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IN CIVIL ENGINEERING

Reduction of pollution levels in the Chatty River through Sustainable Drainage Systems: A case study of the Bethelsdorp River sub-catchment

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Abstract

Chatty River, located in Gqeberha, South Africa, is the largest tributary feeding into the Swartkops Estuary and is among the three significant sources of pollution in the estuary, the other two being the Motherwell Canal and the Markman Canal. The Chatty River Catchment is mainly occupied by low-income residential areas resulting in pollution from stormwater runoff, litter, and raw sewage discharge. There are growing informal settlements and limited agriculture.

In recent years, the high pollution level in the Swartkops estuary has led to the reduction and even halting of various social and cultural activities such as the Redhouse River Mile swimming event, cleansing ceremonies by traditional healers, and baptisms by the Zion Church. SuDS are appropriate for a range of contexts and purposes for example to minimise the impact of development on stormwater quality while maximising amenity and biodiversity through a suite of interventions designed to manage stormwater in a way that mimics nature. This study sought to understand the pollution contribution of the Chatty River and provide recommendations to improve its water quality through the possible inclusion of Sustainable Drainage Systems (SuDS).

The Chatty River's physical, nutrient, and microbiological characteristics were assessed through water quality sampling and historical data review to identify pollutant hotspots. The high mean dissolved inorganic phosphorus (DIP) concentrations, in the form of orthophosphate, indicate eutrophic and hypertrophic conditions in most sections of the Chatty River. The mean nitrogen concentrations, in the form of dissolved inorganic nitrogen (DIN), on the other hand, were below the eutrophic threshold in most sections of the Chatty River. Microbiological pollutant analysis indicated high gastrointestinal health risks to any residents in the catchment who utilised the water for domestic and recreational use. Overall, no consistent relationship was established between pollutant concentrations and rainfall. This could possibly be because of point pollution for example, from overflowing manholes, which was observed to be intermittent. The extent of pollution highlighted by the water quality sampling indicated the need for mitigation measures.

Hydraulic and hydrological models were constructed in PCSWMM, a stormwater management modelling software developed by Computational Hydraulics International (CHI) using the USEPA SWMM model as the 'engine'. Both the Chatty River Catchment as a whole as well as the Bethelsdorp River sub-catchment, located within the Chatty River Catchment, were modelled to test the potential benefits of SuDS inclusion. Various scenarios were tested including: the current situation ('As-is'); the likely Pre-Development situation representing the state before the influence of anthropogenic activities; and various retrofitted SuDS interventions. DIN, DIP and total suspended solids (TSS) were the pollutant indicators tracked in the model. DIN and DIP were used to assess the risk of eutrophication. TSS is a good measure of pollution as pollutants such as heavy metals that attach to suspended particles.

The SuDS interventions included: a constructed wetland, a retention pond, and various infiltration practices. Six scenarios were explored, including various individual interventions, some regional controls and finally, the combination of all the interventions.

Pollutant reduction from the different scenarios ranged from 13-80%. Rehabilitating the wetlands appeared to offer the most significant impact compared to the other regional SuDS interventions in Scenario 1 and 3, with a mean pollutant reduction of 30%. However, a combination of all the interventions had the highest pollutant removal when functioning efficiently of 72% and 80% for DIP and TSS, respectively. This is within the range of treatment required by the City of Cape Town (2009) *Management of Urban Stormwater Impacts Policy* which was used in the absence of a Gqeberha-specific guideline. Installing a treatment train of multiple SuDS interventions is seen as the most effective strategy to adequately improve water quality in the catchment to meet the standards presented by various guidelines.

Table of contents

List of Tables

List of Figures

Technical terms

Absorption	The taking up of one substance into another body, e.g., stormwater runoff into a plant.
Adsorption	The process of removal of pollutants by attaching pollutants to soil or aggregate.
Anthropogenic	Having to do with man, or caused by humans.
Attenuation	Reduction of peak stormwater flow.
(Bio) Filtration	Trapping of polluting sediments through the soil, aggregate matrix or plants.
Bioretention area	A depressed landscaping area that collects stormwater runoff and infiltrates it through vegetation into the soil for potential later removal by an underdrain, thus prompting pollutant removal.
Catchment	The area contributing runoff to a specific point or single drainage area. This area may be a roof draining to a down pipe, or an urban area draining into a wetland.
Channel	A natural or artificial watercourse through which a body of water flows periodically or continuously or forms connecting links between other bodies of water.
Denitrification	The removal of nitrogen or nitrogen compounds.
Depression storage	The volume over a surface that must be filled prior to the occurrence of runoff.
Detention pond	A depression that is usually dry except following larger storm events when it temporarily stores stormwater. It may allow infiltration of stormwater into the ground.
Ecosystem	A community of plants, animals and organisms interacting with each other and with the non-living (physical and chemical) components of their environment.
Infiltration	A complex process of allowing runoff to penetrate the Earth’s surface and flow through the upper soil surface.
Initial moisture deficit	The difference between a soil’s moisture content at the start of a time period and its moisture content at saturation.
Pollution	The direct or indirect alteration of the physical, chemical or biological properties of the natural environment, including the marine environment, to make it less fit for any beneficial purpose for which it may reasonably be expected to be used, or to make it harmful or potentially harmful to the welfare, health or safety of human beings or to any aquatic or non-aquatic organisms.
Retention pond	A pond-like structure where runoff is detained for a sufficient time to allow settlement and possibly biological treatment of some pollutants.

Runoff	The excess water that flows after precipitation.
Saturated hydraulic conductivity	The rate of water movement through soil under a unit gradient of hydraulic head for a completely saturated soil.
Sedimentation	The removal of sediment particles from runoff by reduction of flow velocities.
Suction head	The mean value of the attraction of water within the soil voids along the wetting front during the infiltration process.
Swale	A shallow vegetated channel designed to conduct and retain water but may also permit infiltration. The vegetation assists in filtering particulate matter.
Treatment train	A combination of different methods implemented in sequence or concurrently to achieve the best management of stormwater. These methods include source control and non-structural and structural measures.
Wastewater	Water containing solid, suspended or dissolved material (including sediment) in such volumes, composition or manner that, if spilled or deposited in the natural environment, will cause, or is reasonably likely to cause, a negative impact.

