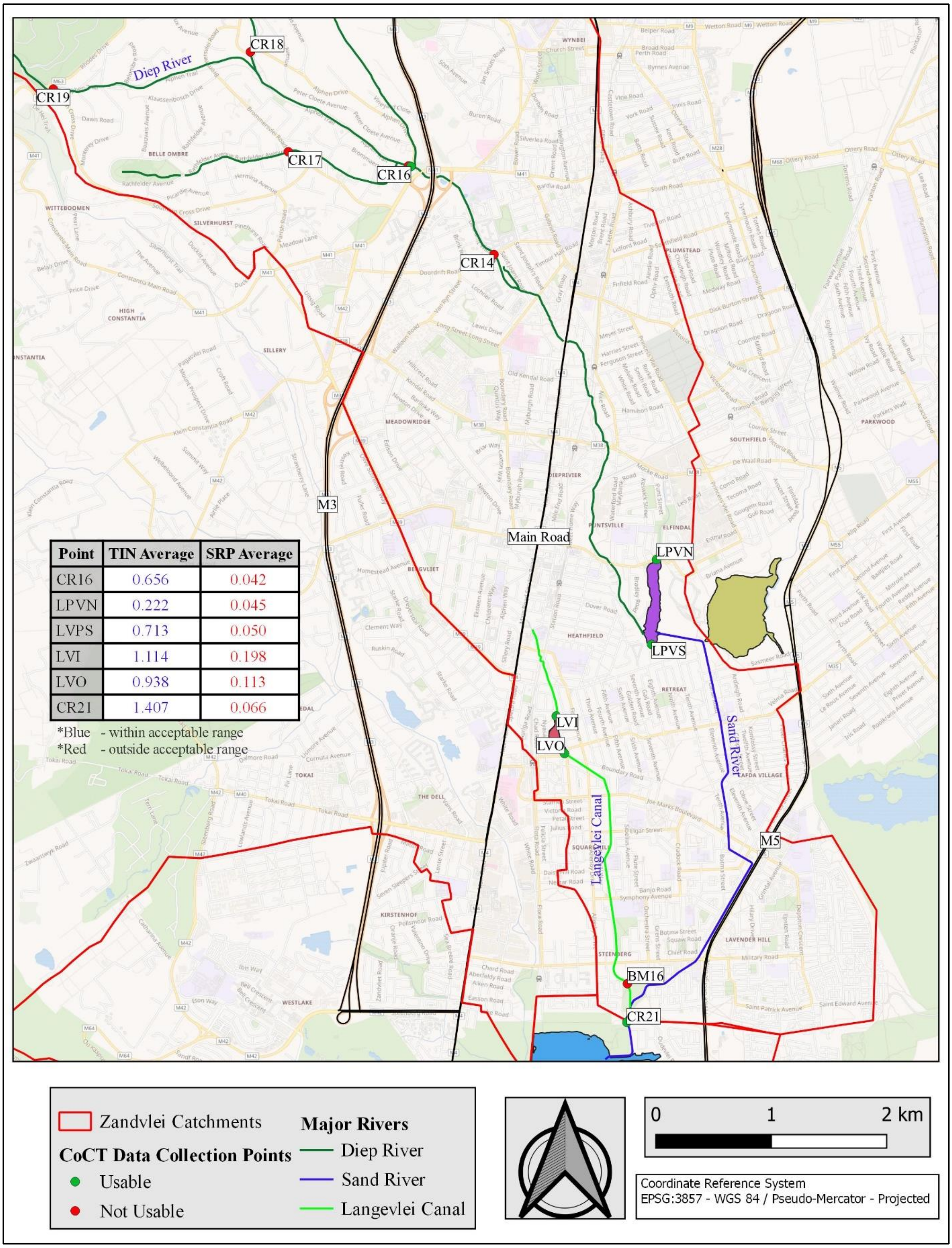
The pen meters were only able to provide data on EC, TDS, pH, and temperature. These parameters often serve as indicators of possible problem areas, with EC values, in particular, being strongly correlated with pollution concentrations (Das et al., 2006), however, it is unclear whether this correlation extends to nutrient concentrations. Aquatic organisms and ecosystems are very sensitive to water pH (Yu et al., 2021), and changes in pH have been shown to affect certain organisms within estuaries directly. Decreases in pH can increase a waterbody or river's heavy metal and nutrient concentrations. High pH levels are known to increase the toxicity of certain heavy metals in estuaries (Attrill & Power, 2000). The data obtained from this testing process was used as a preliminary guide to possible SuDS intervention sites. The testing results (summary in Table 7-1 with the complete set in Appendix C) indicated that the Langevlei Canal had a bigger problem with water quality than the Diep/Sand Rivers, with considerably higher EC, pH, and TDS readings.

Table 7-1: Water Quality Test Results

	EC (µS/cm)			pH			TDS (mg/L)		
	Mean	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**
Confluent	1100	1800	630	8.3	8.8	8.0	600	1000	340
End of Diep/Sand River	800	1500	610	8.1	8.8	7.1	440	810	330
Little Princessvlei	540	980	360	8.2	8.5	7.8	300	540	200
Ian Taylor Rd	470	870	350	8.1	8.6	7.7	260	480	190
St. Joan's Park	430	790	320	8.0	8.3	7.6	240	440	180
Alphen Trail	390	650	290	7.8	8.4	7.3	220	360	160
Greenbelt Trail	320	540	160	7.7	8.0	7.6	170	300	88
End of Langevlei Canal	940	1200	440	8.5	9.0	8.1	520	680	240
Langevlei Bottom	720	1100	560	8.4	9.2	7.5	390	600	310
Langevlei Top	1000	1200	640	8.7	9.4	8.1	550	660	350

7.2 City of Cape Town water quality data

The CoCT Scientific Services Branch has been monitoring the water quality of many of its rivers for decades. Monthly grab samples are taken, and the following parameters are measured: Dissolved Oxygen, Temperature, Salinity, pH, Suspended Solids, Conductivity, Total Phosphates, Orthophosphates, Nitrites and Nitrates, Ammonia, and *E. coli*. This data was obtained from the CoCT and contained records spanning from 2000 to 2020 for 12 locations within the catchment (Figure 7-3). However, after analysing the data, it became apparent that many of the sampling points were inappropriate for use in this project due to a lack of stormwater constituents measured and a low number of data entries leaving only six of the sampling points; CR16, Little Princessvlei North (LPVN), Little Princessvlei South (LPVS), Langevlei Inflow (LVI), Langevlei Outflow (LVO) and CR21 (Figure 7-3). The data from these sites were used to identify sections of the stormwater network that increased the nutrient levels of the river and guide preliminary SuDS intervention sites.



Point	TIN Average	SRP Average
CR16	0.656	0.042
LPVN	0.222	0.045
LVPS	0.713	0.050
LVI	1.114	0.198
LVO	0.938	0.113
CR21	1.407	0.066

*Blue - within acceptable range
*Red - outside acceptable range

Coordinate Reference System
EPSG:3857 - WGS 84 / Pseudo-Mercator - Projected

Figure 7-3: CoCT Grab Sample Points – adapted from Wikimedia Maps (Wikimedia, n.d.)

Figure 7-4: CR16 Sampling Point (outflow of Alphen Drive culvert)

Figure 7-5: Little Princessvlei North (LPVN) Sampling Point

Figure 7-6: Langevlei Inflow (LVI) Sampling Point

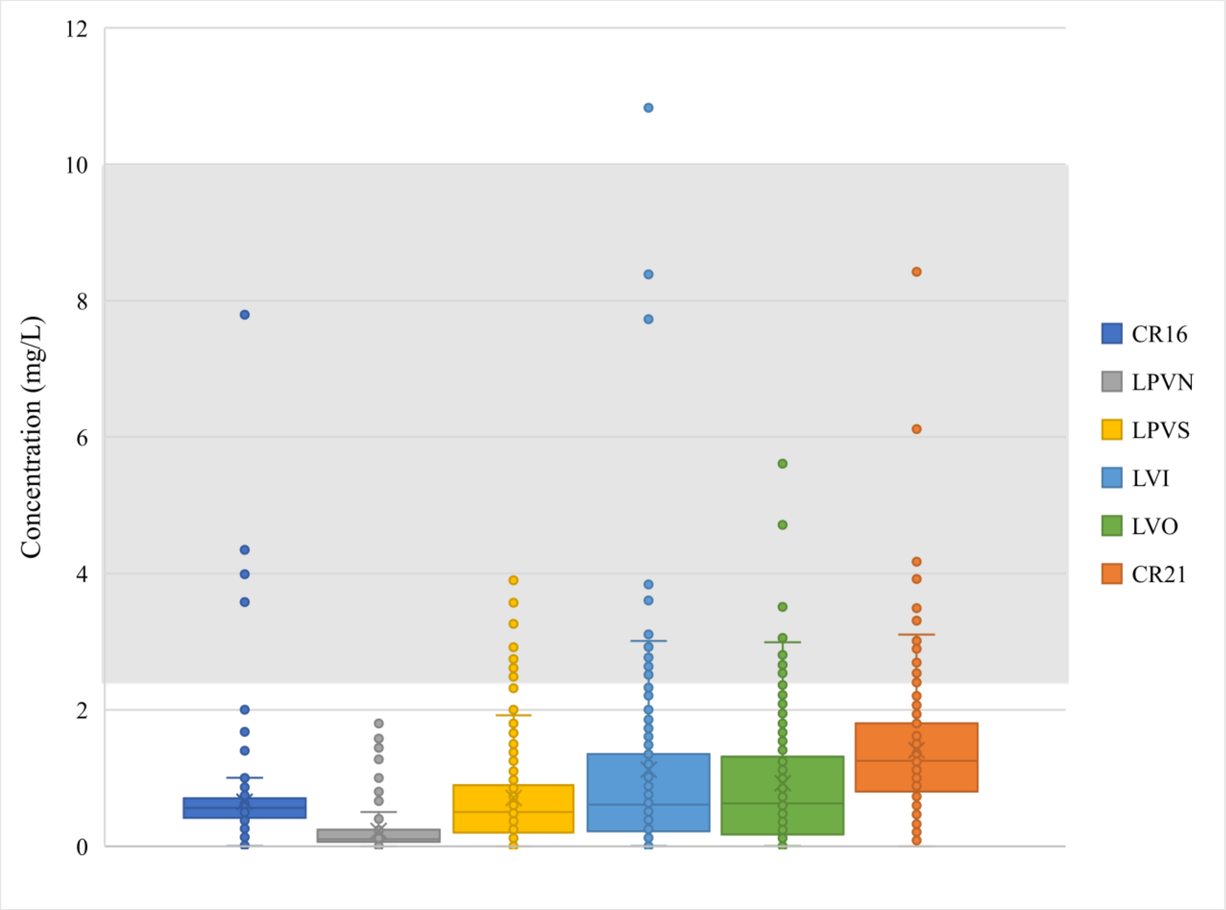
Figure 7-7: Langevlei Outflow (LVO) Sampling Point

Figure 7-8: CR21 Sampling Point (after confluent of Sand River and Langevlei Canal)

7.2.1 Total Inorganic Nitrogen

The mean TIN concentrations measured by the CoCT fell below the eutrophic range (Table 2-7), shown in Figure 7-9. However, the Langevlei Canal sites (LVI and LVO) and the Sand River site after the confluent (CR21) had multiple measurements that fall within the eutrophic range and may cause the estuary to experience eutrophic periods.

LVI and LVO provided mean measurements that were double the TIN concentrations seen at the Diep River sites (CR16, LPVN and LPVS). However, the testing site at the bottom of the catchment provided the largest readings. This may be due to the high-density urban areas present in the lower reaches of the catchment that drain into the river system.



*Grey band represents the eutrophic range

Figure 7-9: TIN Concentrations in Diep Catchment (2000 – 2020)

The data indicates a trend of increased TIN concentrations during winter at all of the monitoring sites apart from CR16. The increased winter concentrations can be attributed to the increased rainfall and runoff of stormwater received by water bodies. As the runoff increases, the potential for nutrients and sediments to be collected and delivered to rivers and water bodies increases.

The nutrients and sediments used as indicators build up on surfaces during antecedent dry days; however, the build-up is limited due to physical processes such as wind that redisperse nutrients and sediments (Tiefenthaler et al., 2002). As few high runoff flows are experienced in summer, the nutrients and sediments are not generally collected or deposited into the river systems during this period. The low rainfall and associated low runoff flows generally experienced in summer correlate with the observed TIN concentration drops in the river network.

On the other hand, CR16 shows a mean increase of 30% in TIN concentrations from winter to summer. This may be due to the agricultural lands that drain into the river network upstream of this point. Agricultural fertilizers and animal excrement are major sources of inorganic nitrogen. Additionally, the highly affluent areas upstream of CR16 are characterised by residences with extensive gardens that may be plied with fertilisers and substantial water during summer periods that may be contributing to the runoff and hence the increased TIN levels. Figure 7-10 provides the mean seasonal TIN concentrations.

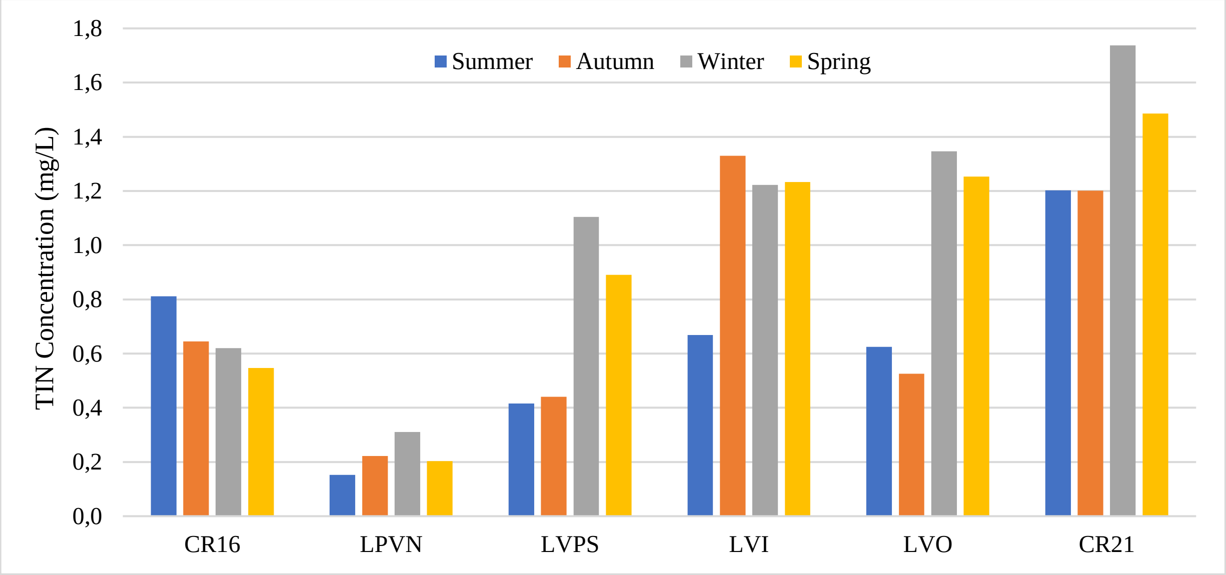
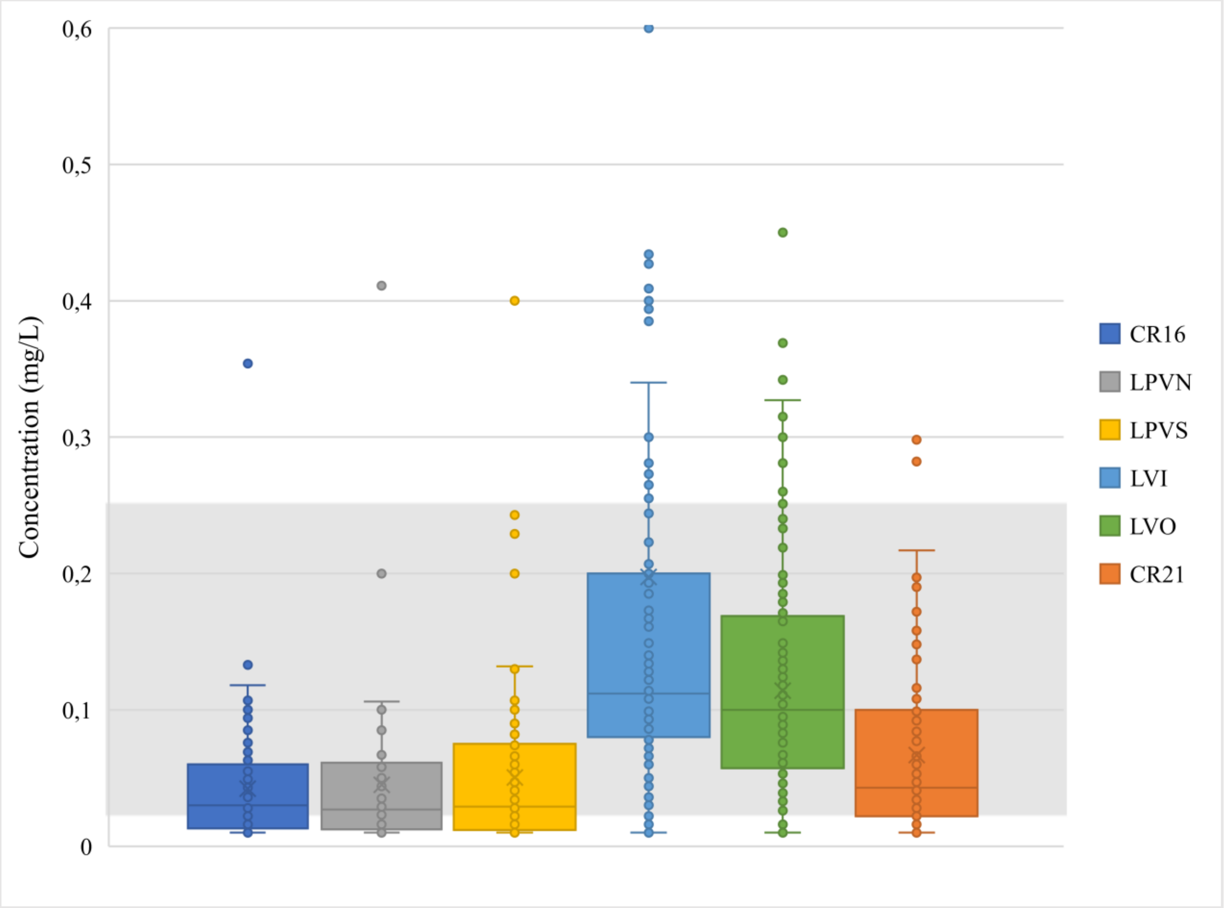


Figure 7-10: Seasonal Mean TIN Concentrations at Diep Catchment Monitoring Sites (2000 – 2020)

7.2.2 Soluble Ready Phosphorus

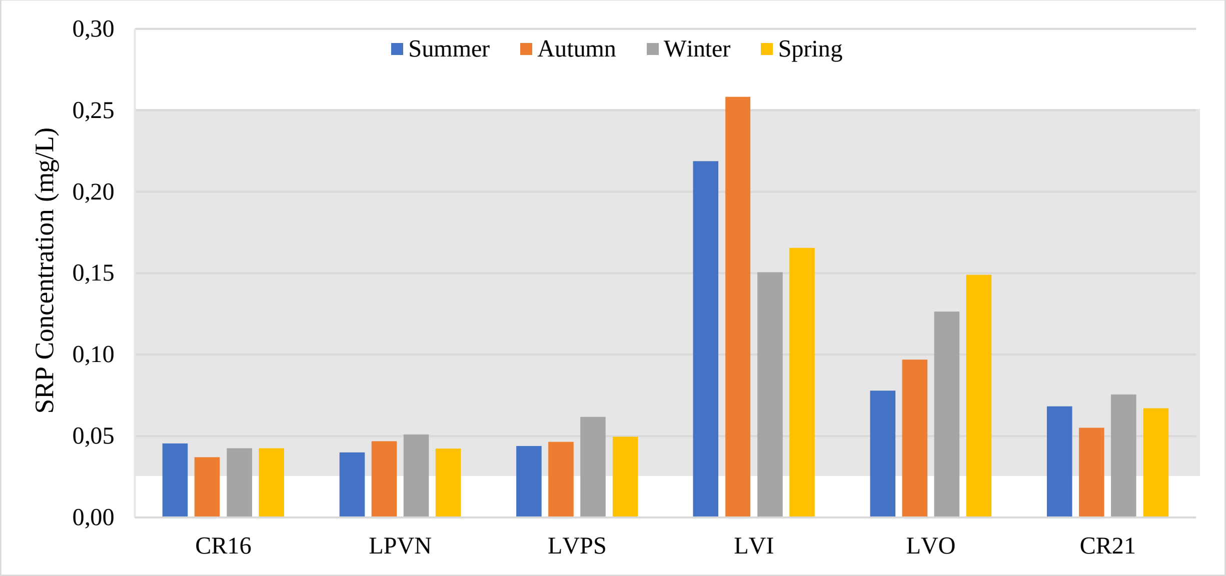
The measured SRP mean concentrations fell within the eutrophic range at every CoCT monitoring site within the catchment. Langevlei Vlei Inflow (LVI) and Langevlei Outflow (LVO) (Figure 7-11) consistently indicated the highest concentrations, with many readings above the upper limit of the eutrophic range. This shows potential for a hypertrophic state with highly productive algae and plant growth and excessively low biodiversity. CR16 (below Alphen Road along the Diep River), Little Princessvlei North (LPVN) and Little Princessvlei South (LPVS) presented mean concentrations that were above the lower limit of the eutrophic range, albeit marginally. CR21 (after the confluent of the Diep/Sand River network and Langevlei Canal) has a mean concentration that falls in between those seen from the Sand River and the Langevlei Canal. There is a large drop in SRP between LVO and CR21. As SRP is often introduced into a system from fertilisers (DWAF, 1996), the high concentrations at LVI and LVO may be due to the large areas of low-density residences, often accompanied by extensive lawns and multiple sports fields, upstream of the monitoring sites. There are no large producers of SRP between LVO and CR21; thus, the inflow of runoff in this area may dilute the SRP concentration at CR21.



*Grey band represents the eutrophic range

Figure 7-11: SRP Concentrations in Diep Catchment (2000 – 2020)

Figure 7-12 provides the mean seasonal SRP concentrations. No consistent seasonal trend is apparent, but LPVN, LVPS, LVO and CR21 all had higher mean concentrations in winter than in summer. As with the trends seen in TIN concentrations, this may be due to the limited build-up of nutrients and sediments used as indicators (because of physical processes such as wind that redisperse the constituents) and the increased runoff during winter. CR16 concentrations do not vary significantly between seasons; however, LVI has a significantly larger summer concentration with a mean increase of 45% over the 20-year monitoring period.



*Grey band represents the eutrophic range

Figure 7-12: Seasonal SRP Mean Concentrations at Diep Catchment Monitoring Sites (2000 – 2020)

7.3 EMC value development

As the primary objective of this project was to determine the effectiveness of SuDS in reducing the indicator loads that enter Zandvlei, EMCs were used to model stormwater quality rather than more data-intensive process-based methods (Section 2.6).

River and water body pollutants enter the system in two main ways: point and diffuse or non-point sources. Point pollution has always been identified as a significant issue, however, it is relatively easy to identify and address. Meanwhile, the high population density of cities and the frequently poor drainage systems that service them have resulted in urban non-point pollution becoming an increasingly serious global problem (Li *et al*., 2017).

While the CoCT grab samples are highly valuable in locating areas of high pollutant concentrations and guiding SuDS deployment, they are not directly usable in the PCSWMM model. PCSWMM requires EMC values to model pollutant wash-off and transportation through the network. Each land use within the catchment can be associated with a separate EMC for each pollutant (Lin, 2004).

Preliminary EMC values (Appendix E) were developed for the land uses in the catchment from published data (District Department of the Environment, 2014; Järveläinen *et al*., 2017; Kayhanian *et al*., 2007; Mitchell, 2005; Nordeidet *et al*., 2004; Song *et al*., 2019; Tuomela *et al*., 2019; USEPA, 1983; Wicke *et al*., 2021); however, these were all European or American studies. EMC values vary with geographic locations (Tuomela et al., 2019) but no Cape Town data was available. Therefore, the published values had to be adjusted for the Cape Town context. The hydrological model simulation was run with the preliminary EMC values, and the calculated indicator concentrations were compared to the CoCT water quality data for the study area. The EMC values were adjusted for each land use until the calculated concentrations were within an acceptable range of the measured concentrations at multiple points. Table 7-2 provides the EMC values used in the model. Values were developed for SRP and TIN as they are the primary causes of eutrophication (Section 2.4), and Total Phosphorus (TP) and Total Suspended Solids (TSS) as the CoCT guidelines (Section 2.8) for the management of stormwater impacts requires developers to achieve TP and TSS reductions of 45% and 80% respectively.

Table 7-2: EMC Values used in the model simulations (mg/L)

Land use	**SRP/OP**	**TIN**	**TP**	**TSS**
Agricultural	0.300	1.284	1.05	30.0
Commercial	0.150	1.500	0.15	23.0
Environmental Conservation	0.080	0.420	0.05	12.0
Industrial	0.110	0.804	0.10	6.5
Institutional	0.110	0.918	0.165	8.96
Public Open Space	0.080	1.188	0.20	10.0
Residential – High	0.140	1.500	0.45	7.0
Residential – Medium	0.042	0.400	0.25	10.0
Residential – Low	0.041	1.000	0.05	6.0
Residential – Very Low	0.160	1.600	0.40	22.0
Rural	0.029	0.675	0.10	8.0
School Grounds	0.123	0.600	0.25	7.0
Sports Fields	0.022	0.500	0.165	7.17
Roadways	0.011	1.446	0.10	8.5
Train Line	0.022	1.200	0.05	7.39

7.4 Modelling SuDS in PCSWMM

The selection and placement of SuDS were based on several key aspects (Section 2.2.5). The most limiting factor in this project was available open space as SuDS can require large areas. Open space can be very limited in urban environments, such as in the Diep Catchment. Although there were several open spaces available for SuDS implementation, the location of these concerning their proximity to the river network and the presence of existing infrastructure, such as pipe networks, had to be considered. The source of indicator loads was another guiding aspect when placing SuDS. Several areas, such as large agricultural and industrial areas, appear to be introducing significant indicator loads into the river system as identified from the CoCT water quality data (Section 7.2). These areas became the primary targets for SuDS intervention.

SuDS may be implemented in PCSWMM using the '*LID Control*' tool. The tool has nine SuDS available (Table 7-3). Unfortunately, no Regional Controls are included in this tool; however, it is possible to model Regional Controls by manipulating landscapes, conduits, junctions, and storage units.

Table 7-3: SuDS readily available in PCSWMM (CHI, 2019)

Available in '*LID Control*' Tool	
Source Control	**Local Control**
Rain Gardens	Bio-retention Cells
Green Roofs	Infiltration Trenches
Rain Barrels	Vegetative Swales
Rooftop Disconnection	
Permeable Pavements	
Possible Regional Control SuDS	
Detention Pond	
Retention Pond	
Constructed Wetlands	

SuDS can be placed in a PCSWMM model in two separate ways (CHI, 2019). They can be placed in an existing sub-catchment where they displace a portion equal to the size of the SuDS (Figure 7-13 left). This approach allows multiple SuDS to be implemented in a single sub-catchment and allows the outflow from SuDS to be directed to a separate sub-catchment subarea or to the sub-catchment's outlet. However, this approach does not allow the creation of treatment trains as the outflow of one SuDS cannot be directed into the inflow of another SuDS. The second approach is slightly more intensive as it requires a new sub-catchment to be created for the sole purpose of housing a single SuDS (Figure 7-13 right). The latter approach was used during this project as it allows SuDS to be cascading with the outflow of one SuDS flowing into another one.

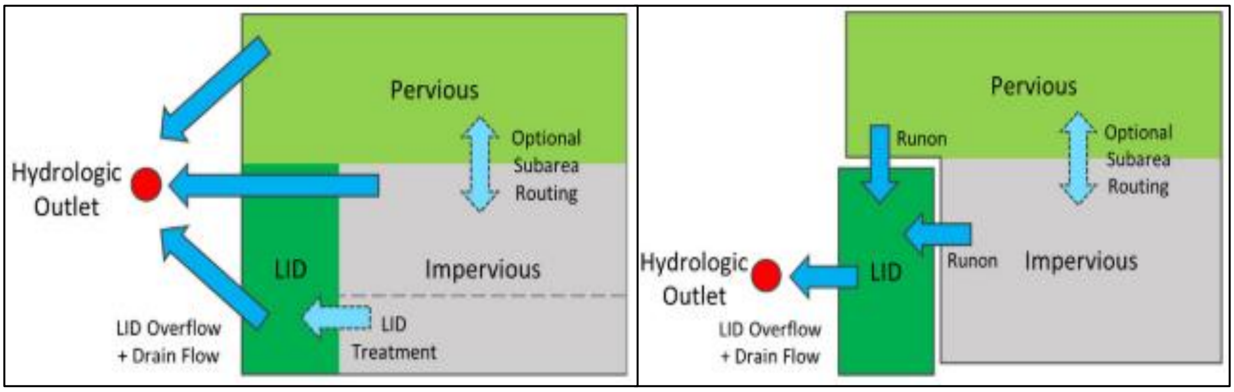


Figure 7-13: SuDS Placement Approaches (CHI, 2019)

The pollutant removal abilities of the SuDS in PCSWMM are modelled by the user assigning treatment functions for each pollutant. These can be basic percentages or include decay expressions to show deterioration of the SuDS over time (CHI, 2021). The treatment results can either be percentage removal or an outflow concentration.

HRT plays an important role in the removal capacity of large SuDS, such as constructed wetlands and retention ponds, with higher HRT often resulting in greater treatments (Section 2.5) (Rahman *et al*., 2020 & Toet *et al*., 2005). HRT is a ratio of the volume of a pond to the inflow flow rate and represents the length of contact time between the treatment system and the stormwater. Treatment equations were derived for this project as first order decay functions with Hydraulic Retention Time (HRT) as the independent variable. Decay functions require data specific to each intervention site; as it was not possible to collect this data during this project, generalised first order decay functions were derived from experimental data (Table 7-4) published for the four modelled indicators (SRP, TIN, TP and TSS) and are presented in Table 7-5.

Climatic factors, such as temperature, have a significant impact on the treatment ability of SuDS, with higher temperatures generally correlating with higher removal efficiencies (Akratos & Tsihrintzis, 2007). Therefore, only sources that investigated systems in similar climates to that of Cape Town were considered in the hope that this would, to some extent, cater for the impact of temperature variation. Figure 7-14 presents the TSS first order decay function curves indicating the fraction of TP remaining as a function of the HRT (SRP, TIN and TP first order decay function curves are provided in Appendix F). As the treatment abilities of wetlands and ponds depend on several other environmental and hydrological factors such as the vegetation type and porous media used, high-level and low-level treatment equations were derived for each indicator to provide a possible treatment range.

Table 7-4: Experimental Data showing Removal Efficiency (%)
from Abbassi *et al*. (2011), Akratos & Tsihrintzis (2007), and Kabenge *et al*. (2018).

Indicator	**HRT (hr)**	**48**	**72**	**96**	**120**	**144**	**192**	**336**	**480**
SRP	**High potential**	-	77.4	84.2	87.6	90.4	-	-	-
	Low potential	-	-	-	-	37.3	77.8	-	87.5
TIN	**High potential**	-	60.9	69.2	74.6	82.6	-	-	-
	Low potential	-	-	-	-	19.1	77.9	74.9	87.5
TP	**High potential**	-	-	-	-	91.7	97	-	89
	Low potential	5.1	-	17.2	-	30.5	63.4	-	-
TSS	**High potential**	-	92.6	95.9	96.3	98.4	-	-	-
	Low potential	-	72.2	84.5	86.1	94.1	-	-	-

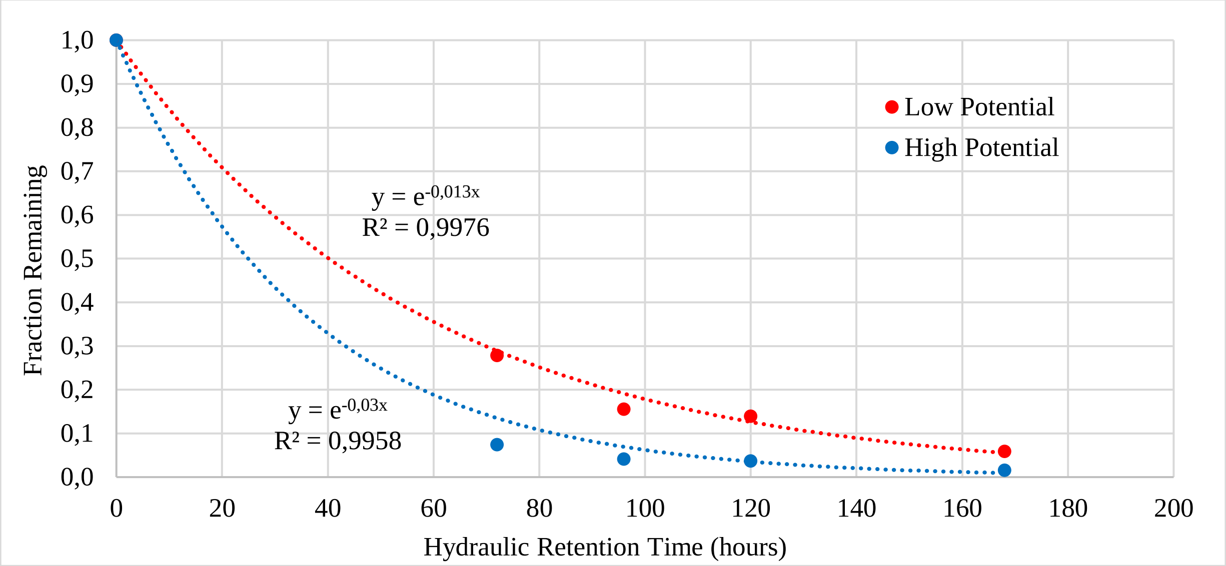


Figure 7-14: TSS Decay Function Curves

PCSWMM requires treatment equations be defined in terms of fractional removal. Therefore, the treatment equations were developed from the decay function curves in the form of:

$$R = 1 - e^{-k * HRT}$$ **Equation 7-1**

With:

R = fractional removal

k = decay coefficient

HRT = hydraulic retention time (hour)

Table 7-5: Treatment Equations – derived from experimental data collected by Abbassi *et al*. (2011); Akratos & Tsihrintzis (2007); and Kabenge *et al*. (2018)

Indicator	**Treatment Equations**	
	High-level Removal	**Low-level Removal**
SRP	$R = 1 – e^{-0.016 * HRT}$	$R = 1 – e^{-0.0048 * HRT}$
TIN	$R = 1 – e^{-0.012 * HRT}$	$R = 1 – e^{-0.004 * HRT}$
TP	$R = 1 – e^{-0.007 * HRT}$	$R = 1 – e^{-0.0043 * HRT}$
TSS	$R = 1 – e^{-0.03 * HRT}$	$R = 1 – e^{-0.013 * HRT}$

Debo & Reese (2003) recommend designing and sizing SuDS based on the required Water Quality Volume (WQV). WQV is the volume of water treated by SuDS during moderate events where the SuDS primary function is stormwater treatment. Often the 1 in 6-month storm is used, but any storm with a return index of less than a year or an event with a rainfall depth less than a specified value may be utilised. For this project, WQV was used to determine preliminary design sizes for SuDS. Equations 7-1 and 7-2 were used to calculate WQVs.

$$WQV = {}^{P\,R_V\,A}/_{1000}$$ **Equation 7-2**

With:

P = total rainfall depth required to be treated (mm)

R_V = volumetric runoff coefficient

A = area to be drained (m^2)

$$R_V = 0.05 + 0.009\,x\,I$$ **Equation 7-3**

With:

I = Impermeable cover percentage (%)

There are several methods to determine the rainfall depth to be treated, P. For this project, the depths were calculated by determining the 1 in 6-month design storm for each rain gauge. PCSWMM can use the input rainfall series to determine the maximum rainfall intensity (mm/hr) for a specified return period but not provide the required total rainfall depth (mm). The rainfall intensities were found for each of the five rain gauges used in the model (Figure 6-1), using the default Gringorten Plotting Position Formula. The maximum rainfall values were then used to create 24-hour design storms using PCSWMM’s Design Storm Creator. Once the design storms were generated, they provided a total depth (mm) for the WQV calculations. The design storms are presented in Table 7-6, while WQV calculations and further design requirements for each SuDS intervention utilised are provided in Appendix H.

Once the initial SuDS sizing was complete, it was necessary to ensure the maximum WQV depths of each SuDS type (Appendix H) were not exceeded during a WQV design event. During this project, the 6-month, 24-hour Soil Conservation Service (SCS) design storms generated in PCSWMM (Table 7-6) were used as the WQV design event. The outflow flow rate from any SuDS intervention during the WQV design event should not exceed that of the pre-development model (Section 8.2). If the maximum allowable WQV depth was exceeded in any SuDS or the outflow flow rate was too large during the WQV design event, the SuDS design and size were altered. This process was repeated until all the SuDS utilised in a model were deemed acceptable during the WQV design event.

Table 7-6: Rain Gauge Design Storms

Rain Gauge	Design Storm RI	Maximum Rainfall (mm/hr)	Total Rainfall Depth(mm)
Tafelberg	6-month	8.97	42.85
Versfeld Avenue		7.55	36.05
Wynberg		7.31	34.90
Corsair Crescent		10.53	50.30
Vineyard Road		6.62	31.62

Upon completing the design storm simulations, a long-term simulation was conducted. The long-term simulation used the five rainfall gauges with 12 years of data (Section 5). As well as having a maximum allowable WQV depth, each SuDS type has a maximum allowable emergency storage depth (Appendix H). The long-term simulation was conducted to ensure that no SuDS experienced a depth that exceeded this which would result in flooding of the surrounding areas. If the maximum allowable emergency storage depth was exceeded, the SuDS design was altered, and the process began again with the design storm simulations. The iterative process was conducted until neither the maximum allowable WQV depth nor the emergency storage depth was exceeded in any SuDS during the associated events. The conceptual SuDS designs, configurations and sizes are described in Section 8.3.

7.5 Summary

This chapter detailed the processes to develop the water quality model on PCSWMM. The creation of the model included three stages: stormwater testing and data collection, EMC development, and SuDS design and sizing. The combined PCSWMM model was used to develop additional scenarios, including a pre-development model and five SuDS scenarios investigating various treatment train designs, detailed in Chapter 8.

8. Model Scenarios

This section details the design of various scenario models developed on PCSWMM. Seven scenarios were developed, including: an ‘As-is’ scenario to represent the Diep Catchment in its current state, a ‘Pre-development’ scenario to illustrate what the condition of the estuary might have been before development and five SuDS scenarios with various treatment trains implemented.

8.1 As-is Scenario

The As-is scenario was developed to represent the Diep Catchment in its current state. It includes the topography and river networks (open channels, natural streams, pipes, and ponds) of the catchment and the current land uses observed in the catchment. The existing stormwater pipe network was limited to pipes with diameters larger than 675mm to maintain a simulation run time of less than a day. Additionally, three ponds, represented by storage units in PCSWMM, were included in the model: Langevlei, Little Princessvlei and Maynardville Park Pond. Several smaller ponds are to be found adjacent to the rivers; however, as these are either unutilised or provide negligible attenuation storage during large storm events, they were not included in the As-is model.

The model includes: five rain gauges, a pipe, canal and river network 34.6 km in length, 291 junctions, and a single outfall. The total catchment area was 26.72 km^2, split into 229 sub-catchments (Figure 6-1). The development of the As-is model is described in greater detail in Section 6.2.

8.2 Pre-development

A pre-development scenario was developed to estimate the Diep Catchment outflows before development began in the catchment. The scenario was important because it indicated the likely natural conditions, including possible indicator loads and flow rates, that probably best represent sustainable conditions. For this scenario, the following changes were made to the As-is model:

- All land-use types and subsequent catchment properties were set to ‘Environmental Conservation.’
- The pipe network, made up of circular conduits, was removed.
- Conduits with regular cross-sections were given more natural shapes instead of the rigid rectangular shape currently used.
- Culverts were removed and replaced with conduits.

- Manning’s roughness coefficients for conduits were changed to represent vegetative lined channels.

The scenario results are limited as the path taken by the river trunk is an altered one as the natural channels have been controlled to allow urbanisation. Unfortunately, it was not possible to recreate the natural flow paths as no data was available to do so. Additionally, the scenario was not calibrated as flow data was not available for a time before urbanisation. Thus, this scenario is merely a ‘best guess’.

8.3 SuDS scenarios

As the primary purpose of this project was to determine the feasibility of using SuDS to improve Zandvlei’s water quality, five SuDS treatment scenarios were developed:

- Scenario 1 is based on the concept of source controls and managing rainfall as close to its source as possible. It utilised subarea routing to simulate rooftop disconnections, rain gardens and infiltration trenches. Additionally, five swales were utilised.
- Scenario 2 reintroduces four existing wetlands and two retention ponds that lie adjacent to the river trunk back into the primary system. Currently, these systems are only used to attenuate stormwater during large storms. This scenario links them to the river to treat stormwater and provide attenuation.
- Scenario 3 sees the addition of a large wetland at the convergence of the Sand River and Langevlei Canal in the lower reaches of the catchment.
- Scenario 4 uses a combination of source controls from Scenario 1 and the new wetland developed in Scenario 3.
- Scenario 5 combines two wetlands and a retention pond from Scenario 2 with the new wetland developed in Scenario 3.

The proposed SuDS scenarios were theoretical. Each scenario is modelled with a high and low treatment ability to provide a possible treatment range. While they may present viable solutions, any implementation will require further investigations to determine site suitability, including limiting factors such as groundwater tables, soil suitability, environmental impacts, and existing infrastructure, which were all outside this project's scope.

8.3.1 Scenario 1 – Source Controls

Source controls are employed to capture, manage and treat stormwater as close to the source as possible (Armitage et al., 2013). Scenario 1 was developed using source controls to reduce runoff volumes from sites and thus reduce the pollutant loads received downstream.

Scenario 1 shows the effects that residential areas, schools, commercial areas, or any other area with pervious open space may have on reducing pollutants. In reality, this would be achieved by implementing rooftop disconnections, rain gardens and infiltration trenches to promote infiltration on-site and reduce runoff. Designing and modelling these systems for every site in PCSWMM is highly intensive and would introduce additional uncertainty into the model as many input parameters would be estimated; thus, an alternative approach was used. The scenario utilised PCSWMM's subarea routing function to reduce the runoff from various sites. PCSWMM sub-catchments are divided into three subareas, Pervious, Impervious, and Impervious with no depression storage. By default, all subareas are independently drained by the sub-catchment outlet. However, PCSWMM allows users to direct a percentage of the runoff from one subarea to another. Runoff from impervious subareas may be directed onto pervious subareas to allow infiltration and reduce runoff drained by the sub-catchment outlet (CHI, 2021). Sites with pervious areas such as large residences, farms, and schools had their runoff routed from the impervious areas to the pervious areas. Other land uses with large, impermeable surfaces such as car parks in commercial areas can utilise permeable pavements. To develop the treatment range for Scenario 1, a high and low subarea routing percentage was used for each land use. The higher percentages were reduced by 10% to provide the lower percentage. The high and low subarea routing percentages were then used to simulate the high and low reduction potentials, respectively. The subarea routing percentages are provided in Table 8-1.

Table 8-1: Subarea Routing Percentages

Land Use	Subarea Routing (%)	Land Use	Subarea Routing (%)
Agricultural	60 - 70	Residential – Low	75 - 85
Commercial	0	Residential – Very Low	90 - 100
Environmental Conservation	90 - 100	Rural	0
Industrial	0	School Grounds	50 - 60
Institutional	40 - 50	Sports Fields	90 - 100
Public Open Space	60 - 70	Roadways	0
Residential – High	0	Train Line	0
Residential – Medium	60 - 70		

Additionally, several swales were introduced to agricultural sites and other large open areas where slopes less than 3% were present (Figure 8-1). All swales were designed with a vegetation height and maximum design stormwater level of 100 mm. Additional swale design requirements are provided in Appendix H. Swale design and dimensions were adjusted until this criterion was met. The maximum runoff depth observed in each swale during the design storm simulation is provided in Table 8-2.