Acronyms and abbreviations

ARC	Agricultural research commission
BeST	Benefit of SuDS Tool
BMP	Best Management Practice
BRC	Bethelsdorp River Catchment
C.A.P.E	Cape Action for People and the Environment
CBD	Central Business District
CIRIA	Construction Industry Research and Information Association
CHI	Computational Hydraulics International
CMAs	Catchment Management Agencies
CRC	Chatty River Catchment
CRCCH	Cooperative Research Centre for Catchment Hydrology
CSIR	Council for Scientific and Industrial Research
DCIA	Directly Connected Impervious Area
DEM	Digital Elevation Model
DIN	Dissolved Inorganic Nitrogen
DIP	Dissolved Inorganic Phosphorus
DO	Dissolved oxygen
DWS	Department of Water and Sanitation
EC	Electrical conductivity
E. *coli*	Escherichia coli
EMC	Event mean concentration
EMP	Estuary Management Plan
EPA	Environmental Protection Agency
GIS	Geographic information systems
GPS	Global Positioning System
HRT	Hydraulic Retention Time
ICM	Integrated Coastal Management
ISE	Integral Square Error
ISRIC	International Soil Reference and Information Centre
LID	Low Impact Development
MAP	Mean Annual Precipitation

MUSIC	Model for Urban Stormwater Improvement Conceptualisation
NMU	Nelson Mandela University
NSE	Nash-Sutcliffe Efficiency
PCSWMM	Personal Computer Stormwater Management Model
PES	Present Ecological State
R^2	Coefficient of determination
REC	Recommended ecological category
RI	Return Interval
SANLC	South African National Land Cover
SASS	South African Scoring System
SAWS	South African Weather Service
SDG	Sustainable Development Goal
SLAMM	Source Loading and Management Model
SOTER	Soils and Terrain Database
SRP	Soluble reactive phosphorus
SRTC	Sensitivity Radio Tuning Calibration
SuDS	Sustainable Drainage Systems
SUSTAIN	System for Urban Stormwater Treatment and Analysis Integration
SWMM	Storm Water Management Model
TDS	Total Dissolved Solids
TSS	Total Suspended Solids
TWQR	Target Water Quality Range
UCT	University of Cape Town
UK	United Kingdom
USCS	Unified Soil Classification System
USEPA	United States Environmental Protection Agency
WASH	Water, Sanitation and Hygiene
WDT	Watershed Delineation Tool
WQV	Water Quality Volume
WRC	Water Research Commission
Wunderground	Weather Underground
WWTW	Wastewater treatment works

1. Introduction

1.1 Background

Chatty River, the largest tributary draining into the Swartkops estuary (Nel, 2014), is located north of the Gqeberha central business district (CBD) (Figure 1-1). It drains townships such as Soweto on the Sea, KwaMagxaki, Kwa-Dwesi and Zwide. Much of the catchment is covered in low-income residential areas.

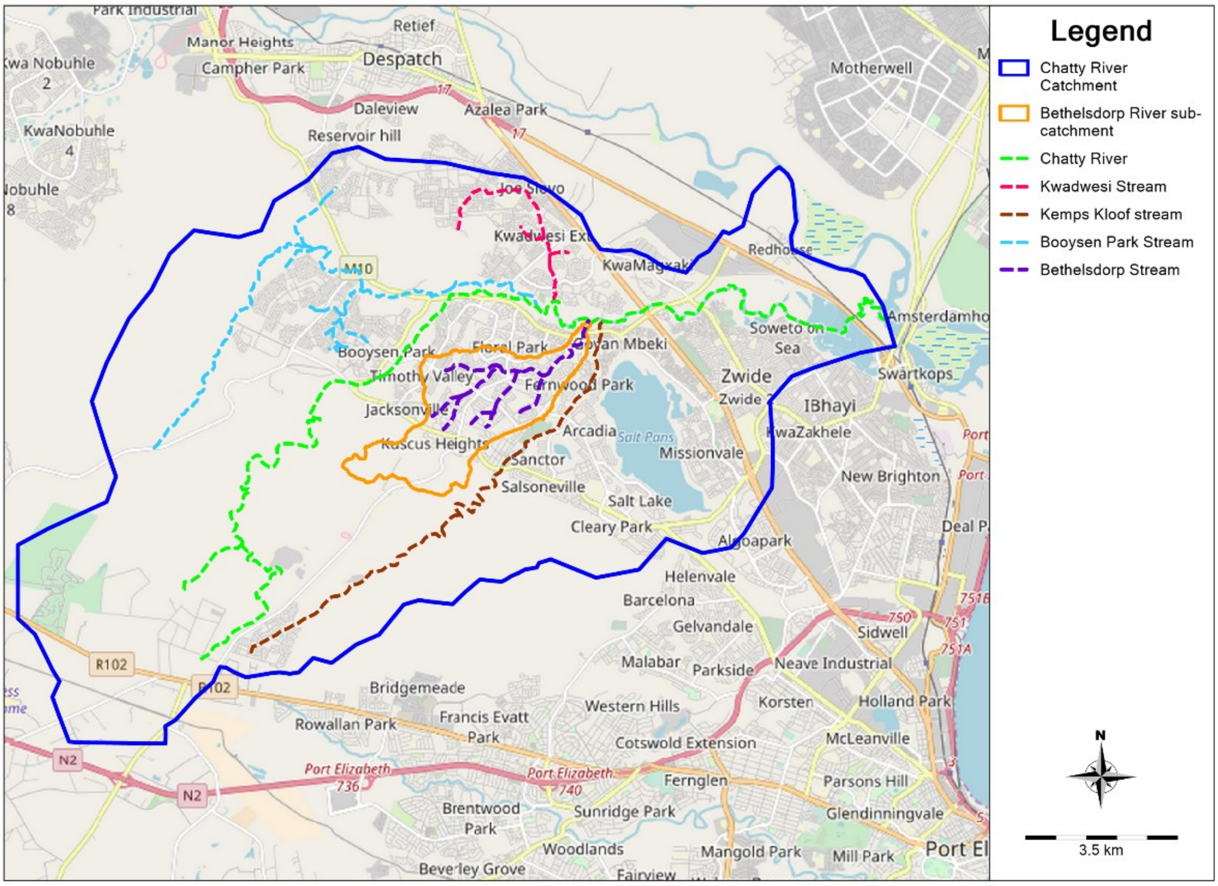


Figure 1-1: Chatty River and its tributaries

The Swartkops Estuary (Figure 1-2), permanently open to the sea, discharges into the Algoa Bay, Indian Ocean, and is approximately 16 km long. Of approximately 260 estuaries in South Africa, Swartkops estuary is ranked the 12th most important (Turpie *et al.*, 2012). The estuary's importance is based on biodiversity, size, habitat, and zonal type rarity and excludes functionality. The estuary is well known as a bird and fish species nursery area. It has essential botanical components such as the intertidal salt marsh and intertidal benthic microalgae (Adams & Riddin, 2019).