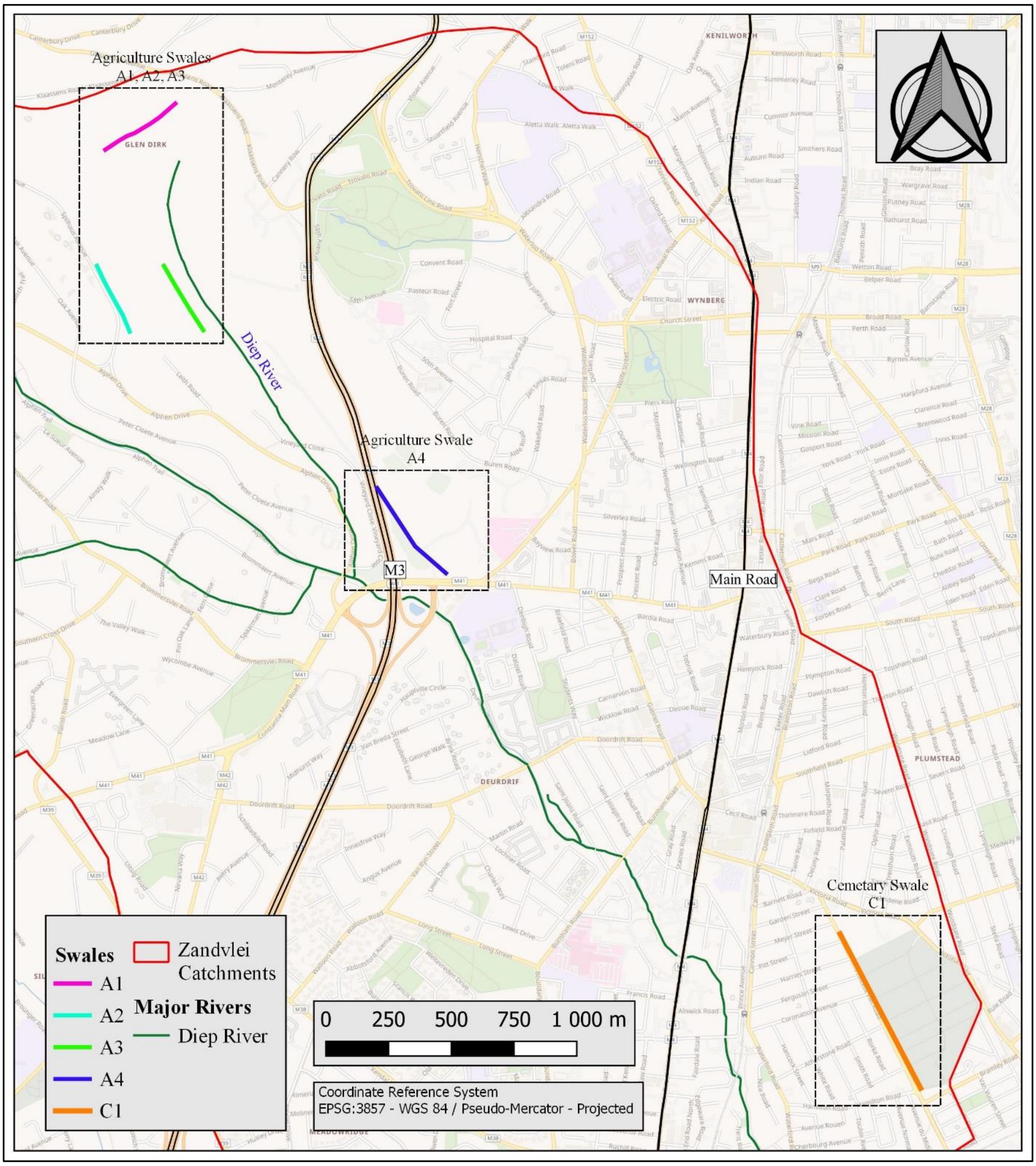


Figure 8-1: Scenario 1 Swale Locations – adapted from Wikimedia Maps (Wikimedia, n.d.)

Table 8-2: Swale Design Details and WQV Depth

Swale	Length (m)	Berm Height (m)	Side Slope (1:X)	Base Width (m)	Longitudinal Slope (%)	Maximum Design Storm Depth (mm)
A1	340	0.5	3	1.0	2.0	84
A2	300	0.5		1.7	2.0	95
A3	300	0.6		1.0	3.0	83
A4	430	0.5		1.5	2.3	81
C1	600	0.5		1.0	1.5	84

The agricultural areas on either side of the Simon Van Der Stel Freeway in the Constantia and Wynberg suburbs (Figure 8-1) are suspected of producing high indicator offloads. These areas produce crops that often require fertilisers, pesticides, and other products that may negatively impact runoff quality. The steep slopes in some of these areas can cause further contamination as high runoff velocities erode soils and gather suspended solids. As these are productive areas, large SuDS interventions are likely not realistic as they would reduce the productive agricultural land. Thus, swales were deemed the most effective interventions. Four swales were placed in these areas, details of which are provided in Table 8-2. The contours and site boundaries guided swale placement. Swales ran along the contours to reduce the slope and as close to boundaries as possible to reduce the intrusion to productive agricultural land. The catchment areas drained by the agricultural swales are shown in Figures 8-2 and 8-3. All runoff from the catchments is directed towards the swales.

Figure 8-2: Agricultural Areas drained by A1, A2 & A3

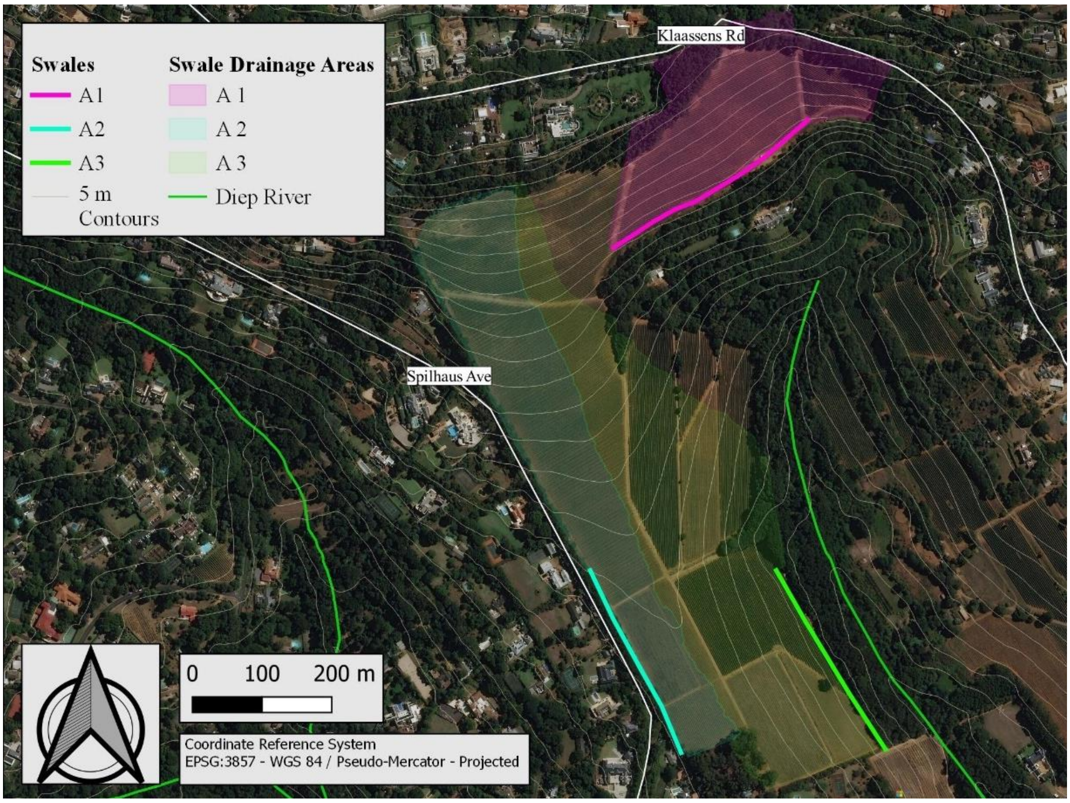


Figure 8-3: Agricultural Swales A1, A2 & A3 – from Bing Maps (Microsoft Bing, n.d.)

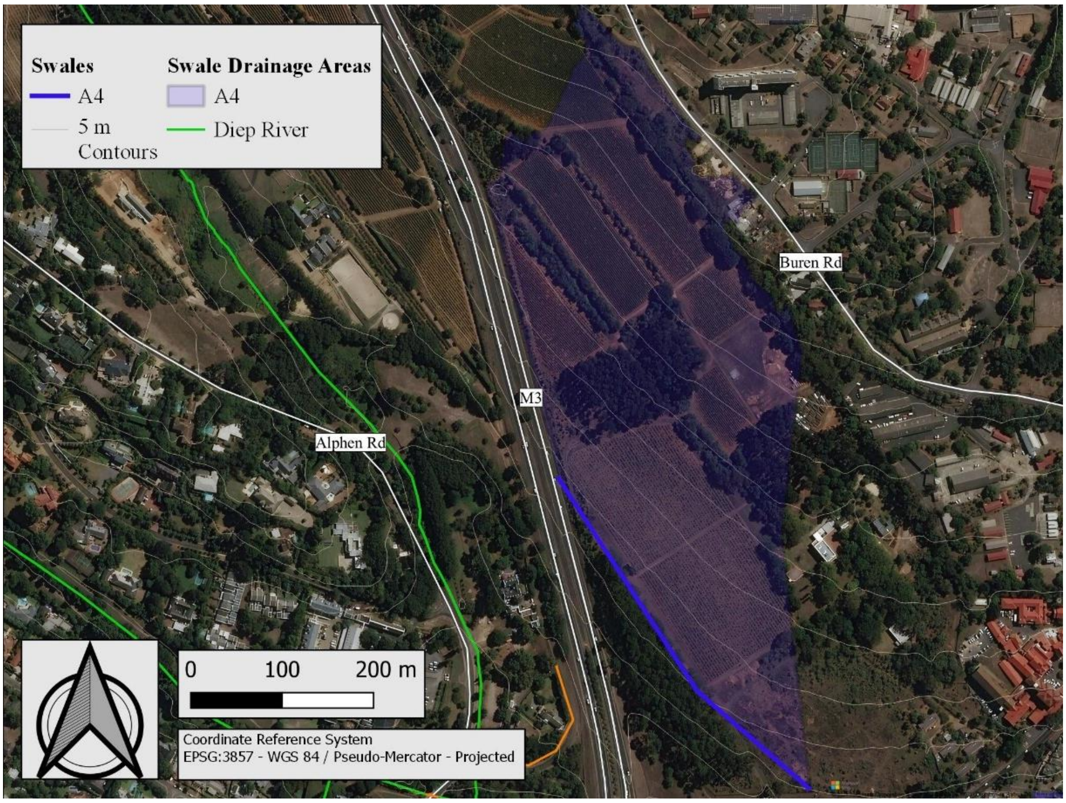


Figure 8-4: Agricultural Swales A4 – adapted from Bing Maps (Microsoft Bing, n.d.)

Figure 8-5: Cemetery Area to be drained by C1

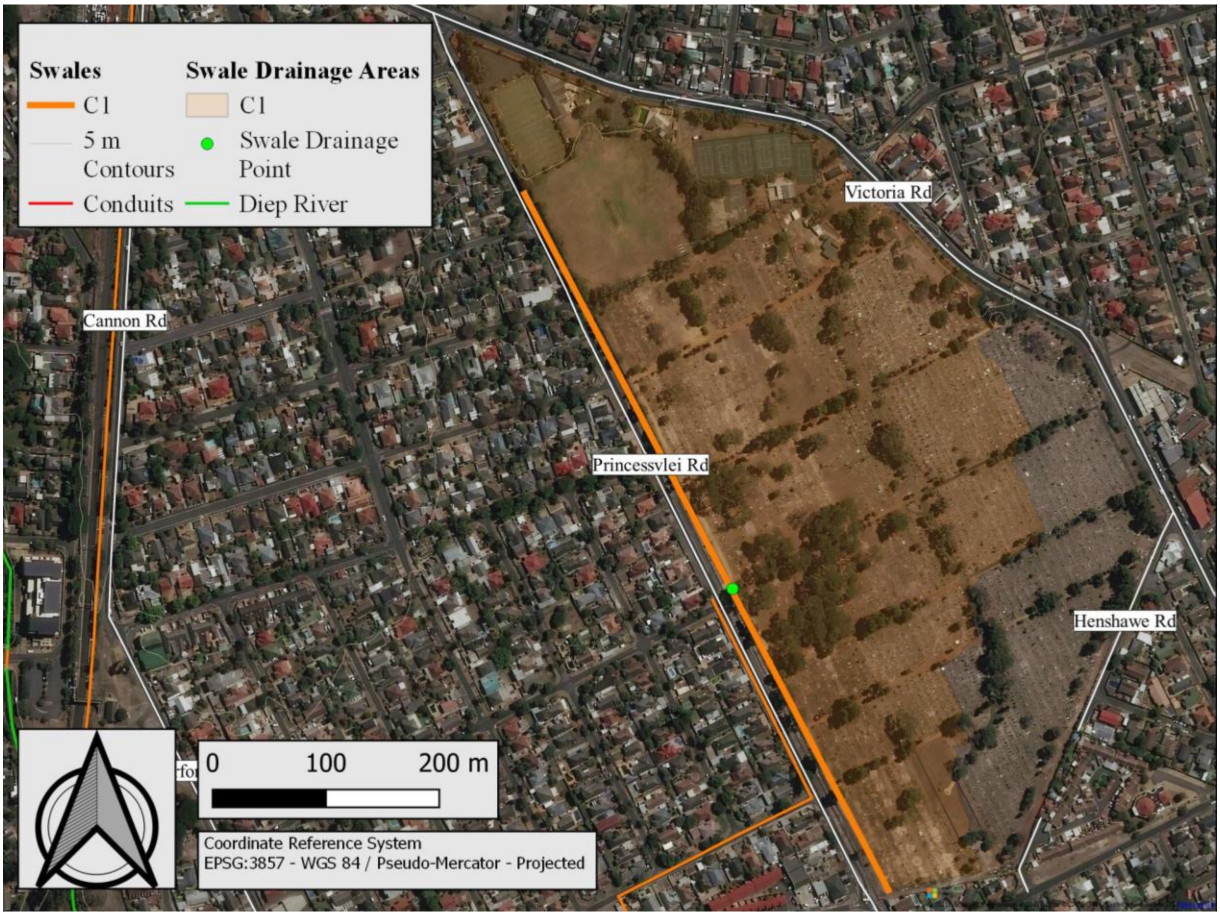


Figure 8-6: Cemetery Swale C1 – adapted from Bing Maps (Microsoft Bing, n.d.)

A single swale was developed in the model along the lower boundary of the Plumstead Cemetery (Figures 8-5 & 8-6). This area produces large volumes of runoff due to its size. The inclusion of a swale can reduce this volume. It is neighboured by a sports club that may utilise nutrient-based fertilisers to maintain the playing fields; the cemetery swale also collects the runoff from this site. The runoff from both sites currently enters a pipe network to be drained by the river network downstream. Runoff exiting the swale may be directed towards the stormwater network, or a small irrigation dam may be developed to capture the runoff and allow the sports club and the cemetery to water their extensive open areas during dry periods.

8.3.2 Scenario 2 – Existing Wetlands and Ponds

Zandvlei and its catchments have experienced a long history of modification due to settlement development and the need for space (Jack & Hoffman, 2006). Scenario 2 reincorporates small, existing wetlands and retention ponds that would have once dominated the landscape. The relatively flat topography of the Diep Catchment, especially in the lower reaches, used to support an extensive floodplain wetland; however, urban development and the subsequent construction of transportation networks/corridors have reduced the extent of the large flood plain wetland to small, isolated wetlands areas scattered around the catchment (Obree, 2004). Several of these systems provide attenuation storage in the river network during large storm events, while others are entirely disconnected from the system. This scenario is based on the idea of removing the berms/divisions that have prevented flow into the wetlands to reintroduce the SuDS and reinvigorate their treatment abilities.

Table 8-3: Existing Wetland Scenario SuDS Design Details

SuDS	Surface Area (m^2)	Vegetative fraction	Slope (%)	Full Depth (m)	Permanent Storage Depth (m)	WQV Depth (m)	Maximum Depth (m)
Ian Taylor Rd Wetland	4132	0.2	0.69	2.1	1.2	0.57	1.53
Langevlei Wetland	4100	0.2	0.21	2.1	0.7	0.91	1.26
Roscommon Rd Wetland	13100	0.	0.1	2.1	1.2	0.36	1.58
Sunbury Rd Wetland	13500	0.2	0.26	1.9	1.0	0.49	1.59
M3 Freeway Retention Pond	2735	0.1	0.35	2.5	1.0	0.69	1.71
St. Joan’s Rd Retention Pond	5600	0.1	0.115	2.0	1.0	0.45	1.49

Scenario 2 incorporates four existing wetland areas, an existing retention pond, and an additional retention pond was developed, all of which are modelled as storage units in PCSWMM (Figure 8-7). The design details of all the systems included are shown in Table 8-3. Additional design requirements are shown in Appendix H. The wetlands and retention ponds suggested in this scenario should be coupled with a suitable pre-treatment system or sediment forebays to enhance the SuDS lifespans and reduce clogging.

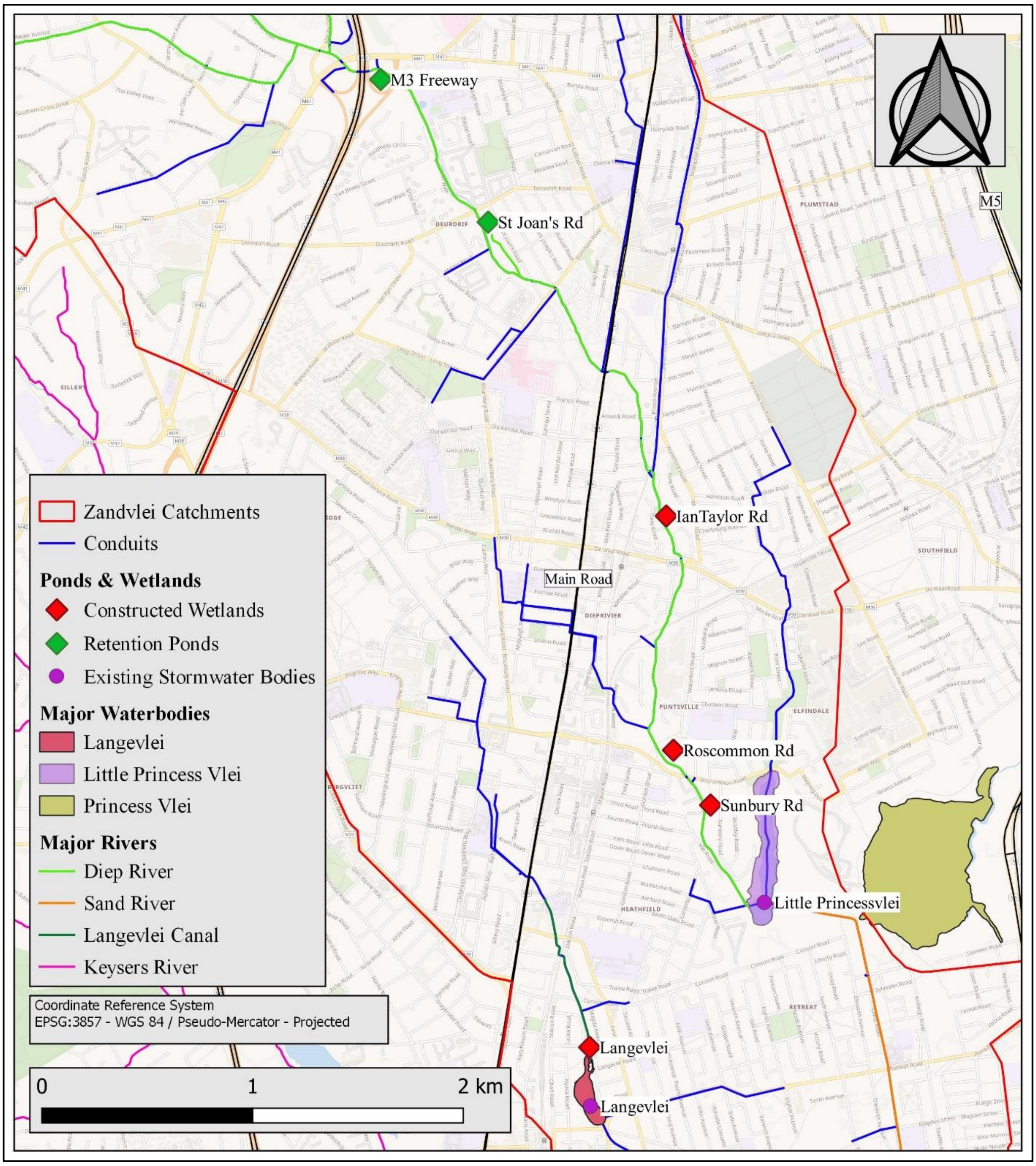


Figure 8-7: Existing Wetlands and Retention Pond Locations

8.3.2.1 Ian Taylor Road Wetland

Medium-density residential areas surround Ian Taylor Road. A small wetland was disconnected from the Diep River when the river section was channelised. The concrete surfaces of the channel do not allow stormwater to enter the wetland. A large berm further separates the two systems.

Figure 8-8: Existing Overgrown Marsh/Wetland Area on Ian Taylor Road

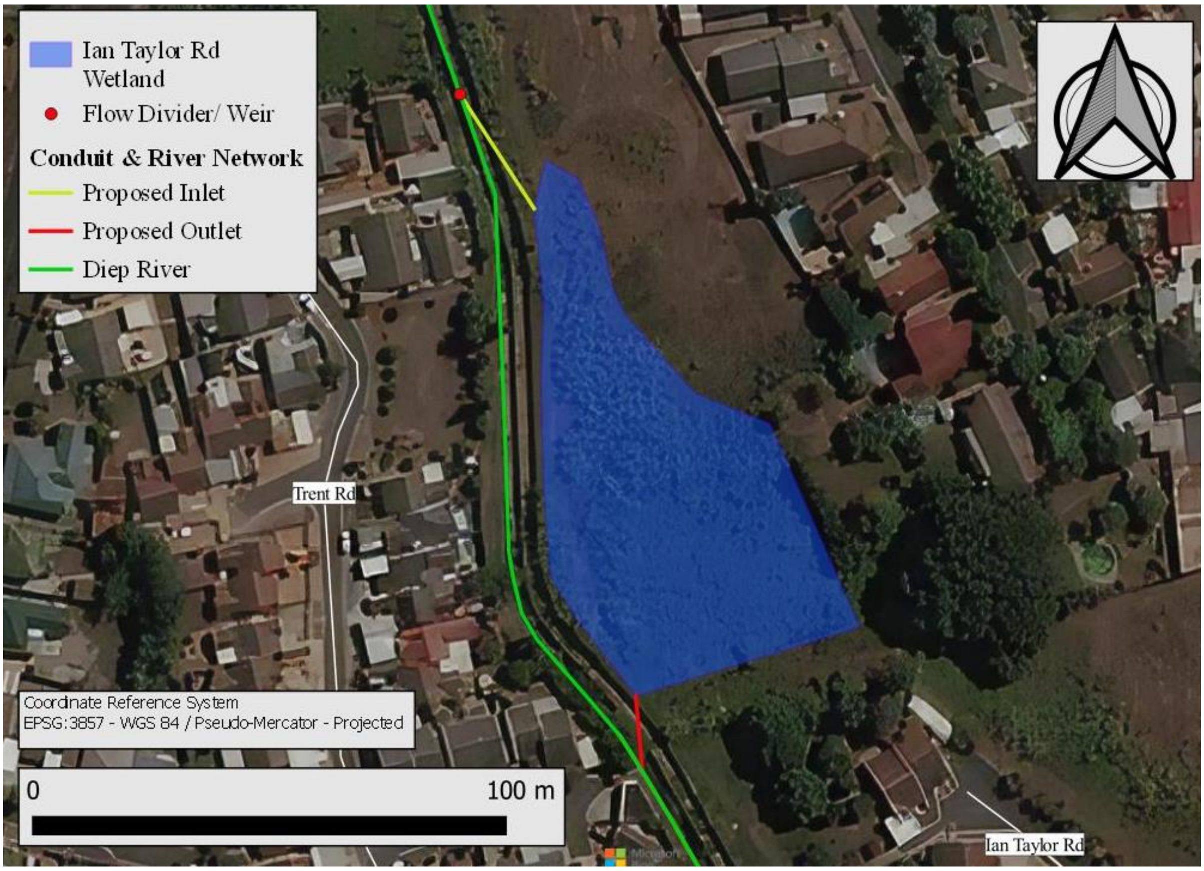


Figure 8-9: Proposed Layout of Ian Taylor Road Wetlands

Low flows from smaller, more frequent storms are the primary target for SuDS as they carry the largest contamination loads. The Ian Taylor Road Wetland of Scenario 2 suggests implementing a flow divider or weir upstream of the wetland to divert low flows into the wetland (Figure 8-9). As the area utilised by the wetland is small, the flow into the system should be limited to protect the wetland from damage and reduce the risk of flooding.

8.3.2.2 Langevlei Wetland

Langevlei, situated in Retreat, is fed by the Langevlei canal. The channelised river section, constructed with concrete linings, runs through a series of large, open areas before entering the vlei. The vlei currently has a small marsh area at the inflow before expanding into an open water body.

Figure 8-10: Proposed location of Langevlei Wetlands

A constructed wetland area at Langevlei was developed in Scenario 2 by enclosing the upstream marsh area with a berm and weir system. The wetland will allow flow rates to be reduced and meander through the system, enhancing the treatment capacity. The berms alongside the outflow weir will act as an overflow into the vlei if very large flows are experienced. It may be necessary to implement check dams or small weirs to reduce the flow rate in the inflow channel. The upstream areas consist primarily of residential areas, but several schools are in the area. The development of a wetland here may, additionally, afford environmental education opportunities. The proposed reconfiguration of the wetland is shown in Figure 8-11. The open areas surrounding the vlei are utilised for recreational purposes, so limiting any additional health and safety risks would be necessary.

Figure 8-11: Langevlei Wetland Area – adapted from Bing Maps (Microsoft Bing, n.d.)

8.3.2.3 Roscommon Road Wetland

The Diep River passes under Roscommon Road approximately 800 m before flowing into Little Princessvlei (Figure 8-12). Upstream of this culvert, a large, existing wetland has been circumvented by the Diep River. This is again due to the river being channelised. The wetland occupies approximately half of a large open space. The space is not used for recreational activities; however, a well-used footpath does split the area.

To reintroduce this wetland, a flow divider or weir is required upstream to control the maximum flow received by the wetland. Low flows should be targeted, but the large flows that can damage the wetland should be routed through the existing river channel. The existing wetland will have to be reinvigorated and cleared out as it was overgrown and unmaintained during the period of this investigation.

Figure 8-12: Existing Roscommon Road Wetland

8.3.2.4 Sunbury Road Wetland

Almost immediately downstream of the Roscommon Wetland exists another circumvented wetland system (Figure 8-13). This wetland is situated alongside Sunbury Road and only receives flow from the river network during very large events, although it treats small volumes of runoff from the immediate surroundings. The elongated shape of the wetland would allow for extended retention times if flows were allowed to meander.

Figure 8-13: Existing Sunbury Road Wetland Configuration

As with the Ian Taylor Road and Roscommon Road wetlands, the reintroduction of this system would require a flow divider or weir system upstream to redirect low flows into the wetland rather than through the existing channel (Figure 8-14). The existing shape of the wetland reduces the chances of dead zones (Melbourne Water, 2005) and creates a wetland with good hydrodynamic flow conditions allowing for longer retention times and improving the treatment abilities of the SuDS. The upstream areas consist primarily of residential areas, but a small industrial zone is present as well; the wetland would allow this zones effluent, considered to present a significant ecological risk (Coastal & Environmental Consulting, 2010), to be treated. The berm between the existing concrete channel and the wetland will act as an overflow to prevent flooding of the nearby residential area and drain into the existing channel in the event of extreme storms.

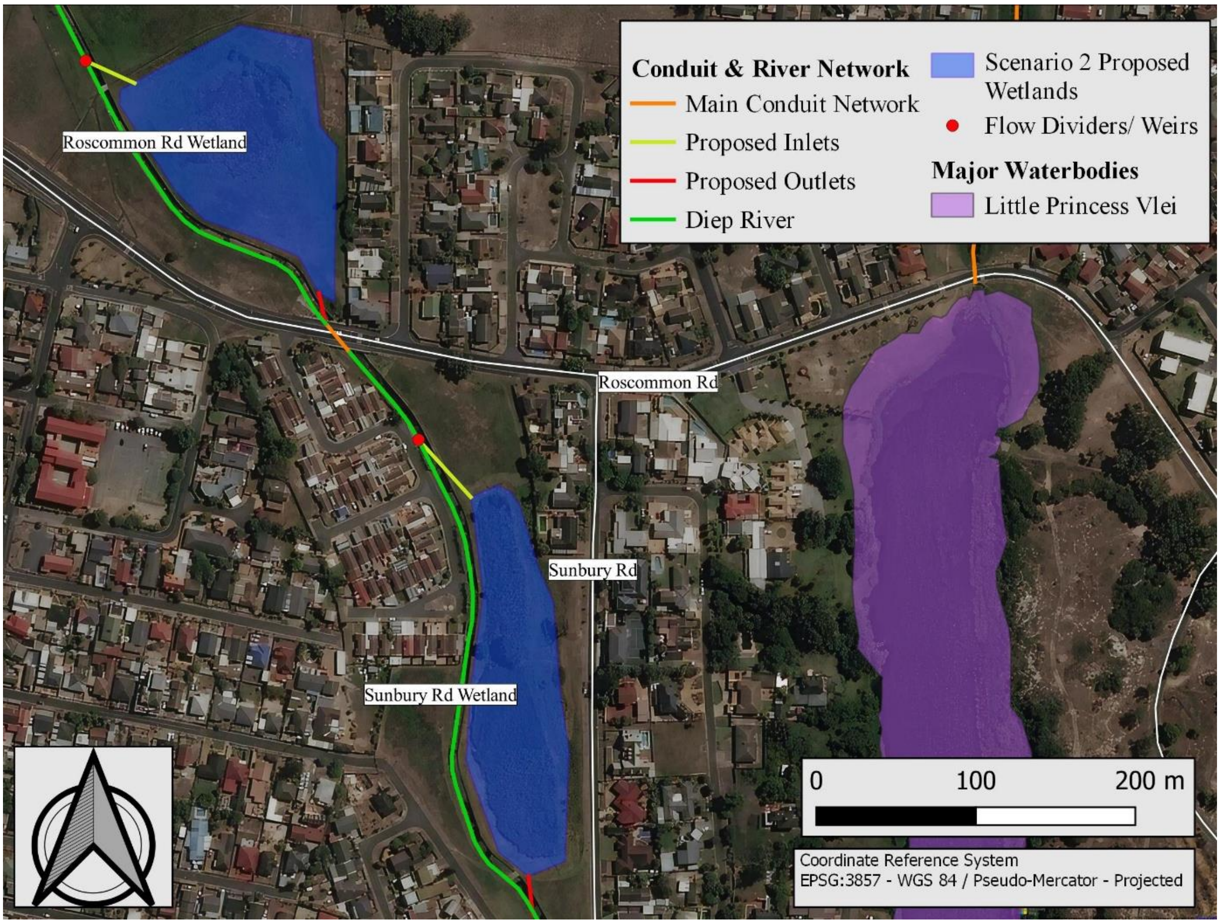


Figure 8-14: Proposed Layouts of Roscommon Road and Sunbury Road Wetlands – adapted from Bing Maps (Microsoft Bing, n.d.)

8.3.2.5 M3 Freeway Retention Pond

The upper reaches of the Diep Catchment are categorised by very low-density residential areas, a small agricultural area, and natural landscapes. These are associated with low runoff volumes and indicator (SRP, TIN, TP & TSS) concentrations. However, an existing retention pond is situated downstream of these areas immediately after the culvert under the M3 Freeway. Currently, the pond is utilised only during very large storm events to provide attenuation storage.

In Scenario 2, the retention pond was altered (Figure 8-15) to receive low flows during small storm events (<6-month RP) whilst continuously providing the required attenuation storage during larger events. The risk of flooding the surrounding areas is small as the immediate surroundings have very steep slopes that direct runoff into the pond. Unlike other systems used in this scenario, the M3 retention pond is currently in use and would not require a significant amount of maintenance and refurbishment before being used to reduce indicator loads. Retention ponds are generally considered to have lower treatment potential than constructed wetlands; however, a retention pond would provide adequate treatment due to the nature of the upstream developments.

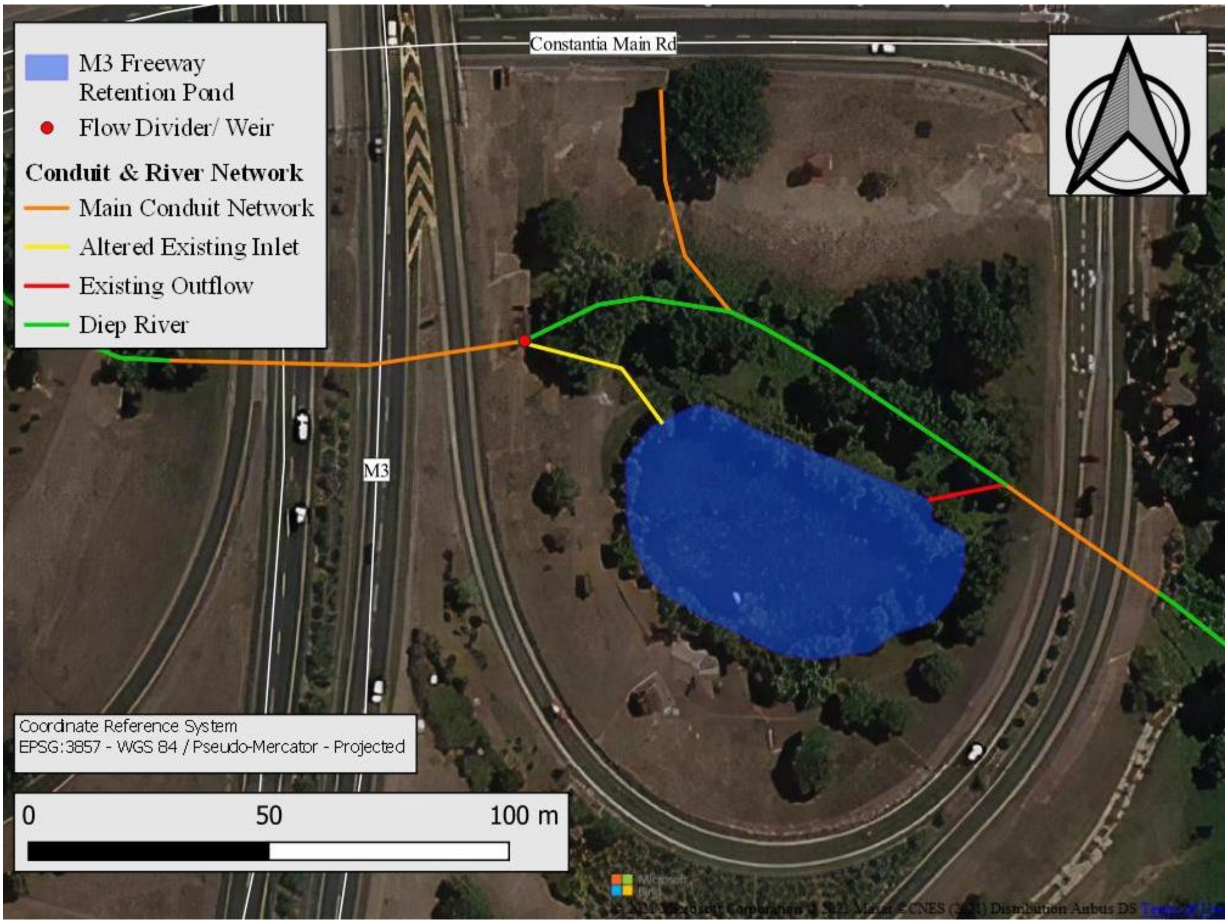


Figure 8-15: Proposed M3 Freeway Retention Pond Layout – adapted from Bing Maps (Microsoft Bing, n.d.)

8.3.2.6 St. Joan’s Road Retention Pond

The corner of Doordrift Road and Saint Joan’s Road is a large open area zoned by the CoCT as a stormwater pond (Figures 8-16 & 8-17). This open area has small banks around the edges and a grass lining. Currently, the area functions as a detention pond with a large overflow area upstream to allow the river to spill onto the grass-lined system. When the land is not being used as a detention pond, it is used for small recreational activities such as dog walking; however, another open field adjacent to this site may be used for the same purposes, so this site may be utilised without disrupting recreational activities.

Figure 8-16: St. Joan's Road Detention Pond Layout

Figure 8-17: Overflow Structure at St. Joan’s Road Detention Pond

The grass-lined area was modelled as a retention pond in Scenario 2 (Figure 8-18). The conversion is simple as the site already contains berms around the edges and an overflow. Additionally, a high water table is present. The new pond would allow stormwater to be treated and provide some level of attenuation. The development of the pond would additionally extend the blue-green corridor present immediately upstream. The berm between the concrete channel and the open area will act as an emergency overflow and reduce flood and damage risks to the nearby infrastructure.

Figure 8-18: Proposed St Joan's Road Retention Pond Layout – adapted from Bing Maps (Microsoft Bing, n.d.)

8.3.3 Scenario 3 – New Wetland

The third SuDS scenario employed the idea of a single, large scale regional control at the confluence of the Sand River and the Langevlei Canal before they enter the Zandvlei Estuary. Currently, this is a large unused open area bounded by the two rivers making access for recreational activities difficult. The small triangular marsh area does not receive any runoff from the concrete-lined canals. Meantime, during large storm events, a litter trap (Figure 8-19) in the Sand River gets blocked, and stormwater thus often floods onto the site saturating the ground.

A constructed wetland that would receive all the runoff from both river systems was considered for this 0.5 km^2 area in Scenario 3 (Figure 8-20). The entire triangular site would need to be excavated to allow a permanent water body and a temporary storage area. The design details for this scenario are provided in Table 8-4.

Figure 8-19: Upstream (left) and Downstream (right) of Sand River Litter Trap

Table 8-4: New Confluent Wetland Design Details

SuDS	**Surface Area (m^2)**	**Vegetative fraction**	**Slope (%)**	**Full Depth (m)**	**Permanent Storage Depth (m)**	**WQV Depth (m)**	**Maximum Depth (m)**
New Confluent Wetland	14850	0.2	1.1	2.1	1.0	0.48	1.48

As all the runoff from the entire catchment will be channelled towards this system, a suitable emergency overflow will be required to protect the wetland. The surrounding areas are open spaces, so there is also a significant opportunity to expand the wetland or utilise this space for an overflow system. Additionally, as the runoff collects large volumes of sediment and litter, a sediment basin and litter trap should be designed upstream of the new wetland.

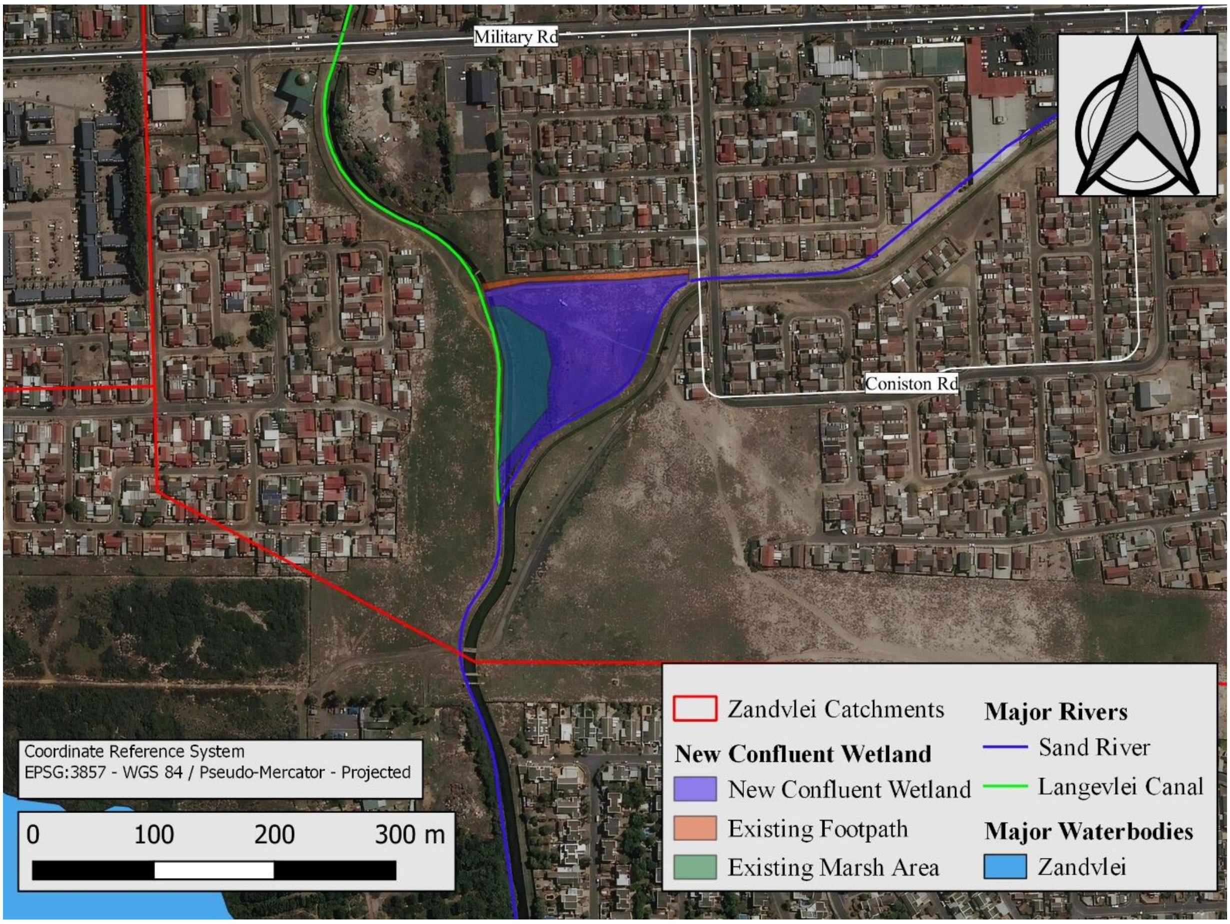


Figure 8-20: New Wetland Location – adapted from Bing Maps (Microsoft Bing, n.d.)

8.3.4 Scenario 4 – Source Controls & New Wetland

The fourth scenario consists of elements from Scenarios 1 and 3. A more holistic treatment train is developed by creating a combination of the scenarios. This scenario included the large wetland at the confluent of the Langevlei Canal and the Sand River from the third scenario. The rooftop disconnections, rain gardens and infiltration trenches modelled as subarea routing percentages (Section 8.3.1) in Scenario 1 were also included. This scenario creates a mixture of source and regional controls to manage the catchment's stormwater runoff.

8.3.5 Scenario 5 – New & Existing Wetlands

The final scenario combined existing wetlands (Scenario 2) and the new wetland at the confluent (Scenario 3). The regional controls do not target specific areas of high indicator inflow but treat the entire system at locations where large areas are available. This scenario would likely have a large impact on the water quality received by Zandvlei but may leave isolated areas in the catchment with poor water quality. The wetlands and ponds incorporated in this scenario include:

- New Confluent Wetland
- Existing Wetlands and Ponds
    - Ian Taylor Road Wetland
    - Sunbury Road Wetland
    - M3 Freeway Retention Pond

8.4 Summary

This chapter discussed the seven scenarios developed during this project. An ‘As-is’ scenario was developed to represent the catchment in its current condition. A pre-development scenario was created to estimate the indicator quantities the catchment may have produced before urban development began as an idealised ultimate objective. Five SuDS scenarios were developed to test various intervention measures. The results obtained from the various scenarios are provided in Chapter 9.

9. SuDS Scenario Results and Discussion

This chapter discusses the results obtained from the PCSWMM model scenarios expressed as indicator (SRP, TIN, TP & TSS) removal percentages for each of the five SuDS scenarios. The As-is Scenario acted as the baseline against which improvements are measured, while the Pre-development Scenario provides the ultimate goal of the SuDS scenarios.

9.1 As-is Scenario

All scenarios were simulated for 12 years and 11 months, meeting the recommendations discussed in Section 5-1. Scenario loadings were obtained from the outfalls, the lowest modelled point of the catchment area. The As-is Scenario produced the following values at the outfall for the entire simulation period:

• Total Volume	61.8 x 10^6 m^3
• Mean Flow Rate	0.176 m^3/s
• Max Flow Rate	5.19 m^3/s
• Total SRP load	4.4 tonnes
• Total TIN load	49.9 tonnes
• Total TP load	11.1 tonnes
• Total TSS load	541 tonnes

9.2 Pre-development

As described in Section 8.2, the Pre-development Scenario was developed to represent the catchment before urban development began. The values obtained from this scenario are estimates as calibration was not possible.

The outflow rates experienced by the As-is and Pre-development scenarios are compared in Figure 9-1 for a 6-month return period storm event. This graph illustrates the extent to which impermeable surfaces have reduced the infiltration ability of the catchment and have subsequently significantly increased the outflow rates and volumes experienced in the lower reaches of the catchment.