Figure 1-2: Swartkops estuary draining into the Algoa Bay
(Adams & Riddin, 2020)

1.2 Research Problem

The Swartkops Estuary is of economic, ecological, and social importance in the Nelson Mandela Bay area. However, studies by various scholars such as *inter alia* Pretorious (2014) and Adams & Riddin (2019), indicate that it experiences high pollution levels. The high level of pollution has negatively affected the health of the estuary and the occurrence of various recreational activities, such as the Redhouse River Mile swimming event and traditional activities such as cleansing ceremonies by traditional healers.

Previous studies indicate that the Chatty River, a tributary flowing into the estuary, and Markman Canal and Motherwell Canal, other inlets into the estuary, are severely polluted. Although previous studies have identified potential point and diffused sources of pollution in the Swartkops Estuary, more information is required to understand the extent and sources of pollution from the Chatty River Catchment and various measures that may improve water quality in the River and subsequently, the estuary. This study focused on diffused sources as the primary source of pollution due to the sporadic nature of the point pollution sources in the catchment.

1.3 Research aim and objectives

This project aimed to determine the hydrological variability and pollutant inputs of the Chatty River sub-catchments. In addition, the research aimed to explore the various opportunities and potential impact of modelled Sustainable Drainage Systems (SuDS) interventions on water quality through a scenario-based approach. The Bethelsdorp River Catchment, draining the Bethelsdorp River, a tributary of the Chatty River was used as a case study to assess the performance of the modelled SuDS.

1.4 Overview of the method

The method employed to achieve the objectives of the study were:

- A desktop study of the Chatty River Catchment and Swartkops Estuary and an initial site visit to define the drainage network, study area and understand the challenges faced.
- Water quality sampling and testing at various points of the Chatty River and its tributaries to complement historical data acquired from the DWS and identify areas with higher pollutant concentrations.
- Collection of data relevant to the site, that is, topography maps, hydrological reports, land use data, meteorological data, soil data, vegetation data and historical water quality data.
- Development of a hydrological and hydraulic model of the Chatty River study area and Bethelsdorp sub-catchment using PCSWMM to simulate runoff, flow and pollutant loads in the river network before and after urban development.
- Conceptual development, design and modelling of various SuDS scenarios that may aid in the reduction of pollution in the Bethelsdorp stream.
- Comparison of the relative performance of the various SuDS interventions concerning pollutant removal.

1.5 Research justification

This study complemented those conducted by Nelson Mandela University (NMU) with funding from the Water Research Commission (WRC) through the project entitled: '*Restoration of estuaries using a socio-ecological systems framework'*. It was intended to help inform decisions made regarding water quality improvement in the Nelson Mandela Bay Municipality (NMBM) and estuary management forums of the Swartkops Estuary, such as the Cape Action for People and the Environment (C.A.P.E) forum.

This investigation contributes to understanding the extent of pollution in the Chatty River, how the water quality in the Chatty River and the overall health of the Swartkops Estuary may be improved through SuDS using the Bethelsdorp River sub-catchment as a case study, and gaps in knowledge of the catchment. It is hoped that this will lead to an improvement in water management practices and strategies that promote aesthetically pleasing environments and uplift the residents' liveability. It could be an example for other Catchment Management Agencies (CMAs) across South Africa to emulate hence contributing to sustainable cities and communities.

1.6 Assumptions and limitations

Several assumptions were made while developing the hydrological and hydraulic models where data collection was challenging, and data were insufficient or unreliable. The limitations were considered in the analysis and use of the results. The investigation was restricted to the Chatty River and its tributaries.

The use of only one rain gauge was equivalent to assuming that the rainfall was distributed equally over the entire catchment. Multiple rain gauges particularly with at least one within the Bethelsdorp River sub-catchment would have improved the representivity of the rainfall model.

A surface water model was developed. Continuous flow data was challenging to collect due to repeated equipment theft therefore the model was calibrated using peak flow data. As a result, a comprehensive representation of the flow regime during a storm event was not captured.

Land use maps and satellite imagery were used to identify the various land uses in the area for water quality and quantity modelling. However, undocumented land use and point pollution from poorly maintained manholes observed during site visits led to increased uncertainty in the water quality model. Time constraints limited the study of undocumented land use such as, grazing in open spaces, and the several point pollution sources. The analysis of point sources would require extended time on site for preliminary monitoring and local community and stakeholder engagement due to the sporadic nature for example, overflowing manholes. The study therefore focused on diffused source pollution and assumed that adequate infrastructure maintenance would mitigate point pollution sources.

The high-security risk in the study area limited the number of site visits, the duration of sampling, and the continuous sampling from being undertaken during storm events. The PCSWMM model simulations was constrained by the computer's speed and capabilities as the assessment of the impact of different scenarios used hydrographs from event simulations and summarised results from continuous simulations, rather than utilising long-duration hydrographs. . Finally, acquiring sufficiently detailed data faced obstacles such as the provision of incomplete datasets. The following datasets would have enhanced the models:

- Additional rain gauges within the Chatty River Catchment to cater for variable rainfall patterns. Only one reliable rain gauge was identified in the lower reaches of the catchment.
- Stormwater system maps for the Bethelsdorp River sub-catchment (> 600 mm pipes).
- Maps indicating the sewage pump stations in the study area.

- Reliable flow rate data from flow stations in the study area.

1.7 Chapter outline

The chapters in this dissertation cover the following:

- **Chapter 2** is a review of the literature on the impact of urbanisation on river systems and river health monitoring in South Africa. Moreover, it reviews SuDS relevant to this study, providing an overview and methods used to identify opportunities. Finally, the literature review discusses various hydrological and hydraulic modelling software and considerations.
- **Chapter 3** describes the current state of the Chatty River Catchment.
- **Chapter 4** describes the methods implemented during this study.
- **Chapter 5** describes the hydrological model development and the data collected.
- **Chapter 6** discusses the results from water quality sampling and historical data from DWS, and the water quality model development.
- **Chapter 7** details the hydrological and hydraulic modelling results for the Chatty River Catchment
- **Chapter 8** outlines the various hydrological and hydraulic model scenarios created.
- **Chapter 9** presents the results of the Bethelsdorp River sub-catchment modelling and analysis of the performance of various SuDS scenarios to reduce pollutant load flowing into the main Chatty River channel.
- **Chapter 10** presents the conclusions and recommendations.
- The appendices provide supplementary information.