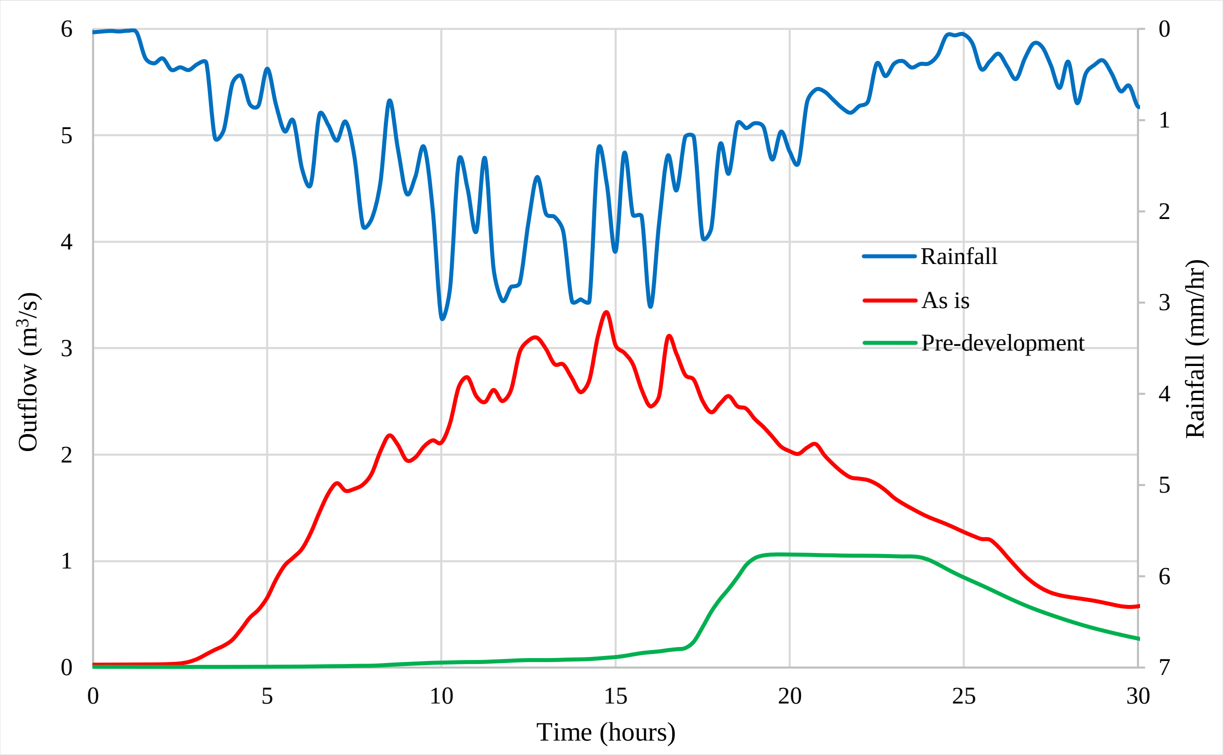


Figure 9-1: 6-month Return Period Storm Event Outflows for As-is & Pre-development Scenarios (16-17 August 2005)

9.3 SuDS Scenarios

SuDS were implemented in a model to reduce the indicator loads deposited into the Zandvlei Estuary. The implemented systems require specified treatment functions; this project utilised treatment equations using HRT as the independent variable (Section 7.4). Two equations were used for each indicator, with a high and low treatment potential. These are provided in Table 7-5.

9.3.1 Indicator load reductions

The outputs of the various SuDS Scenarios are compared to the results obtained from the As-is Scenario. Figure 9-2 presents the percentage reductions in each scenario as this was the requirement of the CoCT (2009) stormwater impact policy (Section 2.8). The indicator loads deposited into Zandvlei from each of the SuDS scenarios are then compared with both the As-is and Pre-development scenarios (Figures 9-3 to 9-6).

Scenario 1, which utilised source controls (Section 8.3.1), provided some level of improvement; however, the scenario presented the lowest removal percentages for all four indicators modelled. This is likely due to the areas targeted by the SuDS; as this scenario required permeable areas to model the runoff controls, areas with small or no pervious areas were not treated. Unfortunately, sites with small or no pervious areas often produce the highest wash-off concentrations. The indicator load reductions obtained from Scenario 1 did not meet the required TP and TSS reductions of 45% and 80%, respectively, set out by the CoCT.

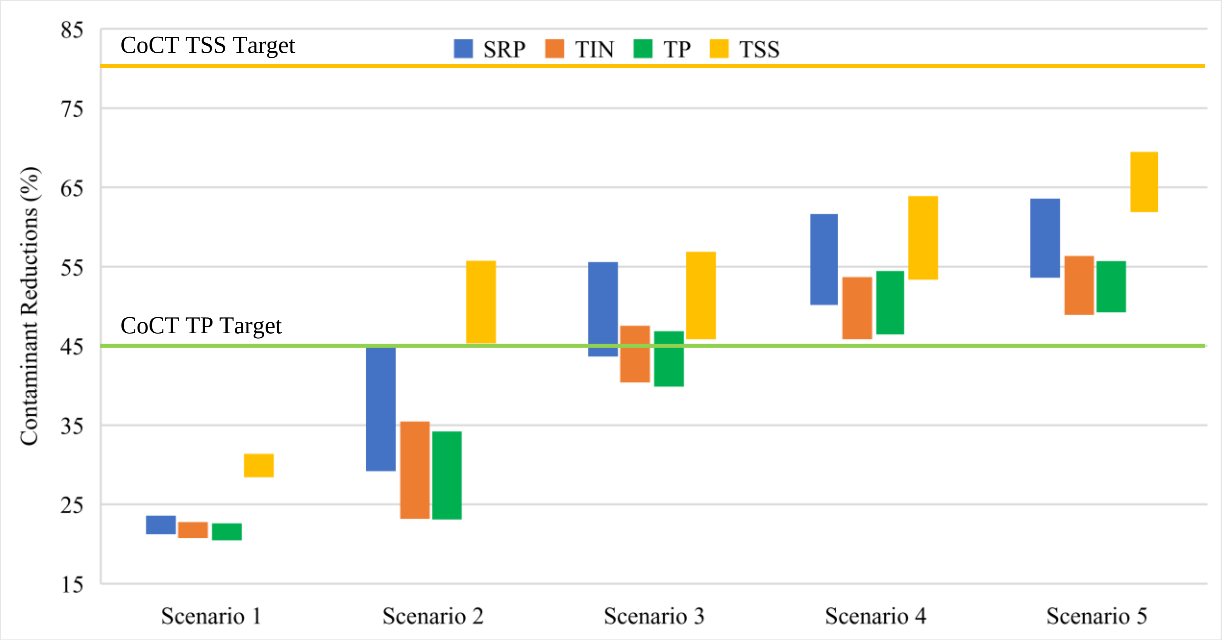


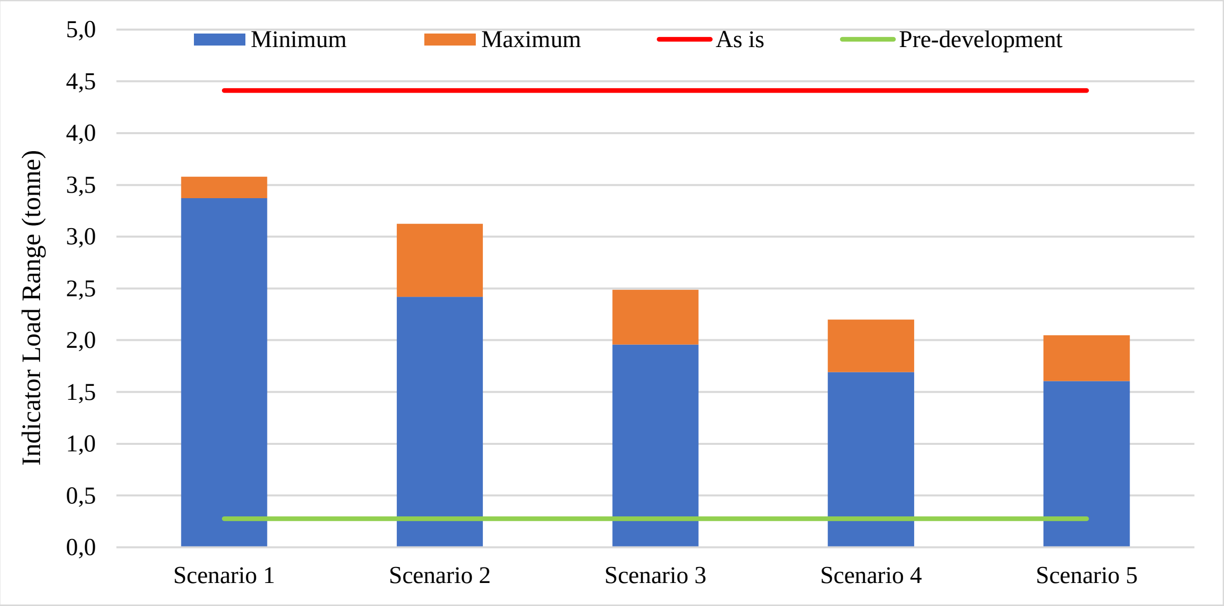
Figure 9-2: Indicator Removal Percentages compared with current levels as modelled in the five SuDS scenarios

Scenario 2 (Existing Wetlands and Ponds) provided larger indicator reductions than Scenario 1. The treatment ability of wetlands is highly variable and depends on the design of each wetland, on-site factors, environmental and hydrological aspects, and maintenance. Scenario 2 provided a large range of possible indicator load reductions as four wetlands and two pond systems were modelled. Unfortunately, this scenario also fell short of the CoCT recommendations, with maximum reductions of TP and TSS being 34 and 56%, respectively, compared with the targets of 45% and 80%.

Scenario 3 (New Wetland) introduced a large regional control as a constructed wetland at the confluent of the two major river systems in the catchment. The wetland would receive the entity of the runoff from both systems. The scenario produced a higher maximum treatment of TP and TSS while providing smaller ranges for SRP, TIN and TP than Scenarios 1 and 2. The CoCT reduction requirement was partially met for TP in Scenario 3. The reduction obtained using the low-level treatment equation was below the target, but the high-level treatment equation provided a reduction above the CoCT target for TP. Unfortunately, Scenario 3 did not meet the TSS reduction requirement.

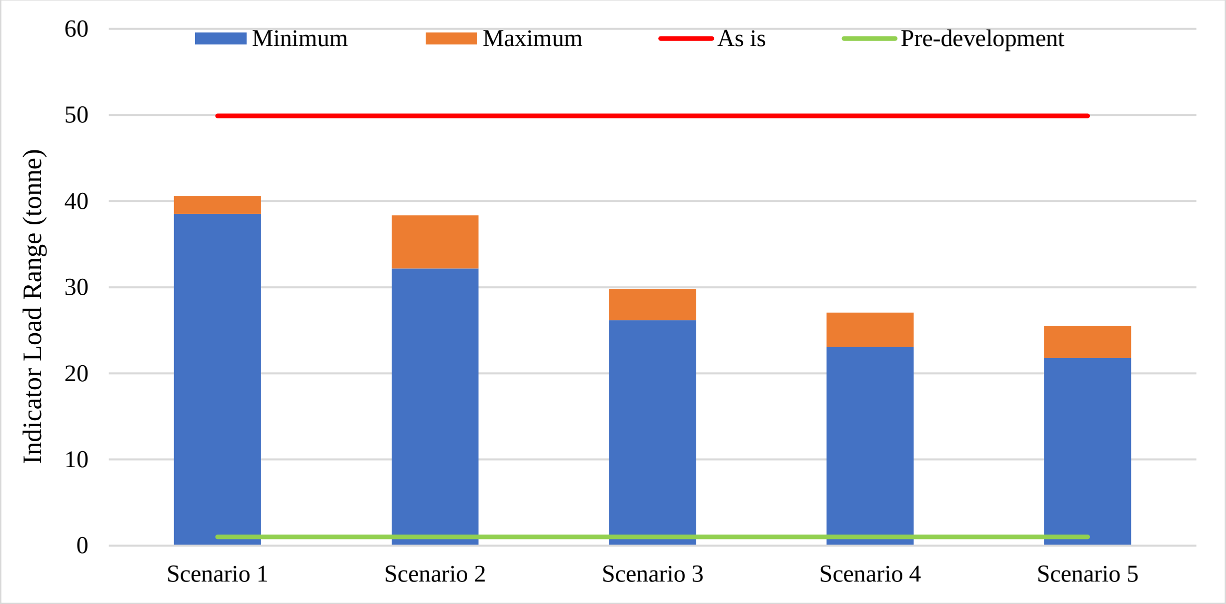
Scenarios 4 and 5 presented the most significant reductions, as expected. These scenarios incorporated SuDS from the first three scenarios to develop treatment trains with controls from multiple intervention stages and create more robust systems. Scenario 4 used the Source Controls from Scenario 1 and Scenario 3's large, constructed wetland at the confluent of the Diep/Sand and Langevlei Canal systems. Scenario 5 incorporated two wetlands and a retention pond from Scenario 2 and the large wetland from Scenario 3. Both Scenario 4 and 5 met the CoCT TP requirement completely, with Scenario 5 providing the greatest reduction in TP. Unfortunately, neither Scenarios 4 nor 5 met the targeted TSS reduction of 80%, as illustrated in Figure 9-2. As the TSS targets were not met in any of the five SuDS scenarios, the rate of siltation within the estuary will not be satisfactorily decreased.

The likely sustainable indicator loads from the Pre-development Scenario were not obtained in any SuDS scenario. Scenario 5, providing the lowest loads for each indicator, presented the closest results to that of the Pre-development Scenario, illustrated in Figures 9-3 to 9-6.



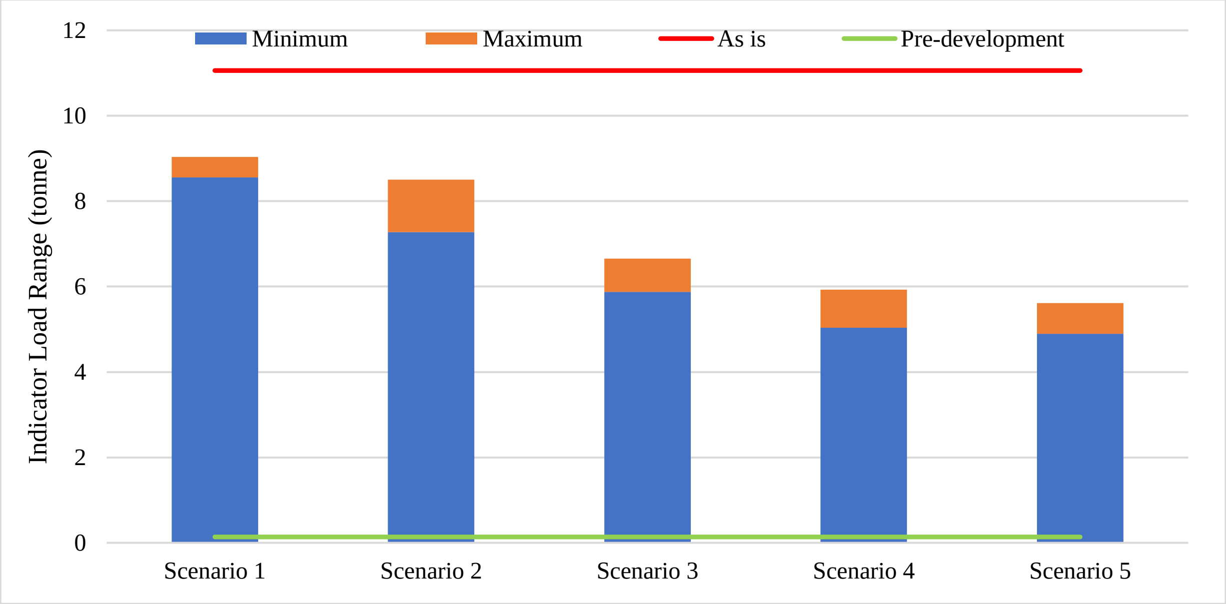
*Orange bars represent the potential treatment range

Figure 9-3: SRP Load Ranges from SuDS Scenarios



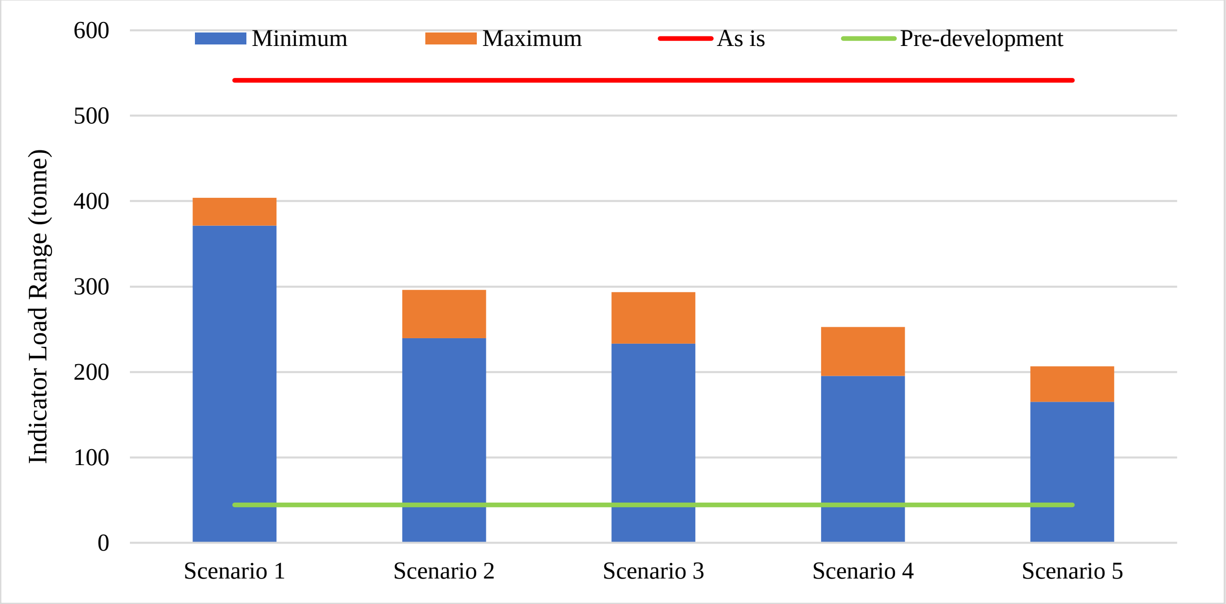
*Orange bars represent the potential treatment range

Figure 9-4: TIN Load Ranges from SuDS Scenarios



*Orange bars represent the potential treatment range

Figure 9-5: TP Load Ranges from SuDS Scenarios



*Orange bars represent the potential treatment range

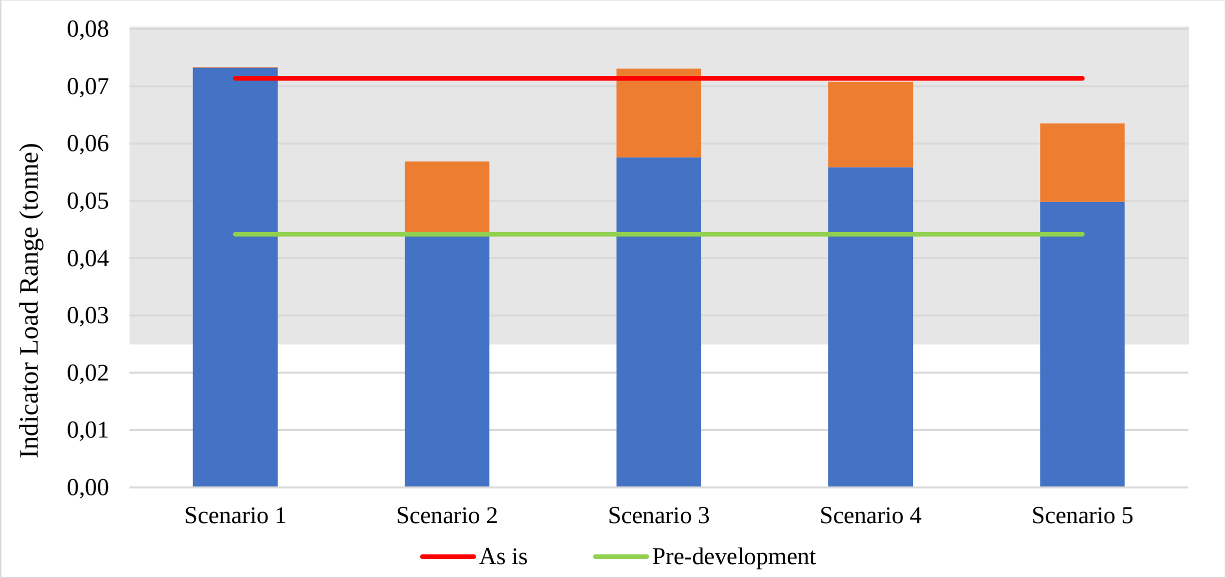
Figure 9-6: TSS Load Ranges from SuDS Scenarios

9.3.2 Outflow concentrations

As mentioned in Section 2.4, excessive phosphorus and nitrogen concentrations cause eutrophication in water bodies. Soluble Ready Phosphorus (SRP) and Total Inorganic Nitrogen (TIN) are the nutrient species responsible for the overgrowth of plants. It is, therefore, important to manage the concentrations of these species in the stormwater being delivered to Zandvlei. Figures 9-7 & 9-8 present the mean outflow concentrations at the model outlet from each SuDS scenario. The figures also provide the range of concentrations in which eutrophication may occur.

For every SuDS scenario, the SRP outflow concentrations are still within the eutrophic range. These concentrations may continue to create eutrophic conditions within Zandvlei. As runoff is captured, stored, and treated in the SuDS systems, a portion is infiltrated or evaporated, reducing the runoff received by Zandvlei. The indicator loads may be reduced, but the concentration has remained within the SRP eutrophic range. The TIN concentrations, however, are all below the eutrophic range.