2. Literature review

This chapter commences with a brief overview of urban river systems and the various threats faced. Sustainable Drainage Systems (SuDS) – potentially suitable approaches to mitigating the impact of anthropogenic activities – are introduced with a background on the philosophy and principles, design, and identification of opportunities and types. Finally, various hydrological modelling software are discussed, highlighting the different considerations to make when choosing one and the potential uses of each.

2.1 Threats to urban river systems

The industrial revolution promoted rapid urbanisation throughout the world beginning in the 1750s (Yuan, Philip & Yang, 2006). Urbanisation has led to the growth of extensive impervious areas through various urban land use practices (Sidek *et al.*, 2014), affecting the natural hydrological cycle (Figure 2-1). Natural freshwater systems have deteriorated significantly regarding water quality, biodiversity, in-stream processes, watershed hydrological regimes and general structure as a consequence (O'Driscoll *et al.*, 2010; Jordaan & Bezuidenhout, 2016; Yuan *et al.*, 2006). It has become a global concern, worsening in almost all rivers in Africa since the 1990s (UNEP, 2016).

Water quality degradation is rendering river systems unfit for recreational, domestic, and other human uses and endangering the health of residents (Chen *et al.*, 2022; De Figueiredo *et al.*, 2007). The pollution of rivers may result from both point or non-point sources. Point sources are linked to specific issues such as broken sewers or industrial discharges into drainage systems (Hranova, 2005). Non-point sources, also called diffused sources, are associated with land drainage and surface runoff that result in pollution entering a drainage system in dispersed ways (Matowanyika, 2010). Monitoring nutrient loading in urban settings may face challenges due to uncontrolled sewage discharge and limited monitoring capacity and technology (Chen *et al.*, 2022). Furthermore, municipal solid waste management is a significant challenge for African municipalities and governing bodies (Achankeng, 2003).

Geomorphological changes in the watershed drainage systems, particularly in urban areas, result from water supply exploitation, channelization of waterways, damming, diversion and burial of rivers (Ceola, Laio & Montanari, 2015). These infrastructural developments have led to a change in flow regimes for example the decrease in peak flow time and increased peak flow discharge and volume (Gurnell, Lee & Souch, 2007). The distraction of riparian buffers, increase flow rates and volume have in turn increased the rate of erosion and magnitude of sediment delivery (Findlay & Taylor, 2006) Furthermore, it has led to habitat fragmentation and biodiversity loss (Hack, Molewijk & Beißler, 2020).

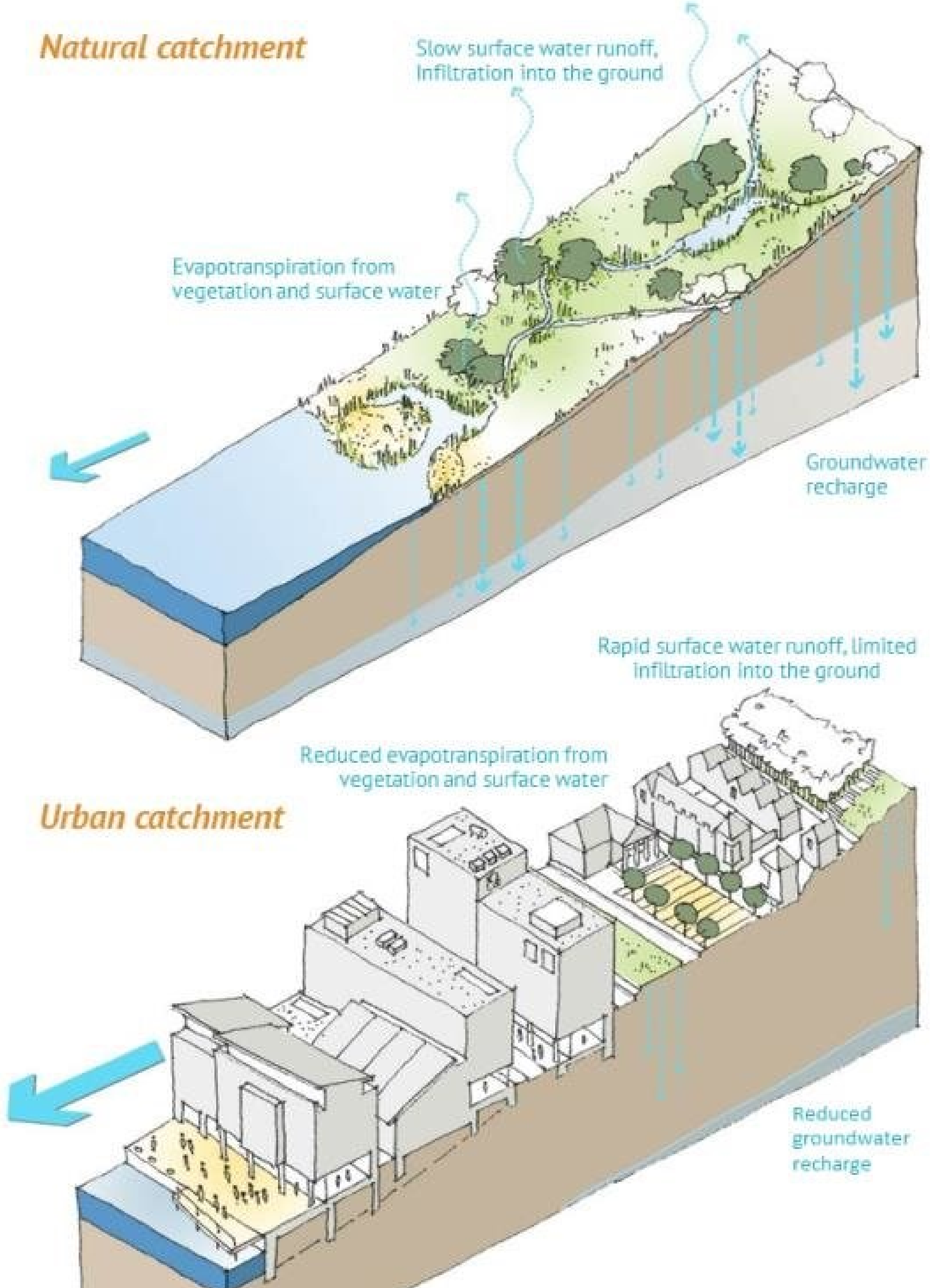


Figure 2-1: Illustration of the pre-development vs post-development hydrological cycle (susDrain, n.d.)

Table 2-1: Ecological Categories of rivers in South Africa (DWS, 2022)

Ecological category	Ecological state	Generic description of ecological conditions
A	Unmodified/ natural.	Close to natural or close to predevelopment conditions within the natural variability of the system drivers: hydrology, physico-chemical and geomorphology. The habitat template and biological components can be considered close to natural or to pre-development conditions. The resilience of the system has not been compromised.
A/B	Close to natural condition most of the time.	Conditions may rarely and temporarily decrease below the upper boundary of a B category.
B	Largely natural with few modifications.	A small change in the attributes of natural habitats and biota may have taken place in terms of frequencies of occurrence and abundance. Ecosystem functions and resilience are essentially unchanged.
B/C	Close to largely natural most of the time.	Conditions may rarely and temporarily decrease below the upper boundary of a C category.
C	Moderately modified.	Loss and change of natural habitat and biota have occurred in terms of frequencies of occurrence and abundance. Basic ecosystem functions are still predominantly unchanged. The resilience of the system to recover from human impacts has not been lost and its ability to recover to a moderately modified condition following disturbance has been maintained.
C/D	The system is in a close to moderately modified condition most of the time.	Conditions may rarely and temporarily decrease below the upper boundary of a D category.
D	Largely modified	A large change or loss of natural habitat, biota and basic ecosystem functions has occurred. The resilience of the system to sustain this category has not been compromised and the ability to deliver Ecosystem Services has been maintained.
D/E	The system is in a close to largely modified condition most of the time.	Conditions may rarely and temporarily decrease below the upper boundary of an E category. The resilience of the system is often under severe stress and may be lost permanently if adverse impacts continue.
E	Seriously modified	The change in the natural habitat template, biota and basic ecosystem functions are extensive. Only resilient biota may survive and it is highly likely that invasive and problem (pest) species may dominate. The resilience of the system is severely compromised as is the capacity to provide Ecosystem Services. However, geomorphological conditions are largely intact but extensive restoration may be required to improve the system's hydrology and physico-chemical conditions.
F	Critically/ Extremely modified.	Modifications have reached a critical level and the system has been modified completely with an almost complete change of the natural habitat template, biota and basic ecosystem functions. Ecosystem Services have largely been lost. This is likely to include severe catchment changes as well as hydrological, physio-chemical and geomorphological changes. In the worst instances, the basic ecosystem functions have been destroyed and the changes are irreversible. Restoration of the system to a synthetic but sustainable condition acceptable for human purposes and limiting downstream impacts is the only option.

As a result of changes to river systems as mentioned above, monitoring river health is essential. Factors used to determine the health of river ecosystems in South Africa are the geomorphological characteristics, hydrological and hydraulic regimes, water quality and nature of in-stream and riparian habitats (Ballance *et al*., 2001). A national river health classification system based on an ecological perspective was adopted by the Department of Water and Sanitation (DWS) (Table 2-1). This classification system has been implemented in the River Eco-status Monitoring Programme (REMP) undertaken by the DWS. However, practical realities mean that monitoring river systems has faced several obstacles, such as the inaccessibility of some monitoring sites and a shortage of qualified and accredited South African Scoring System (SASS) personnel to undertake the required tasks (Jafta & Thirion, 2019). Furthermore, the department is faced with financial constraints that affect the undertaking of training of staff, transportation of qualified staff to and from the monitoring sites, and the overall implementation of REMP (Jafta & Thirion, 2019).

Given the consequences of urban development on river systems, it is evident that rehabilitation or enhancement of urban rivers to a less conventionally engineered state, that is, less impervious surfaces, is likely to lead to the restoration of river functions and recovery of biodiversity (Gurnell, Lee & Souch, 2007). Furthermore, it is important to create awareness regarding the potential ecosystem services provided by rivers before they are completely lost (Hack, Molewijk & Beißler, 2020).

2.2 Sustainable Drainage Systems (SuDS)

2.2.1 Overview of SuDS philosophy and principles

Sustainable Drainage Systems (SuDS) are a water management practice utilised to promote sustainable development by restoring the natural hydrological and geomorphic processes (Lim & Lu, 2016). They are systems designed to minimise the impact of development through four pillars, that is, water quality, water quantity, amenity and biodiversity (Woods-Ballard *et al*., 2007). Conventional drainage design generally views stormwater as a nuisance that needs to be removed as fast as possible rather than a resource (Mitchell, 2006). This approach tends to lead to erosion, siltation, and pollution, whereas stormwater has the potential to contribute to the water cycle and preservation of the environment in urban areas (Armitage *et al*., 2013). Surface water is a valuable resource, therefore, unlike conventional design which observes the four pillars separately, SuDS philosophy aims to overlap and deliver multiple benefits (Figure 2-2), hence managing surface water for maximum benefit.

When implemented, the four pillars of SuDS may be achieved through (Ballard *et al*., 2007):

- Controlling runoff rates and volumes to reduce the risk of flooding downstream (attenuation).

- Reducing pollutant concentrations through processes such as filtration and sediment settlement, hence protecting water bodies downstream.
- Promoting infiltration where appropriate, recharging natural groundwater.
- Providing habitats for wildlife in urban areas, creating opportunities for biodiversity enhancement.

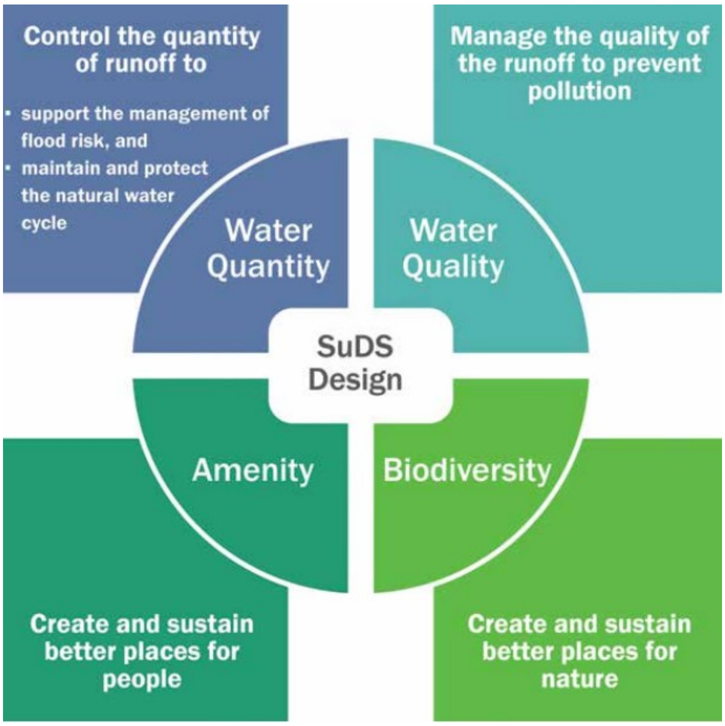


Figure 2-2: Benefits of SuDS (Woods-Ballard *et al*., 2015)

Overall, SuDS aim to promote a resilient, sustainable, and liveable urban environment by managing stormwater in a holistic and integrated way. To hasten the shift to SuDS and for new technologies and practices to take root, there needs to be an addition of expertise and social shifts in awareness and forms of governance to plan and implement SuDS in a timeous and holistic manner (Armitage, 2011; Goulden *et al*., 2018). Furthermore, interdisciplinary partnerships are key to the successful design and management of SuDS and to achieving the outlined objectives (Vice, 2011).