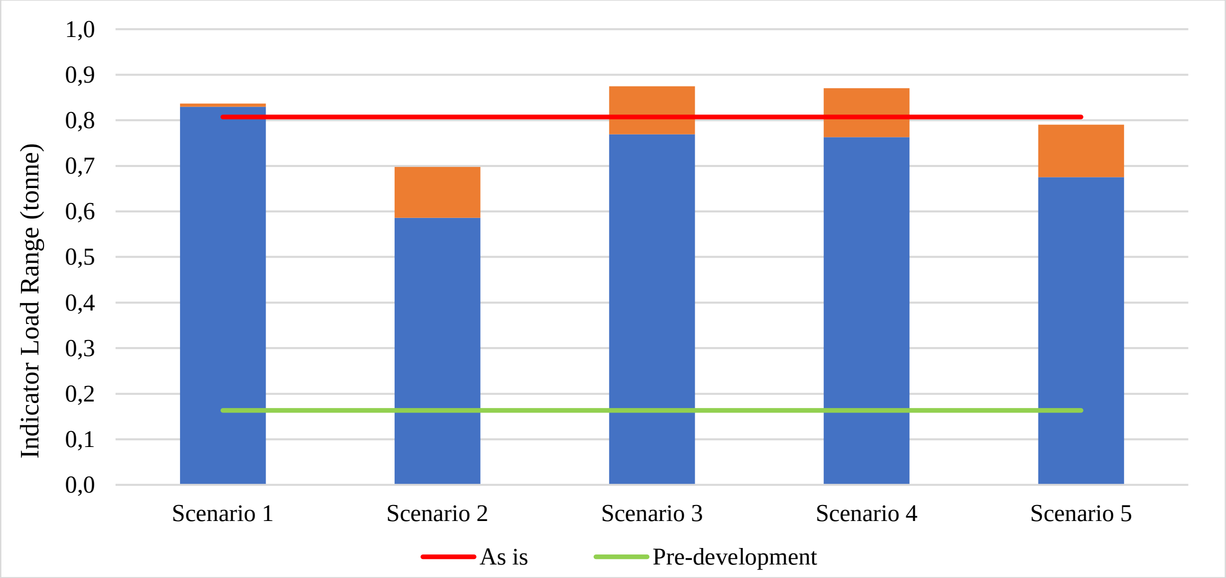
The mean SRP concentration obtained from the As-is Scenario was reduced in four of the five SuDS scenarios, illustrated in Figure 9-7. Scenario 2 and Scenario 5 provided concentrations well below that of the As-is Scenario. Scenario 4 provided a lower mean SRP concentration, however, the concentration obtained from the low-level treatment equation is similar to that of the As-is Scenario.



*Grey band represents the eutrophic range (0.025 – 0.25 mg/L)

*Orange bars represent the concentration range due to high and low treatment potentials

Figure 9-7: SRP Model Outflow Concentrations



*Eutrophic range (2.5 – 10 mg/L)

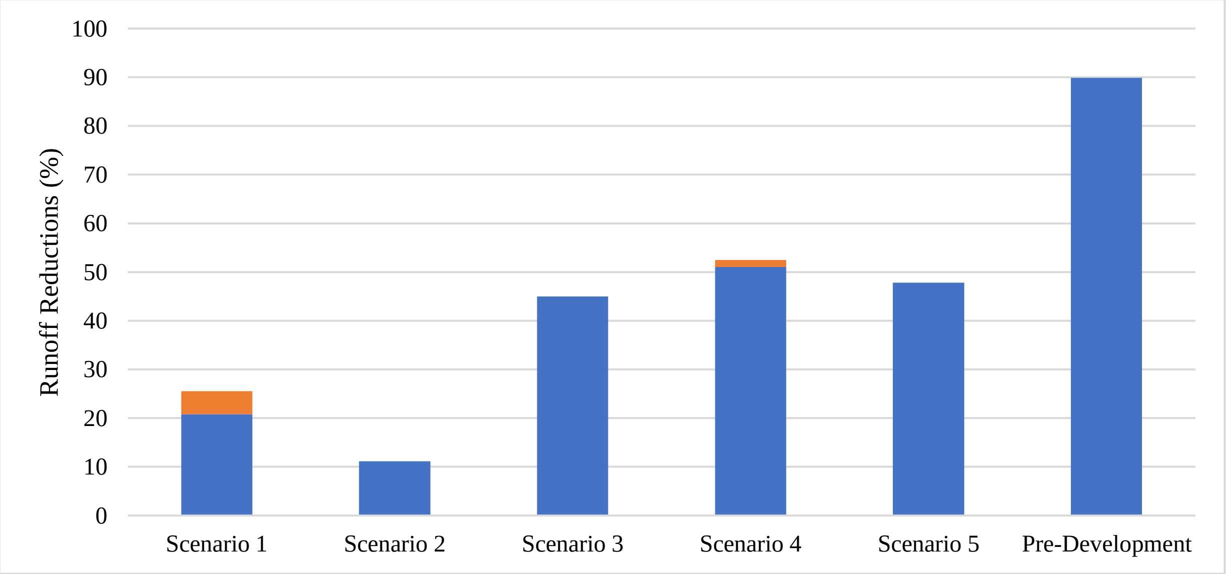
*Orange bars represent the concentration range due to high and low treatment potentials

Figure 9-8: TIN Model Outflow Concentrations

Scenario 1 presented an increased mean SRP outflow concentration despite providing a reduction in the SRP load. As the SRP concentration in waterbodies is a primary cause of eutrophication, the increase in SRP outflow concentration increases the possibility of eutrophication occurring, thus Scenario 1 is not a viable option to improve the water quality within Zandvlei. This increase is likely due to the areas targeted by the SuDS; the pervious areas are associated with producing lower mean wash-off concentrations than the impervious areas. The large impervious areas in the middle and lower reaches of the catchment were not significantly affected in Scenario 1, thus the runoff from these areas continued to flow without treatment into the river networks, resulting in the elevated mean SRP outflow concentration. Scenario 3's large confluent wetland produced a mean SRP outflow concentration below that of the As-is Scenario, however, the concentration obtained using the low-level treatment equation was marginally larger than the As-is Scenario. The SRP load reduction obtained from the low-level treatment equation was lower than the reduction in runoff volume in the large confluent wetland, thus providing a higher outflow concentration.

9.3.3 Runoff

Urban development has significantly increased the impervious surfaces within catchments, causing runoff volumes to increase hugely (Figure 9-1). Furthermore, the channelisation of river networks has increased runoff rates. SuDS can combat these increases by providing areas where stormwater may be slowed and allowed to infiltrate, thus reducing the runoff directed into Zandvlei. It is, therefore, essential to analyse the reduction in runoff volumes and rates brought upon by the implemented SuDS. Runoff reductions are provided as percentage decreases from the As-is runoff volumes (Figure 9-9). Additionally, the runoff rates experienced at the outfall of the As-is and each of the SuDS scenarios during the storm event of 18-21 April 2010 are presented in Figure 9-10.



*Orange bars represent the range between high and low reductions

Figure 9-9: Runoff Reduction Percentages

Scenario 1 provided two runoff values, high and low. It provided a moderate runoff reduction with a range of 21-26%. This is due to how the scenario was modelled (Section 8.3.1). As this scenario targeted land-use types with pervious areas, the problematic sites with large impervious areas were not improved; thus, large runoff volumes still entered the river network.

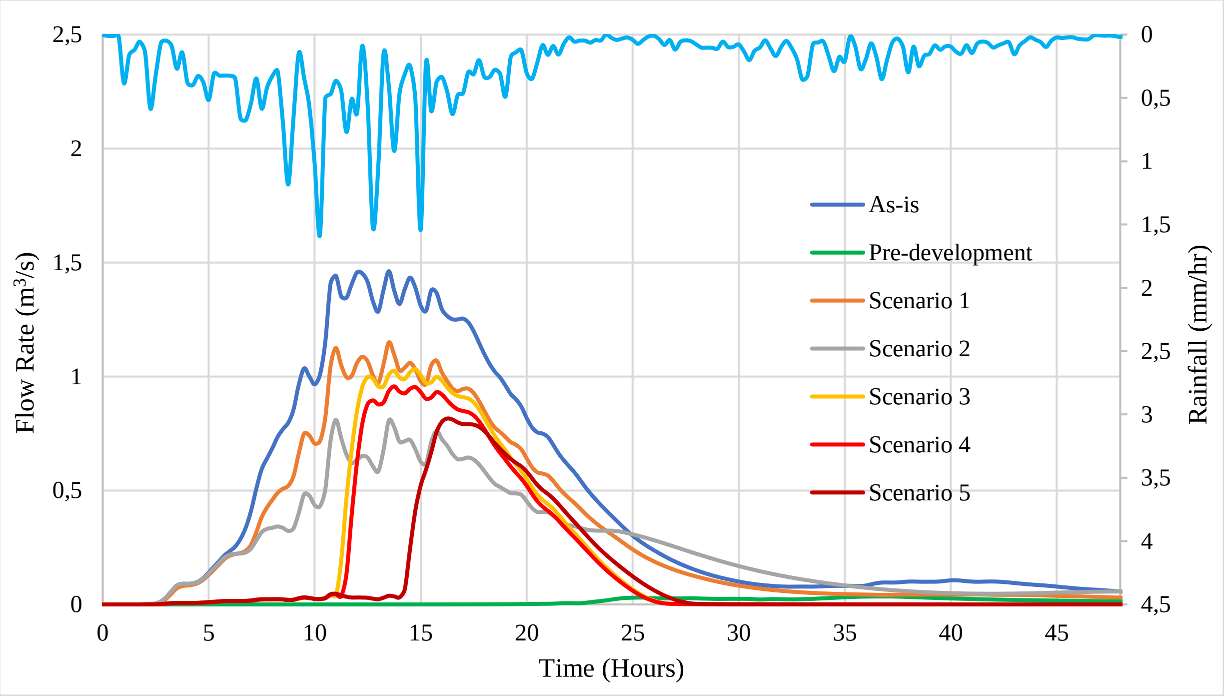


Figure 9-10: Outfall Flow Rates during a Storm Event (18-21 April 2010)

Scenario 2 resulted in a small runoff reduction of 11%. As stated in Section 8.3.2, the reintroduced systems targeted low flows from smaller design events (6-month design storm). The larger flows bypass the new systems and continue down the existing channels until they reach Zandvlei.

The large wetland system receives the entirety of the flows from the Diep/Sand River and Langevlei Canal systems and provides attenuation storage that slows runoff and allows infiltration. As expected, the scenarios that included the large confluent wetland (Scenarios 3, 4, and 5) resulted in the most significant drops in runoff volumes. All three scenarios produced runoff decreases of over 40%. As Scenario 5 includes elements from Scenario 1, this too provided two separate runoff values; however, this range is much smaller than that seen in Scenario 1. Table 9-1 presents the runoff volumes received by Zandvlei over the entire simulation period, while Figure 9-10 illustrates the reduction in runoff from the SuDS scenarios compared to that of the As-is Scenario.

The Pre-development Scenario – the benchmark for all modern stormwater management – provided a runoff volume decrease of approximately 90%. The magnitude of this reduction is to be expected as the scenario had significantly less impervious area, allowing infiltration to occur across the catchment. The reduction is over 35% larger than the best performing SuDS scenario, Scenario 4. The pre-development flows are unlikely to be realistic, however, it remains the objective of SuDS to attempt to achieve this. Figure 9-9 and Figure 9-10 illustrate how SuDS may reduce the runoff flow rates and flow volumes, however, they further illustrate the significant increase in runoff flow rates and volumes due to urbanisation.

Table 9-1: Total Runoff Volumes

	As-is	**Pre-development**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Total Runoff Volume (10^6 m^3)	61.8	46.0	46.0-48.9	54.94	34.0	30.3-31.2	32.3

As illustrated in Figure 9-10, the SuDS scenarios were able to provide stormwater attenuation within the Diep Catchment. Scenario 1 provided the least attenuation due to the small size and location of the SuDS employed in the scenario. Source Controls do not provide large storage areas to attenuate stormwater flows. The placement of SuDS in Scenario 1 also affected the attenuation provided. The Source Controls targeted pervious areas, these areas usually provide runoff at rates lower than that experienced from impervious areas, thus, attenuating stormwater from these areas does not affect the system significantly.

The scenarios that utilised multiple, large-scale SuDS (Scenarios 2 and 5) provided the most attenuation to the system. The ponds and wetlands are designed to provide attenuation storage above the permanent water level, by implementing these systems in several locations within the catchment, large volumes of stormwater may be attenuated during storm events. The large confluent wetland provided a significant amount of attenuation; however, this was less than the combined attenuation achieved by using multiple wetland and pond systems.

9.4 Summary

This section presented the results obtained from the SuDS scenarios. Results were measured against those obtained from the As-is and Pre-development scenarios for indicator load reductions, outflow concentrations and runoff reductions. Scenario 5 provided the most significant indicator load reduction, Scenario 2 obtained the lowest outflow concentration, and Scenario 4 presented the greatest runoff reduction; however, the idealistic results of the Pre-development Scenario were not obtained by any of the SuDS Scenarios. The project is concluded in Chapter 10.

10. Conclusions & Recommendations

The primary objective of this project was to investigate the viability of improving the water quality in Zandvlei Estuary by implementing SuDS in the Diep Catchment. The Diep Catchment has two main river systems: the Diep/Sand River and the Langevlei Canal. Computational models were developed in PCSWMM to investigate the extent to which SuDS implemented in the Diep Catchment may improve water quality. The models were developed using a DEM, land use, soil type, rainfall, and streamflow data. Seven model scenarios were created.

- An As-is model to represent the catchment in its current condition.
- A Pre-development Scenario to provide estimates of runoff and pollutant concentrations before urban development began.
- Five SuDS Scenarios to test various SuDS types and treatment trains:
  - Scenario 1 employed Source Controls to capture and treat runoff as close to its source as possible. This scenario required open space to implement SuDS; thus, only areas with open pervious areas were targeted.
  - Scenario 2 reintegrated and redesigned existing wetlands and ponds into the main river networks. The Diep/Sand River has several small-scale wetlands that have been disconnected from the main river networks. This scenario reintroduces four wetlands and two retention ponds back into the system.
  - Scenario 3 employed a large, constructed wetland at the confluent of the Diep/Sand River and Langevlei Canal. The wetland would capture and treat all the runoff from both systems.
  - Scenario 4 combined the Source Controls from Scenario 1 and the large, constructed wetland from Scenario 3.
  - Scenario 5 utilised two wetlands and a retention pond from Scenario 2 and Scenario 3’s large, constructed wetland.

The City of Cape Town (2009) *Management of Urban Stormwater Impacts Policy* recommends that the implementation of new SuDS should decrease TP and TSS loads by 45 and 80%, respectively. Additionally, the South African Water Quality Guidelines for Aquatic Ecosystems (DWAF, 1996) state that SRP and TIN are responsible for estuaries experiencing eutrophic states, a significant problem for Zandvlei (Thornton *et al*., 1995). Therefore, all SuDS Scenarios were modelled with SRP, TIN, TP and TSS as indicators.

SuDS scenarios were tested with both a high and low treatment to create a potential reduction range. The results were compared to those obtained from the As-is and the Pre-development scenarios. Firstly, the indicator loads were compared to determine the percentage reductions. Scenarios 1 and 2 did not meet the CoCT TP or TSS targets of 45 and 80%

respectively. Scenario 3 partially met the CoCT TP reduction target, with only the higher reduction meeting the target. Scenarios 4 and 5 fully met the TP reduction target. None of the five SuDS scenarios met the 80% TSS target. As a result, sedimentation may occur in Zandvlei at a rate faster than that experienced before urbanisation began. However, the sedimentation rate will be lower than the rate currently experienced. The SuDS scenarios could not reduce the indicator loads to those obtained from the Pre-development Scenario. Scenario 5's results were the closest to those obtained from the Pre-development Scenario; however, there was still a significant difference between the two scenarios' results, with the closest result being Scenario 5's TSS load, approximately double that of the Pre-development Scenario.

Secondly, the mean outfall concentrations were compared for each scenario as SRP concentrations between 0.025 and 0.25 mg/L and TIN concentrations between 2.5 and 10 mg/L can cause eutrophication. None of the scenarios sufficiently reduced the SRP concentrations below the eutrophic range. Thus, eutrophication may still occur in Zandvlei. However, Scenarios 2, 3, 4 and 5 provided lower mean SRP concentrations than the As-is Scenario. The TIN outflow concentrations were all below the eutrophic range, decreasing the chances of eutrophication.

Finally, the runoff reductions were investigated. The Pre-development Scenario resulted in a 90% decrease in runoff volume, over 35% greater than the best SuDS scenario. Runoff being received by Zandvlei was reduced between 10 and 55%, with Scenario 2 and Scenario 4 providing the lowest the highest reductions, respectively.

Sediment forebays enhance the life span of ponds and wetlands and reduce the risk of clogging. Forebays were not modelled during this project, but their presence is desirable. Sediments are allowed to settle to the bottom of the forebay, reducing the loads entering downstream systems. Pre-treatment systems would improve the TSS removal percentages obtained using wetlands and ponds, allowing SuDS scenarios to meet the CoCT TSS targeted reduction.

Several errors and limitations provided challenges and introduced uncertainties into this project:

- Wetlands are living environments and are unlikely to provide a consistent level of treatment. Two treatment equations, derived from published experimental data, were used for each indicator (SRP, TIN, TP & TSS) to provide potential treatment ranges. The treatment equations used HRT as the independent variable, but many factors, such as temperature and vegetation type, influence the treatment potential of wetlands. The results obtained from the SuDS scenarios are thus only estimates.
- The EMC values used during the project were estimated from published data and monthly grab samples collected by the CoCT and were thus only a rough approximation of stormwater constituents emanating from complex physical phenomena.
- Incomplete and erroneous data introduced more areas of uncertainty into the PCSWMM model:

  - Several rainfall gauges were missing data for several months. These had to be patched using nearby gauges to create usable data sets. Most rainfall gauge data had too coarse a resolution to be utilised in the model. These had to be disaggregated to a higher resolution; however, this introduced further uncertainty.
  - The CoCT streamflow data was also incomplete as low flows were able to bypass the measuring point of the sensor.
  - In many instances, the pipe network shapefile did not provide the pipe slope, depth, or diameter. These had to be estimated using the Neighbourhood Planning and Design Guide as a reference.

The following recommendations are made to reduce uncertainties in future research:

- Flow gauges or gauging weirs in the lower reaches of the catchment are recommended. The calibration process in this project was limited due to the location of the only functional flow gauge.
- Rainfall data often had large gaps missing. The stations and gauges measuring the rainfall should be investigated to reduce the likelihood of data not being recorded or being recorded incorrectly.
- The addition of new rainfall gauges in the lower reaches of the catchment areas would help map the highly variable rainfall patterns. However, these would only be useful for model development after several years.
- As the treatment ability of wetlands depends on many environmental factors, the performance of existing stormwater treatment wetlands within Zandvlei’s catchments, or its surroundings, should be investigated to develop local data. Local data may provide a better estimate of the treatment capabilities of any new systems implemented than the use of published values from elsewhere. The inflow and outflow concentrations of pollutant indicators (such as SRP, TIN, TP and TSS) should be monitored to better determine the likely treatment capability of wetlands in the region.
- EMC values played an essential role in this project; unfortunately, no local data on EMC values were available and had to be estimated. EMCs should be measured for land uses in local catchment areas.

Based on the results obtained from the various scenarios, Scenario 5 would provide the most significant improvement to Zandvlei’s water quality. The scenario surpassed the CoCT TP reduction target, however it was not able to meet the 80% TSS reduction. The addition of sediment basins as pre-treatment systems before the ponds and wetlands may allow the TSS reduction to be increased. Additionally, Scenario 5 resulted in lower SRP and TIN outfall concentrations. Many of the wetlands and ponds utilised in the scenario already exist; however, rehabilitation, remediation and maintenance are required of these sites before they may be used effectively. Currently, the location proposed for the large, constructed wetland is unused and contains a small marsh. Unfortunately, the indicator loads from Scenario 5 were substantially larger than the likely sustainable results obtained by the Pre-development Scenario. Therefore, the overall objective of improving the water quality within Zandvlei Estuary using SuDS in the Diep Catchment may be viable, but improving the water quality to the sustainable conditions observed in the Pre-development model will require additional interventions.

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Appendix A – additional SuDS controls

Source Controls

i) Green Roofs

Green roofs are a living layer of soil and vegetation on the rooftop of a building. Shafique & Kim (2017) note that green roofs are exceptional at reducing runoff and attenuating stormwater in urban areas across the globe. Green roofs can retain large volumes of rainwater, thus reducing runoff volumes (Palla et al., 2010). Their ability to retain large volumes of rainwater allows them to provide many benefits, including: reduced flooding, improved air and water quality, improved visual appeal, building thermal regulation, heightened ecological value, and urban cooling (Shafique & Kim, 2017). Flat roofs are the most suitable for this system, but many roof types can be utilised (Woods Ballard et al., 2015).

Figure A-1: Green Roof (CHI, 2019)

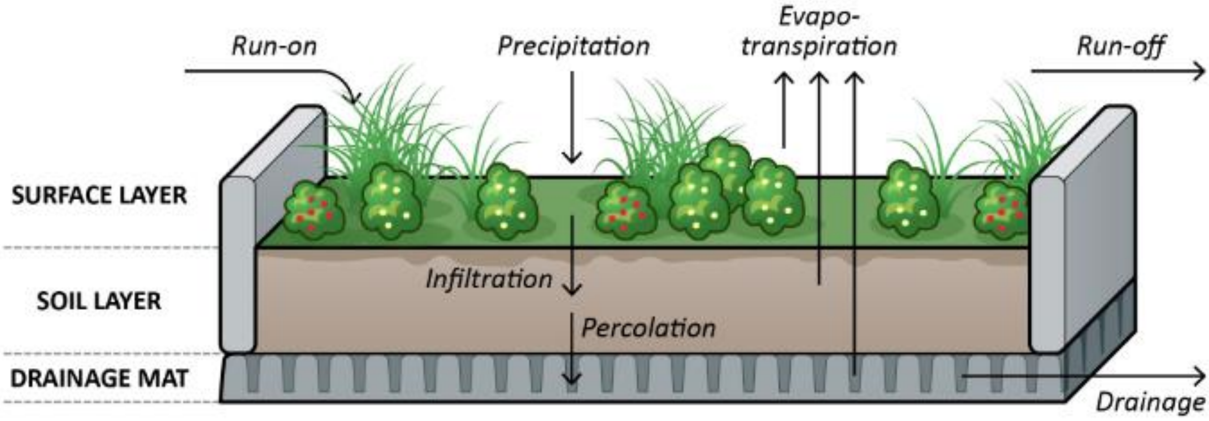


Figure A-2: Green Roof Conceptual Model (CHI, 2019)

ii) Rainwater Harvesting

“Rainwater harvesting is an essential element of effective water conservation where stormwater is utilised as a water supply.” (Armitage et al., 2013). Rain barrels or cisterns are simple structures that can collect and harvest rainwater (Shafique & Kim, 2017) (Figure A-3). Rainwater can be captured from rooftops and other raised, impermeable surfaces. Treatment is optional; however, filters are often included to prevent debris from entering the system. The captured rainwater may be used for many purposes – particularly for non-potable activities such as flushing toilets or irrigation, as this requires little to no treatment. In doing so, rainwater harvesting lowers runoff volumes, protecting downstream systems from large peak flows and contaminated runoff.