2.2.2 SuDS treatment train

The application of SuDS components varies depending on the scope and size of the area. As the catchment size increases in size, a more comprehensive and integrated approach is required to ensure efficient functioning and sustainability. A SuDS treatment train is a sequential combination of several types of SuDS to reduce stormwater quantity while ensuring efficient water quality management (Huertas, Muñoz & Sánchez, 2019). The use of different and complementary removal techniques can achieve enhanced pollutant removal (Bastien *et al.*, 2010). According to the National Water Act, the term pollutant refers to the direct or indirect alteration of the physical, chemical, or biological properties of a water resource, making it less fit for any beneficial purpose for which it may reasonably be expected to be used or harmful or potentially harmful to the welfare, health or safety of human beings, any aquatic or non-aquatic organisms, the resource quality or to property (Department of Water and Sanitation, 1998). Pollutants negatively affect ecosystems and may have detrimental effects on human health and vertebrates such as fish and birds (Nel, 2014).

The treatment process may be initiated by structures such as gross pollutant traps and vegetated swales, which capture litter and sediments and manage such pollutants at the source. The initial stages ensure the effectiveness of the treatment train in the later stages of treatment (Ahmed *et al.*, 2019). The following stages may include filtration and biofiltration, nitrification and photosynthesis, adsorption, precipitation, plant uptake and biodegradation (Armitage *et al.*, 2013).

Table 2-2: A summary of pollutant removal processes in a treatment train
(Wilson, Bray & Cooper, 2004)

Pollutant	Removal mechanisms in SuDS
Nutrients (Phosphorus and Nitrogen)	Sedimentation, biodegradation, precipitation, denitrification
Sediments (Total suspended solids, TSS)	Sedimentation, filtration
Hydrocarbons (TPH, PAH, VOC, MTBE)	Biodegradation, photolysis, filtration, and adsorption
Metals	Sedimentation, adsorption, and volatilisation
Pesticides	Biodegradation, adsorption, volatilisation
Cyanides	Volatilisation, photolysis
Litter	Trapping, removal during routine maintenance
Organic matter, BOD	Filtration, sedimentation, biodegradation

The treatment train utilises various forms of control. They include: source controls near the source of runoff hence delaying or preventing runoff from entering the drainage system (Woods-Ballard *et al.*, 2015); local controls acting as the second ‘line of defence’ mainly in public areas; and finally, regional controls, which are usually the final ‘line of defence’. Through the use of a treatment train, the shock load effect is reduced on regional controls (Bastien *et al.*, 2010). Figure 2-3 is a diagrammatic representation of the different controls in the treatment train. Examples of each are highlighted below (Armitage *et al.*, 2013):

- Source controls – green roofs, grass filter strips and permeable pavements

- Local controls – filter strips, swales, and sand filters
- Regional controls – retention ponds, detention ponds and constructed wetlands.

The improvement of water quality through SuDS varies from system to system. Each system, therefore, needs to be assessed to account for local variability and optimise the treatment train to be implemented (Ahmed *et al*., 2019). Table 2-3 provides indicative mitigation capacities.

Table 2-3: Potential pollutant removal capacities of various SuDS (Armitage *et al*., 2013)

	Mitigation indices		
Type of SuDS component	**TSS**	**TP**	**TN**
Filter Strips	50 - 85	10 - 20	10 - 20
Swale	60 - 90	25 - 80	30 - 90
Bio-retention areas	50 - 80	50 - 60	40 - 50
Detention basin	45 - 90	20 - 70	20 - 60
Wetland	80 - 90	30 - 40	30 - 60
Retention pond	75 – 90	30 - 50	30 – 50
Key: TSS – Total suspended solids; TP – Total Phosphorus; TN – Total Nitrogen			

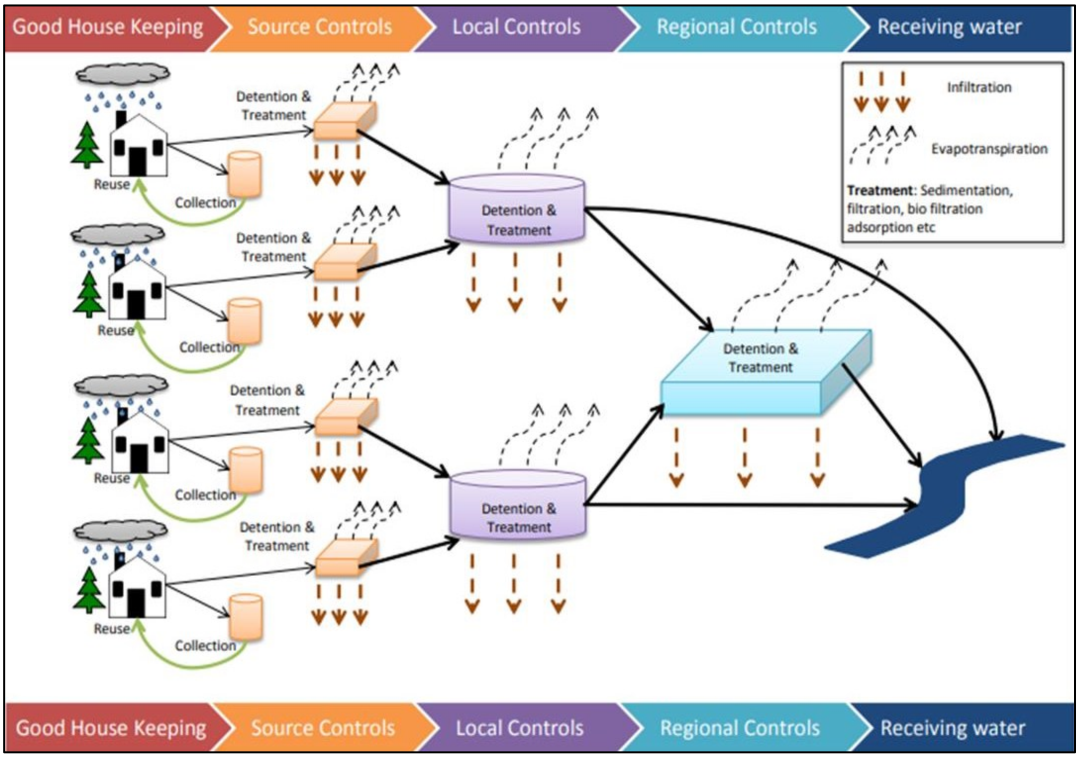


Figure 2-3: The SuDS Treatment Train (Armitage *et al*., 2013)