Figure A-3: Simple Rainwater Harvesting System (Left). Rainwater Harvesting Conceptual Model (Right) (CHI, 2019)

iii) Permeable Pavements

Permeable pavements, unlike conventional pavements, allow water to infiltrate through pores or gaps between pavers (AECOM, 2013). The paving layer may be in the form of porous paving or paving blocks. The infiltrated water is temporarily stored beneath the surface layer of the system before it is allowed to infiltrate into the ground, used for non-potable purposes or released downstream at a pre-determined rate (Woods Ballard et al., 2015). Well-designed permeable pavements can effectively reduce runoff volumes, protect downstream systems from poor water quality and provide urban cooling (Ariza et al., 2019)

Figure A-4: Permeable Pavement showing gaps between pavers (CHI, 2019)

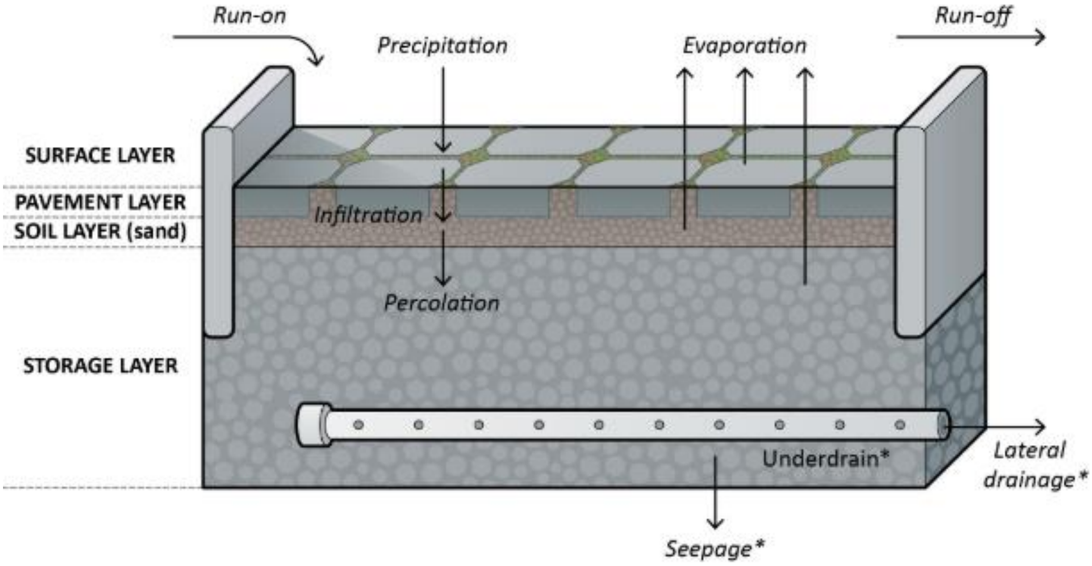


Figure A-5: Permeable Pavement Conceptual Model (CHI, 2019)

Local Controls – Bio-retention Cell

Bio-retention cells are landscaped depressions, usually shallow, used to capture runoff. The cells contain vegetation with sand and gravel layers below to filter runoff. The systems can reduce runoff volumes by providing storage and promoting infiltration (Woods Ballard et al., 2015). Bio-retention system designs can be adjusted (shape, dimensions, plants, and materials used) to fit most sites, allowing the cells to be implemented effectively in various developments. Bio-retention cells effectively remove nutrients, sediments and heavy metals (Armitage et al., 2013). Additionally, bio-retention cells promote biodiversity and provide microclimate cooling.

Figure A-6: Bio-retention Cells (CHI, 2019)

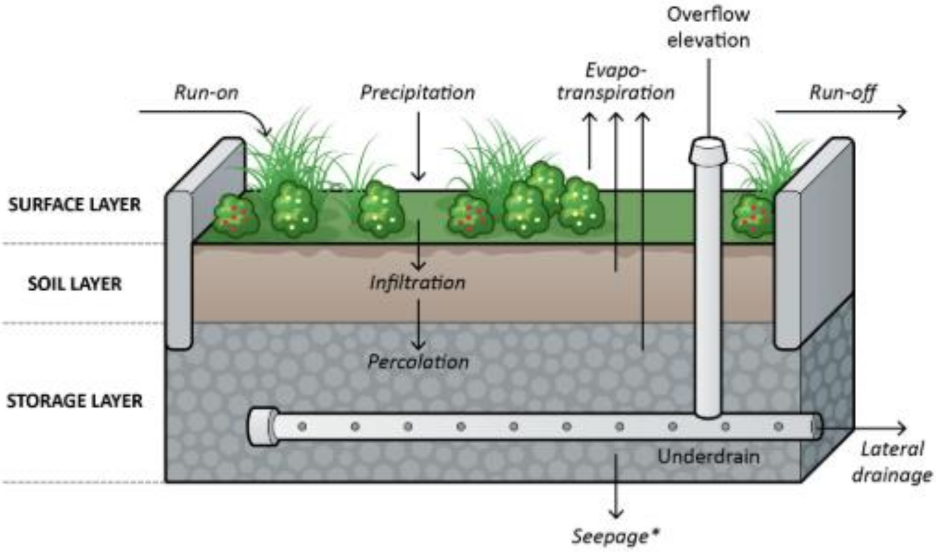
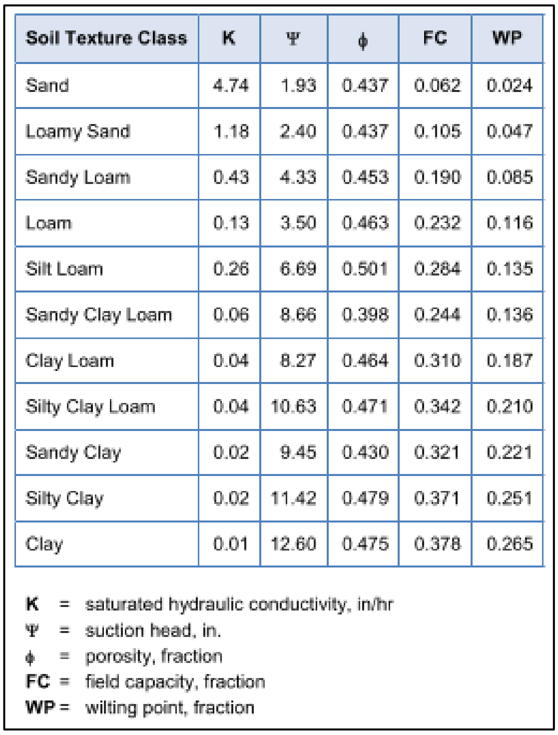


Figure A-7: Bio-retention Cell Conceptual Model (CHI, 2019)

Appendix B – reference tables

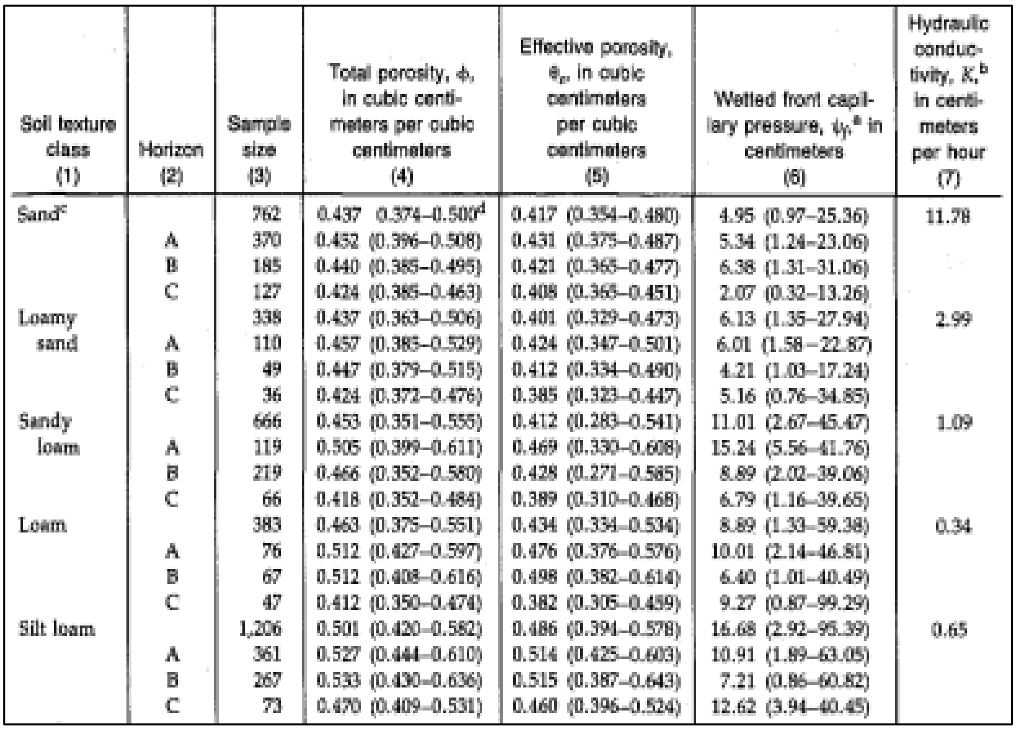
Table B-1: Green-Ampt Soil Properties (Rossman, 2015)



Soil Texture Class	K	Ψ	ϕ	FC	WP
Sand	4.74	1.93	0.437	0.062	0.024
Loamy Sand	1.18	2.40	0.437	0.105	0.047
Sandy Loam	0.43	4.33	0.453	0.190	0.085
Loam	0.13	3.50	0.463	0.232	0.116
Silt Loam	0.26	6.69	0.501	0.284	0.135
Sandy Clay Loam	0.06	8.66	0.398	0.244	0.136
Clay Loam	0.04	8.27	0.464	0.310	0.187
Silty Clay Loam	0.04	10.63	0.471	0.342	0.210
Sandy Clay	0.02	9.45	0.430	0.321	0.221
Silty Clay	0.02	11.42	0.479	0.371	0.251
Clay	0.01	12.60	0.475	0.378	0.265

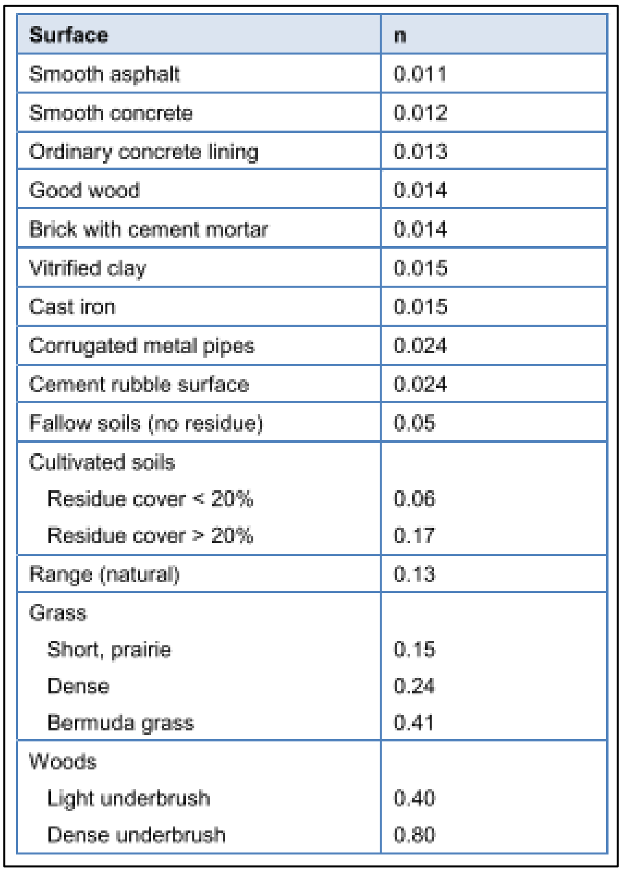
K = saturated hydraulic conductivity, in/hr
Ψ = suction head, in.
ϕ = porosity, fraction
FC = field capacity, fraction
WP = wilting point, fraction

Table B-2: Green-Ampt Soil Properties (Maidment, 1993)



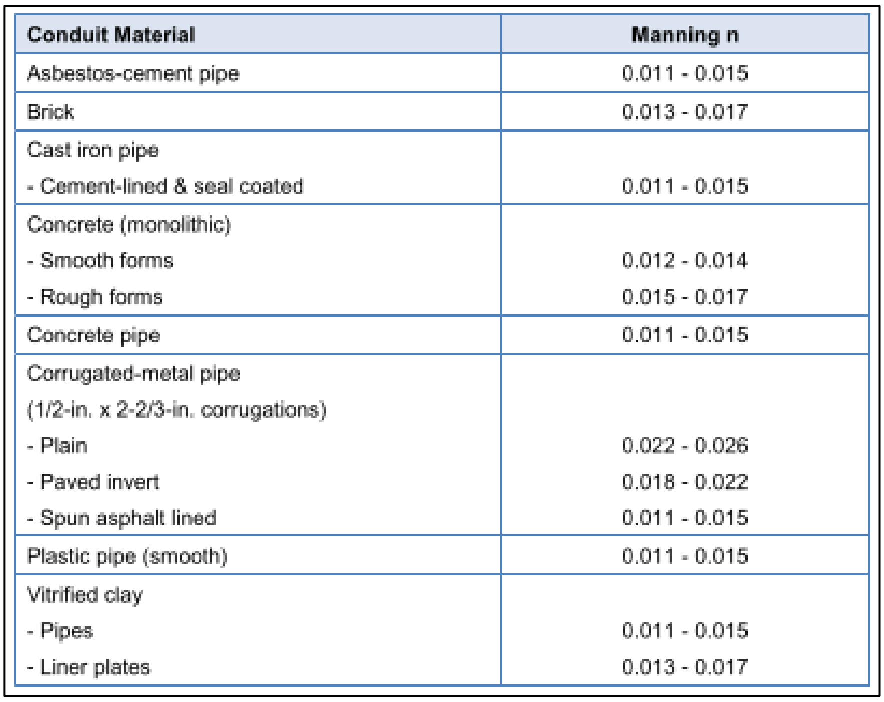
Soil texture class (1)	Horizon (2)	Sample size (3)	Total porosity, ϕ, in cubic centimeters per cubic centimeters (4)	Effective porosity, θ_e, in cubic centimeters per cubic centimeters (5)	Wetted front capillary pressure, ψ_f,[a] in centimeters (6)	Hydraulic conductivity, K,[b] in centimeters per hour (7)
Sand[c]		762	0.437 0.374–0.500[d]	0.417 (0.354–0.480)	4.95 (0.97–25.36)	11.78
	A	370	0.452 (0.396–0.508)	0.431 (0.375–0.487)	5.34 (1.24–23.06)	
	B	185	0.440 (0.385–0.495)	0.421 (0.365–0.477)	6.38 (1.31–31.06)	
	C	127	0.424 (0.385–0.463)	0.408 (0.365–0.451)	2.07 (0.32–13.26)	
Loamy sand		338	0.437 (0.363–0.506)	0.401 (0.329–0.473)	6.13 (1.35–27.94)	2.99
	A	110	0.457 (0.385–0.529)	0.424 (0.347–0.501)	6.01 (1.58–22.87)	
	B	49	0.447 (0.379–0.515)	0.412 (0.334–0.490)	4.21 (1.03–17.24)	
	C	36	0.424 (0.372–0.476)	0.385 (0.323–0.447)	5.16 (0.76–34.85)	
Sandy loam		666	0.453 (0.351–0.555)	0.412 (0.283–0.541)	11.01 (2.67–45.47)	1.09
	A	119	0.505 (0.399–0.611)	0.469 (0.330–0.608)	15.24 (5.56–41.76)	
	B	219	0.466 (0.352–0.580)	0.428 (0.271–0.585)	8.89 (2.02–39.06)	
	C	66	0.418 (0.352–0.484)	0.389 (0.310–0.468)	6.79 (1.16–39.65)	
Loam		383	0.463 (0.375–0.551)	0.434 (0.334–0.534)	8.89 (1.33–59.38)	0.34
	A	76	0.512 (0.427–0.597)	0.476 (0.376–0.576)	10.01 (2.14–46.81)	
	B	67	0.512 (0.408–0.616)	0.498 (0.382–0.614)	6.40 (1.01–40.49)	
	C	47	0.412 (0.350–0.474)	0.382 (0.305–0.459)	9.27 (0.87–99.29)	
Silt loam		1,206	0.501 (0.420–0.582)	0.486 (0.394–0.578)	16.68 (2.92–95.39)	0.65
	A	361	0.527 (0.444–0.610)	0.514 (0.425–0.603)	10.91 (1.89–63.05)	
	B	267	0.533 (0.430–0.636)	0.515 (0.387–0.643)	7.21 (0.86–60.82)	
	C	73	0.470 (0.409–0.531)	0.460 (0.396–0.524)	12.62 (3.94–40.45)	

Table B-3: Manning's Roughness Coefficient for Overland Flow (Rossman, 2015)



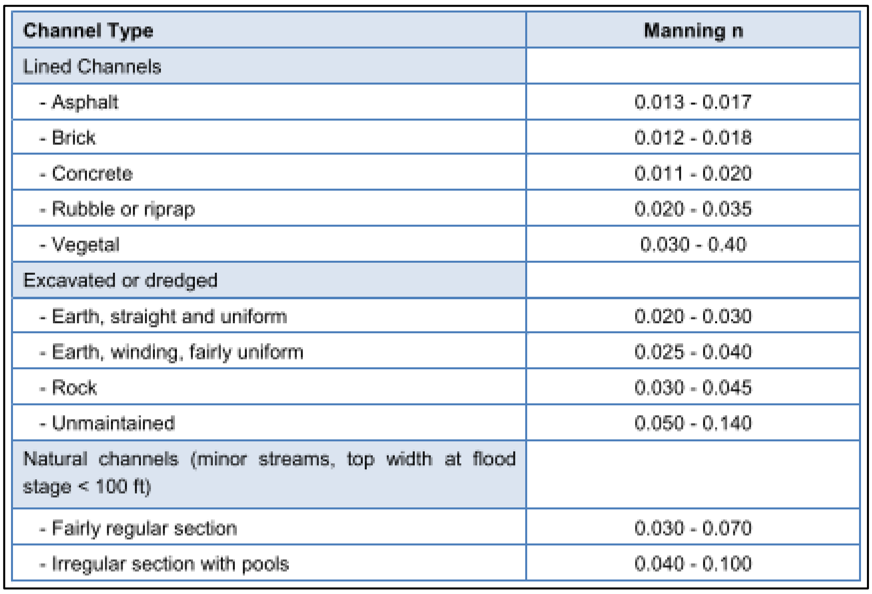
Surface	n
Smooth asphalt	0.011
Smooth concrete	0.012
Ordinary concrete lining	0.013
Good wood	0.014
Brick with cement mortar	0.014
Vitrified clay	0.015
Cast iron	0.015
Corrugated metal pipes	0.024
Cement rubble surface	0.024
Fallow soils (no residue)	0.05
Cultivated soils	
Residue cover < 20%	0.06
Residue cover > 20%	0.17
Range (natural)	0.13
Grass	
Short, prairie	0.15
Dense	0.24
Bermuda grass	0.41
Woods	
Light underbrush	0.40
Dense underbrush	0.80

Table B-4: Manning's Roughness Coefficient for Closed Conduits (Rossman, 2015)



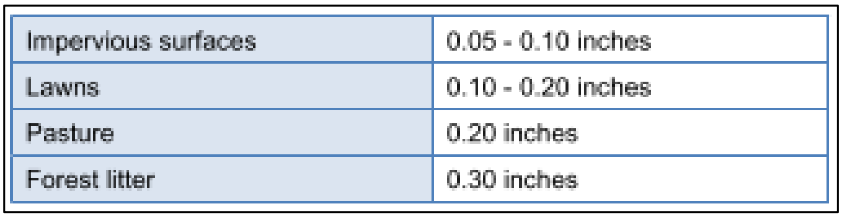
Conduit Material	Manning n
Asbestos-cement pipe	0.011 - 0.015
Brick	0.013 - 0.017
Cast iron pipe	
- Cement-lined & seal coated	0.011 - 0.015
Concrete (monolithic)	
- Smooth forms	0.012 - 0.014
- Rough forms	0.015 - 0.017
Concrete pipe	0.011 - 0.015
Corrugated-metal pipe	
(1/2-in. x 2-2/3-in. corrugations)	
- Plain	0.022 - 0.026
- Paved invert	0.018 - 0.022
- Spun asphalt lined	0.011 - 0.015
Plastic pipe (smooth)	0.011 - 0.015
Vitrified clay	
- Pipes	0.011 - 0.015
- Liner plates	0.013 - 0.017

Table B-5: Manning's Roughness Coefficient for Open Channels (Rossman, 2015)



Channel Type	Manning n
Lined Channels	
- Asphalt	0.013 - 0.017
- Brick	0.012 - 0.018
- Concrete	0.011 - 0.020
- Rubble or riprap	0.020 - 0.035
- Vegetal	0.030 - 0.40
Excavated or dredged	
- Earth, straight and uniform	0.020 - 0.030
- Earth, winding, fairly uniform	0.025 - 0.040
- Rock	0.030 - 0.045
- Unmaintained	0.050 - 0.140
Natural channels (minor streams, top width at flood stage < 100 ft)	
- Fairly regular section	0.030 - 0.070
- Irregular section with pools	0.040 - 0.100

Table B-6: Depression Storage Depths (Rossman, 2015)



Impervious surfaces	0.05 - 0.10 inches
Lawns	0.10 - 0.20 inches
Pasture	0.20 inches
Forest litter	0.30 inches

Appendix C – water quality test results

Water quality tests to measure Electrical Conductivity (EC), Total Dissolved Solids (TDS), pH and temperature were conducted at weekly intervals at several locations along the river network using three OHAUS pen meters: ST20 to test pH, ST20C-B to test EC and ST20T-A to test TDS (OHAUS, n.d.). Additionally, all three pen meters test temperature. The data obtained from this testing process was thus used as a preliminary guide to possible SuDS intervention sites. The results of the testing process are provided in Table C1.