2.2.3 Identifying opportunities and the selection of SuDS

The consideration of social, economic, environmental and cultural factors is essential when selecting a reliable SuDS intervention (Pathak *et al.*, 2019). The system's location and size to be implemented depend on factors such as space availability, design objectives, climate, soil properties, and vegetation.

The prioritization of these factors may differ from location to location. For example, in places like Singapore, a key determinant is the availability of land (Lim & Lu, 2016). Different decision-making tools may be used to select the most suitable SuDS. Figure 2-4 shows a decision-making tool used to choose the most suitable SuDS for areas in Glasgow and Edinburgh. As observed, social, economic, and environmental aspects are considered.

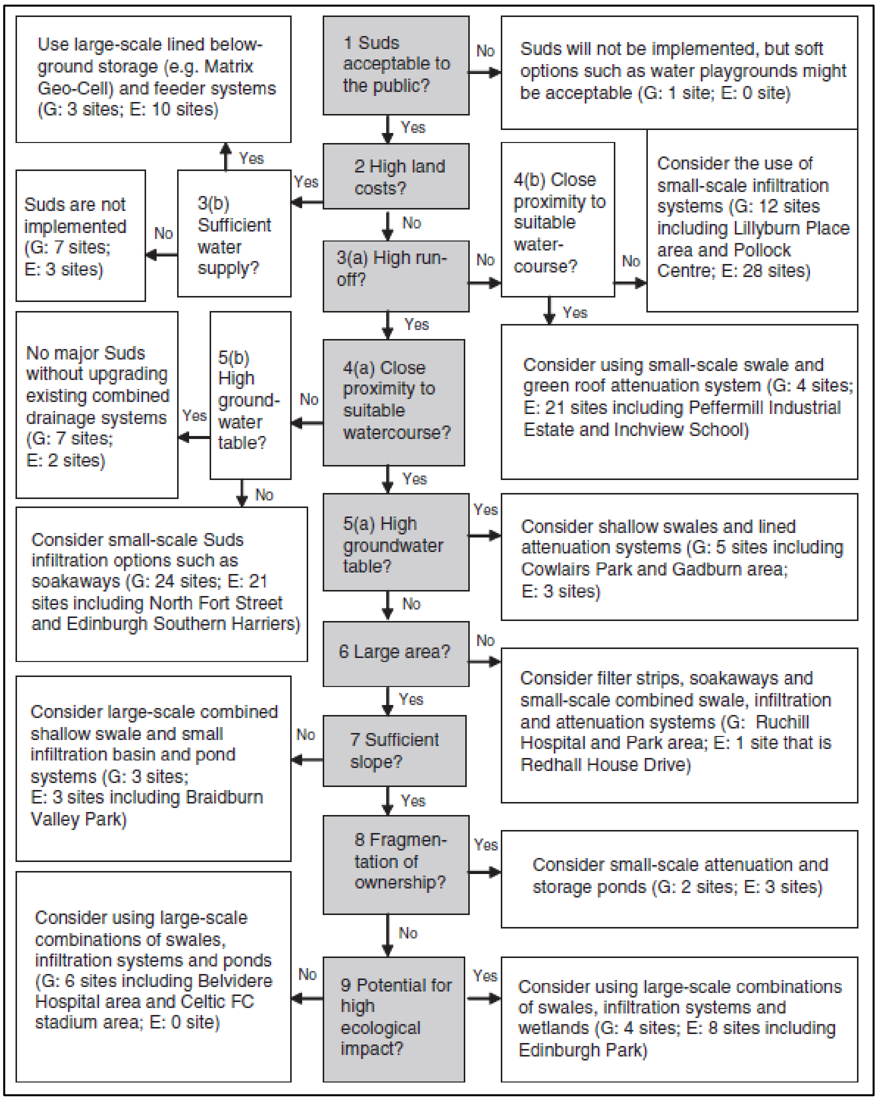


Figure 2-4: A SuDS decision-making tool used on sites in Glasgow and Edinburgh (Scholz, 2006)

2.2.4 Selected SuDS options

2.2.4.1 Filter strips

Filter strips are uniformly graded and gently sloping strips of grass, or any other dense vegetation, designed to treat runoff adjacent to impermeable areas through sedimentation, filtration and infiltration (Woods-Ballard *et al*., 2015). They are commonly used as vegetated buffer systems along stream banks (Armitage *et al*., 2013).

When utilised as pre-treatment options in treatment trains, especially to aid SuDS implemented as source and local controls SuDS, filter strips are both effective and prevent clogging (Armitage *et al*., 2013; Flanagan *et al*., 2017). Figure 2-5 shows an example of a roadside filter strip.

Figure 2-5: Filter strip draining into filter drain (Woods-Ballard *et al*., 2015)

2.2.4.2 Swales

Swales are shallow, flat-bottomed, vegetated, and open channels developed to convey, treat and attenuate surface water runoff (Woods-Ballard *et al*., 2015). They are particularly suitable for providing stormwater conveyance and treatment on sites with limited space and linear environments such as roadways (Yu *et al*., 2013; Ekka *et al*., 2021). Swales are more aesthetically pleasing than concrete channels and can replace conventional pipework and curb -and-gutter drainage collection systems for residential subdivision streets (Armitage *et al*., 2013; Willis, Cunningham & Ryan, 2013; Woods-Ballard *et al*., 2015). Figure 2-6 is an example of a swale implemented beside an access road.