Table C-1a: Water Quality Test Results

Test Location	Date	12-Oct	19-Oct	26-Oct	03-Nov	09-Nov	17-Nov	26-Nov
Confluent	**Time**	10:15	10:05	10:25	09:35	09:35	09:45	09:25
	EC (µS/cm)	1090	1077	891	1072	625	1845	1032
	pH	8.46	7.98	8.39	8.22	8.14	8.42	8.75
	TDS (mg/L)	600	592	490	590	344	1015	568
End of Diep/Sand River	**Time**	-	10:30	10:35	09:50	09:50	10:05	09:38
	EC (µS/cm)	-	764	607	719	627	1476	613
	pH	-	8.07	8.77	7.94	7.14	8.57	8.07
	TDS (mg/L)	-	420	334	396	345	812	337
Little Princessvlei	**Time**	10:45	10:55	11:00	10:20	10:15	10:35	10:10
	EC (µS/cm)	505	554	430	489	360	980	449
	pH	7.80	8.11	8.1	8.15	8.19	8.53	8.42
	TDS (mg/L)	278	305	237	269	198	539	247
Ian Taylor Rd	**Time**	11:00	11:10	11:12	10:30	10:25	10:45	10:20
	EC (µS/cm)	409	484	380	430	346	872	371
	pH	7.67	7.83	8.05	8.04	8.19	8.49	8.63
	TDS (mg/L)	225	266	209	237	190	480	204
St. Joan's Park	**Time**	11:10	11:25	11:26	10:50	10:35	11:00	10:35
	EC (µS/cm)	407	435	332	405	324	792	347
	pH	8.04	7.58	8.03	8.15	7.97	8.1	8.33
	TDS (mg/L)	224	239	183	223	178	436	191
Alphen Trail	**Time**	11:20	11:45	11:45	11:10	10:55	11:10	10:50
	EC (µS/cm)	390	390	331	374	323	652	294
	pH	7.32	7.82	7.4	7.7	8.11	8.35	8.19
	TDS (mg/L)	2145	215	182	206	178	359	162

Table C-1b: Water Quality Test Results

Test Location	**Date**	**12-Oct**	**19-Oct**	**26-Oct**	**03-Nov**	**09-Nov**	**17-Nov**	**26-Nov**
Greenbelt Trail	**Time**	11:30	11:35	11:37	11:00	10:45	-	-
	EC (µS/cm)	314	540	227	160	336	-	-
	pH	7.62	7.6	7.56	7.95	7.59	-	-
	TDS (mg/L)	173	297	125	88	185	-	-
End of Langevlei Canal	**Time**	-	10:15	10:30	09:40	09:40	09:50	09:30
	EC (µS/cm)	-	1235	988	1046	440	-	999
	pH	-	8.33	8.97	8.58	8.12	8.75	8.52
	TDS (mg/L)	-	679	543	575	242	-	550
Langevlei Bottom	**Time**	10:20	10:40	10:45	10:05	10:00	10:15	09:50
	EC (µS/cm)	681	808	640	660	556	1095	586
	pH	7.97	7.87	8.46	8.85	7.54	9.07	9.24
	TDS (mg/L)	375	444	352	363	306	602	322
Langevlei Top	**Time**	10:30	10:50	10:51	10:10	10:05	10:25	10:00
	EC (µS/cm)	1120	1200	640	979	1055	-	1031
	pH	8.13	8.7	9.37	9.01	8.07	8.75	9.13
	TDS (mg/L)	6160	660	352	539	580	-	567

Appendix D – seasonal mean concentrations

The CoCT Scientific Services Branch has been monitoring the water quality of several rivers for decades. Monthly grab samples are taken along rivers throughout the city and its surrounding areas. This data was obtained from the CoCT and contained historic data for six locations within the catchment spanning from 2000 to 2020. Tables C-1 & C-2 provide the seasonal mean concentrations of SRP and TIN in the Diep Catchment Monitoring sites

Table D-1: Seasonal Mean SRP Concentrations (2000 – 2020)

	Summer (mg/L)	Autumn (mg/L)	Winter (mg/L)	Spring (mg/L)
CR16	0.0454	0.0371	0.0425	0.0424
LPVN	0.0400	0.0469	0.0510	0.0423
LVPS	0.0439	0.0464	0.0619	0.0496
LVI	0.2188	0.2582	0.1506	0.1656
LVO	0.0779	0.0969	0.1265	0.1491
CR21	0.0682	0.0551	0.0754	0.0672

Table D-2: Seasonal Mean TIN Concentrations (2000 – 2020)

	Summer (mg/L)	Autumn (mg/L)	Winter (mg/L)	Spring (mg/L)
CR16	0.812	0.645	0.620	0.547
LPVN	0.153	0.222	0.311	0.204
LVPS	0.415	0.441	1.105	0.890
LVI	0.668	1.330	1.223	1.234
LVO	0.625	0.526	1.346	1.253
CR21	1.203	1.201	1.737	1.486

Appendix E – published EMC values

For this project, stormwater pollution was modelled as non-point source EMC values. EMCs represent the mean concentration of a pollutant wash-off experience during a storm event, measured in mg/L. Preliminary EMC values were developed for the land uses in the catchment by gathering published data from District Department of the Environment, 2014; Järveläinen *et al*., 2017; Kayhanian *et al*., 2007; Mitchell, 2005; Nordeidet *et al*., 2004; Song *et al*., 2019; Tuomela *et al*., 2019; USEPA, 1983; & Wicke *et al*., 2021. However, these were all European or American studies. EMC values vary with geographic locations (Tuomela et al., 2019). Therefore, the published values in Tables E-1 to E-3 had to be adjusted for the Cape Town context. The adjustment process is detailed in Section 7.3.

Table E-1a: Published EMC Values for Agricultural, Commercial, Environmental Conservation, and Industrial land uses

Land Use		**Agricultural**			**Commercial**				**Environmental Conservation**			**Industrial**			
Indicator		**TIN**	**TP**	**TSS**	**SRP**	**TIN**	**TP**	**TSS**	**TIN**	**TP**	**TSS**	**SRP**	**TIN**	**TP**	**TSS**
Source	**Mean (mg/L)**	4.9	0.78	303	0.05	1.69	0.31	121	3.2	0.34	40	0.09	2.85	0.33	143
(USEPA. 1983)					80	572	201	69							
(District Department of the Environment. 2014)							300	65		120	50			350	150
(Song *et al*. 2019)					20		85	50.84				120		20	35.57
(Wicke *et al*. 2021)					46	490	270	98							
(Järveläinen *et al*. 2017)	**Set 1**		810	580			280	70		220	40			280	70
	Set 2						300	50.4						300	50,4
	Set 3						430	380						430	380
	Set 4						360	278.43						360	278.43
(Nordeidet *et al*.. 2004)										400	40				

Table E-1b: Published EMC Values for Agricultural, Commercial, Environmental Conservation, and Industrial land uses

Land Use	**Agricultural**			**Commercial**				**Environmental Conservation**			**Industrial**			
Indicator	**TIN**	**TP**	**TSS**	**SRP**	**TIN**	**TP**	**TSS**	**TIN**	**TP**	**TSS**	**SRP**	**TIN**	**TP**	**TSS**
(Mitchell. 2005)											56	600		
(Dzurume. 2020)	4900	750	25		4000	600	30	3200	600	31		5100	600	34

Table E-2: Published EMC Values for Public Open Space and Residential land uses

Land Use		**Public Open Space**				**Residential - High Density**				**Residential - Med Density**				**Residential - Low Density**			
Indicator		**SRP**	**TIN**	**TP**	**TSS**	**SRP**	**TIN**	**TP**	**TSS**	**SRP**	**TIN**	**TP**	**TSS**	**SRP**	**TIN**	**TP**	**TSS**
Source	**Mean (mg/L)**	0.07	0.61	0.30	75	0.15	1.46	0.34	90	0.12	1.58	0.30	86	0.12	1.58	0.34	64
(USEPA. 1983)		26	543	121	70	143	736	383	101	143	736	383	101	143	736	383	101
(District Department of the Environment. 2014)				120	50			350	100			300	60			100	50
(Song *et al*. 2019)		140		310	147	20		70	31.9	20		70	31.9	20		70	31.9
(Wicke *et al*.. 2021)						240	520	435	77	200	400	560	107	200	400	560	107
(Järveläinen *et al*. 2017)	**Set 1**							280	70			200	49				
	Set 2							410	85.1			220	126.				
	Set 3							270	160			250	220				
	Set 4							230	157			90	49.9				
(Nordeidet *et al*. 2004)				400	40												
(Mitchell. 2005)		56	840	220	126	198	980										
(Dzurume. 2020)			450	630	19		3600	600	29		3600	600	29		3600	600	29

Table E-3: Published EMC Values for Rural, Fields and Roadway land uses

Land Use		**Rural**			**Sports Fields**				**Roads**			
Indicator		**TIN**	**TP**	**TSS**	**SRP**	**TIN**	**TP**	**TSS**	**SRP**	**TIN**	**TP**	**TSS**
Source	**Mean (mg/L)**	6.200	0.800	27	0.140	0.660	0.520	98	0.090	0.605	0.441	234
(District Department of the Environment. 2014)											400	150
(Tuomela *et al*. 2019)	**Set 1**						50	11			620	242
	Set 2						50	71			310	232
	Set 3						70	12			240	163
	Set 4						200	397			490	662
	Set 5						2670	75			1310	64
(Song *et al*. 2019)					140		310	147	20		130	143
(Kayhanian *et al*. 2007)	**Set 1**								110		290	112,7
	Set 2								100		300	118
(Wicke *et al*. 2021)									44	400	810	368
(Järveläinen *et al*. 2017)	**Set 1**										400	100
	Set 2										340	157
	Set 3										330	480
	Set 4										340	350
(Nordeidet *et al*.. 2004)							400	40				
(Mitchell. 2005)									178	810	310	175
(Dzurume. 2020)		6200	800	27		660	410	31				

Appendix F – indicator decay function curves

Indicator first order decay function curves curves were derived from experimental data collected by Abbassi *et al*. (2011), Akratos & Tsihrintzis (2007), and Kabenge *et al*. (2018). Tables F-1 to F-4 provide the curves for SRP, TIN, TP and TSS, respectively.

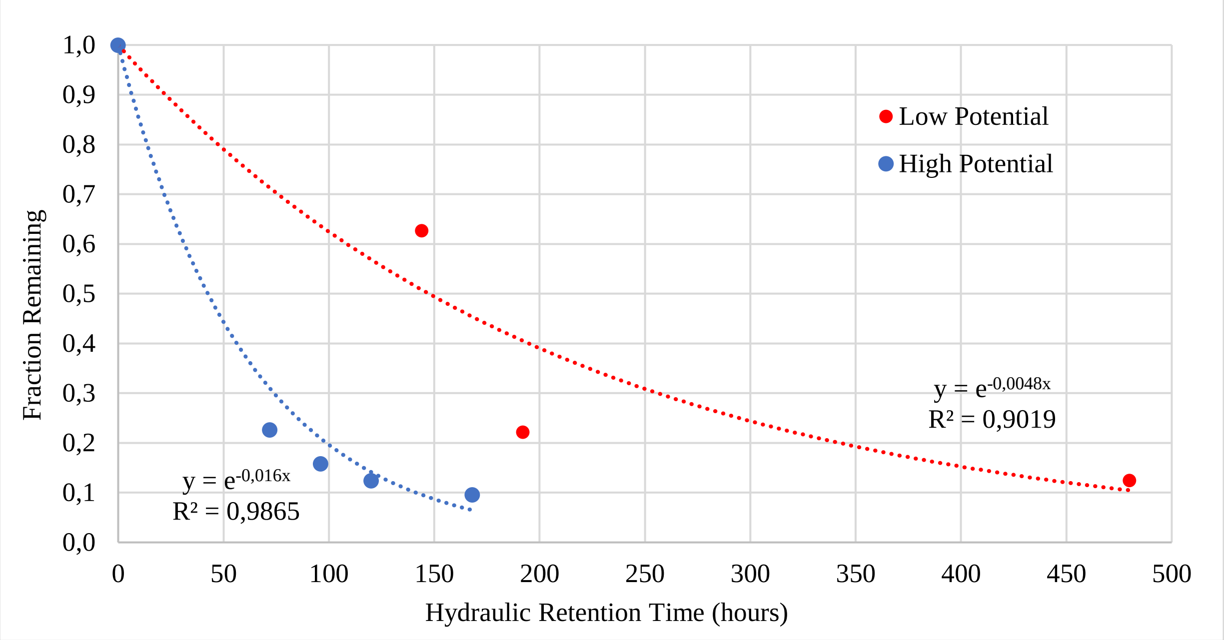


Figure F-1 – SRP Removal Efficiency Curves

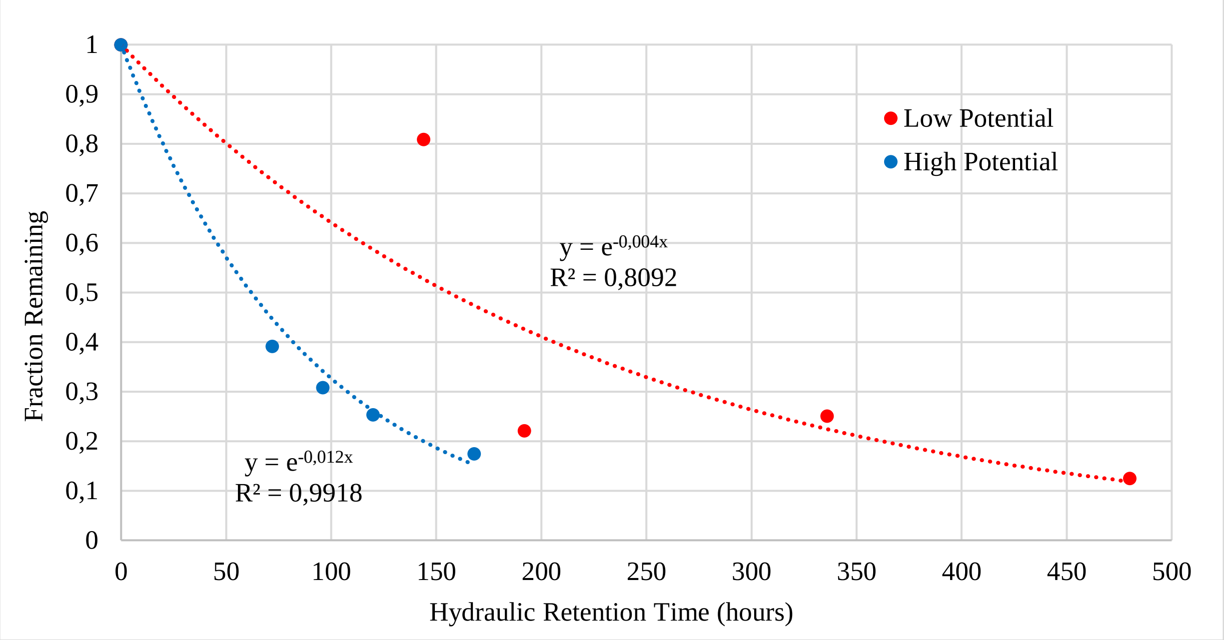


Figure F-2 – TIN Removal Efficiency Curves

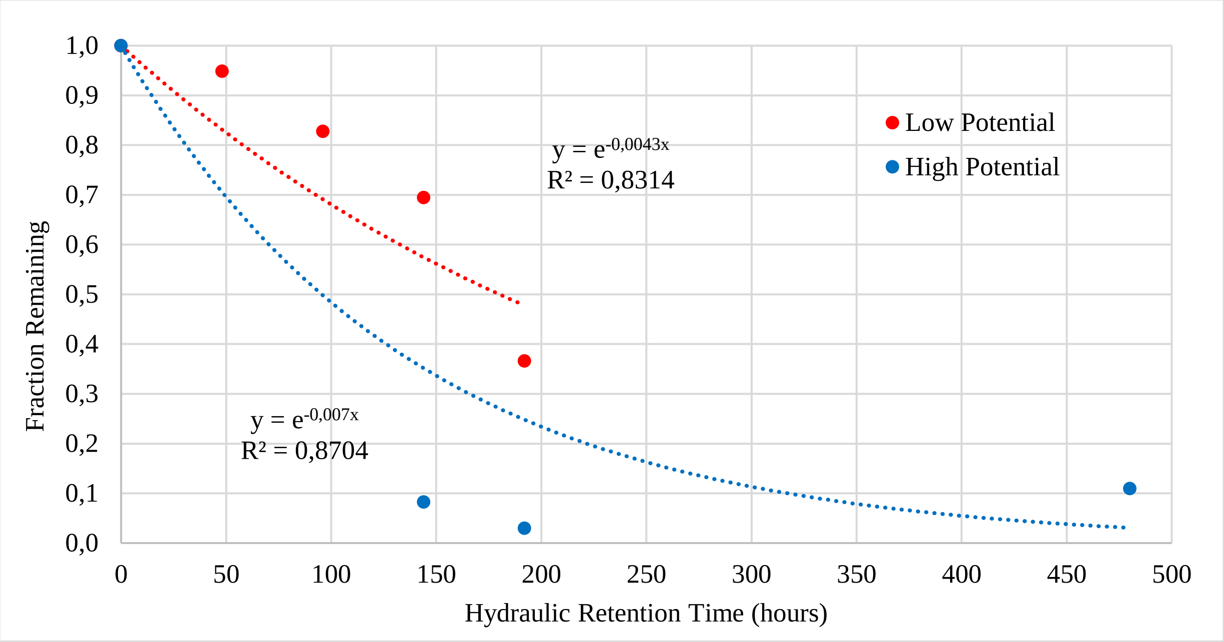


Figure F-3 – TP Removal Efficiency Curves

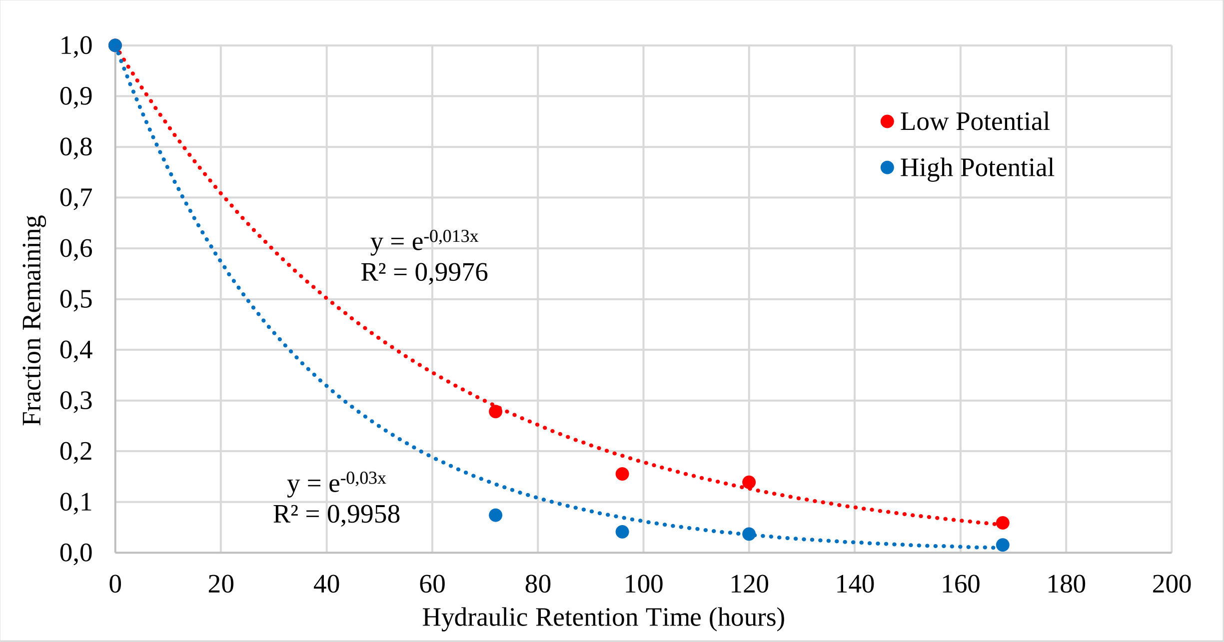


Figure F-4 – TSS Removal Efficiency Curves

Appendix G – SuDS scenario results

The results of the SuDS Scenarios are provided in Section 9.3. The tables provided here present the quantitative results.

Table G-1: Pollutant Loads from SuDS Scenarios

	Range of Indicator Loads over 13 Years (kg x 10^3)				
	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
SRP	3.37 - 3.58	2.42 - 3.12	1.96 - 2.49	1.69 - 2.20	1.61 - 2.05
TIN	38.5 - 40.6	32.2 - 38.3	26.2 - 29.8	23.1 - 27.0	21.8 - 25.5
TP	8.56 - 9.03	7.3 - 8.5	5.9 - 6.7	5.0 - 5.9	4.9 - 5.6
TSS	371.0 - 404.0	239.6 - 296.2	233.3 - 293.3	195.4 - 252.6	165.2 - 206.5

Table G-2: Outflow Concentrations modelled by PCSWMM

	SRP (mg/L)	TIN (mg/L)
Eutrophic Range	0.025 - 0.25	2.5 - 10
Scenario 1	0.0732 - 0.0733	0.83 - 0.84
Scenario 2	0.044 - 0.057	0.59 - 0.70
Scenario 3	0.058 - 0.073	0.77 - 0.87
Scenario 4	0.056 - 0.071	0.76 - 0.87
Scenario 5	0.050 - 0.064	0.68 - 0.79

Appendix H – design calculations

Table H-1: Water Quality Volume Calculations

Scenario	SuDS	P (mm)	I (%)	R_v	Area ($x10^3$ m^2)	WQV (m^3)	WQV with 20% for CC (m^3)
Source Controls	Agricultural Swale 1	34.9	5.6	0.10	65	230	270
	Agricultural Swale 2	36.1	7.3	0.12	100	420	500
	Agricultural Swale 3	34.9	5.6	0.10	150	520	630
	Cemetery Swale	50.3	4.8	0.09	39	180	220
	M3 Swale	34.9	9.3	0.13	180	850	1000
Existing Wetlands	Sunbury Rd Wetland	38.2	21.0	0.24	17000	150000	180000
	Roscommon Rd Wetland	38.2	20.9	0.24	17000	150000	180000
	Ian Taylor Rd Wetland	40.4	19.4	0.22	15000	140000	160000
	M3 Retention Pond	40.4	12.8	0.17	9100	61000	73000
	St Joan's Rd Retention Pond	40.4	13.8	0.17	10000	70000	84000
	Langevlei Wetland	41.0	31.9	0.34	2600	36000	43000
New Wetland	Confluent Wetland	39.1	26.3	0.29	26000	290000	350000

*P = total rainfall depth required to be treated; R_v = volumetric runoff coefficient; I = Impermeable cover percentage; CC = Climate Change

SuDS Design Requirements

Swales

- Bottom Width of 0.5 – 2m
- Longitudinal slopes between 0.5 – 6%.
    - Less than 1.5% for wet swales
- Side slope recommended less than 25%
- The normal maximum depth is 400 – 600mm.
    - Can be deeper if safe
- N = 0.25 for grass-lined swales with a water depth less than or equal to the depth of grass

- Wet Swales
    - Minimum of 150 mm of permanent water
    - Maximum water depth 0.5 m above the permanent water
- 6-month design storm not to flow deeper than 100 mm

Retention Ponds

- 20% of surface area required for sediment forebay
- Maximum WQV depth = 0.5 m above the permanent water body
- Extra 250-400 mm of emergency storage
- The top of the permanent water body lies at 1-1.2 m above the base

Wetlands

- 50% of surface area < 0.5 m deep
- 30% of surface area 0.5 – 1 m deep
- 20% of surface area 1 – 1.2 m deep(NCDWQ. 2007)
- Maximum WQV depth = 0.5 m above the permanent water body
- Extra 250-400 mm of emergency storage
- Inflow invert at 1.7 m or the top of the WQV
- Outflow invert at 1.2 m or the top of the permanent water body
- Needs sediment forebay