Figure 2-6: Example of a vegetated swale (Watch Tower, 2018)

2.2.4.3 Soakaways

Soakaways are designed to rapidly infiltrate water into permeable soil layers (AECOM, 2013). They are usually excavated pits packed with coarse aggregate and other porous media to detain and infiltrate runoff from a single source (Armitage *et al*., 2013). Compared to infiltration trenches and porous pavements, they are considered cheaper as excavations are concentrated in a specific location rather than spread across a much larger area. (Stovin, 2007). Soakaways remove pollution loads through volatilisation, sedimentation, biodegradation and filtration (Wilson, Bray & Cooper, 2004; Woods-Ballard *et al*., 2007). Despite the positive impacts, the rapid movement of water through the soakaway may lead to an increased risk of groundwater contamination. (Armitage *et al*., 2013).

2.2.4.4 Bio-retention areas

A bio-retention area is a depressed landscaped area that collects stormwater runoff and infiltrates it into the soil below through the root zone, thus prompting pollutant removal (Armitage *et al*., 2013). Bioretention, also known as biological retention, is adopted to manage stormwater runoff from relatively small catchments, for example, roads, roofs, and parking lots (Zinger *et al*., 2013). It employs several natural processes including: filtration, adsorption, biological uptake, and sedimentation (Debo & Reese, 2003). Vegetation reduces the peak velocity of runoff, while infiltration reduces the runoff volume, promoting pollutant removal (Osman *et al*., 2019).

Engineered soils and enhanced vegetation also facilitate the removal of pollutants (Ballard *et al*., 2007)

Aside from pollution removal, bioretention systems promote habitat and biodiversity and cooling of the local microclimate due to evapotranspiration (Woods-Ballard *et al*., 2015). They are relatively more expensive than other SuDS techniques due to the maintenance required to enable them to operate efficiently and preserve their aesthetic benefits. Figure 2-7 gives an example of the application of bio-retention areas, highlighting the site before and after construction.

Figure 2-7: Example of bioretention application in a parking area(Ballard *et al*., 2007)

2.2.4.5 Detention ponds

Detention ponds (Figure 2-8), also known as detention basins, are landscaped depressions which are typically kept dry except during major storm events (Woods-Ballard *et al*., 2015). They store stormwater runoff for short lengths of time (Armitage *et al*., 2013). They can be vegetated, providing limited treatment, or hard landscape storage areas, which may not provide treatment (Woods-Ballard *et al*., 2015). Detention ponds may serve multiple purposes, such as recreational facilities and car parks. They, however, have minimal impact on the removal of fines and pathogens from stormwater runoff due to the lack of permanent water in the pond and serve the primary purpose of flood attenuation.

Figure 2-8: Vegetated detention pond (Welsh Water, 2017)

2.2.4.6 Retention ponds

Retention ponds (Figure 2-9), also known as retention basins, are pond-like structures where runoff is retained for sufficient time to allow for settlement and possibly biological treatment of some pollutants (Armitage *et al*., 2013). They promote biodiversity by slowing water flow and storing and treating runoff (Kabisch *et al*., 2017). They utilise sedimentation, filtration, infiltration and biological uptake processes, enabling medium to high pollutant removal capacity (Woods-Ballard *et al*., 2007). If the inflow water is severely polluted, then contact with the public should be limited (Armitage *et al*., 2013).

Figure 2-9: Retention pond (Watch Tower, 2018)

2.2.4.7 Constructed wetlands

Wetlands have a significant role in river systems as they attenuate floods, buffer droughts, enhance water quality, provide erosion control, improve air quality and maintain biodiversity (Kotze, Breen & Klug, 2000; Adeeyo *et al*., 2022; DEA, 2022). Despite their significant role in the ecosystem, particularly in the river system, wetlands are amongst the most threatened habitat in South Africa. As of 2001, it was estimated by Ballance *et al*. (2001) that 50% of wetlands might have been lost country-wide.

Human activity, channelization, effluent disposal, and water abstraction are some factors leading to the loss of wetlands (Ballance *et al*., 2001). Mitchell (2013) further divides threats to wetlands into indirect and direct. Indirect threats include changes in temperature and precipitation, governance and institutional arrangements, and population increase. On the other hand, direct threats are invasive alien biota, threatening indigenous biodiversity and alterations to hydrology and sediment transport through the construction of impoundments.

Figure 2-10: Example of a wetland in a residential area (Leicester City Council, 2020)

Wetland management plans require local, regional and national action and cooperation to strengthen wetland conservation and restoration (Xu *et al*., 2019). Wetland restoration programs are essential to reversing the human-induced stressors on ecosystems and increasing the resilience of wetlands to tackle climate change trends (Erwin, 2009). Constructed wetlands may be developed to contribute to this restoration.

Wetlands comprise of shallow ponds and marshy areas, covered in aquatic vegetation, that provide attenuation and treatment of surface water runoff (Woods-Ballard *et al*., 2015). The use of constructed wetlands as a complex bioreactor in the treatment of stormwater has increased due to the rising cost of fossil fuels used in treatment processes and increasing concern regarding climate change (Lee, Fletcher & Sun, 2009). They provide efficient pollutant removal methods in comparison to other SuDS techniques. (Wilson, Bray & Cooper, 2004). Although organic matter removal often meets the design target, nitrogen removal efficiency is generally poor (Lee, Fletcher & Sun, 2009). Dissolved inorganic nitrogen species (DIN) significantly impact aquatic systems as they are easily taken up by microorganisms (Seitzinger, Sanders & Styles, 2002).

Constructed wetlands (Figure 2-10) provide a vibrant habitat for fish, birds and other wildlife (Armitage *et al*., 2013). They may, however, attract mosquitoes. During long dry periods, constructed wetlands may require supplementary water (Armitage *et al*., 2013). Designers may choose from various wetlands depending on the targeted pollutants, available land and acceptable level of maintenance and management (Lee, Fletcher & Sun, 2009).

2.2.5 Challenges facing SuDS Implementation in developing countries

SuDS have many benefits, as highlighted in Section 2.2.1, however, in the low-income areas of developing countries, its implementation faces several obstacles. Drainage is often the last to be considered after so-called Water, Sanitation and Hygiene (WASH) issues have been addressed. This afterthought leads to costly retrofits of drainage once wastewater and flash flooding issues are identified (Charlesworth *et al*., 2017).

In low-income areas, burgeoning populations, defective or no WASH infrastructure, poor planning, poor service delivery particularly related to waste disposal, limited overall governance and a shortage of context-specific guidelines hinder SuDS implementation (Charlesworth *et al*., 2017). Poor drainage is impacted by inadequate sanitation and environmental conditions with point pollution sources such as overflowing sewers leading to an increased risk of water borne diseases (Parkinson, 2002). Uncollected solid waste, often finding its way to surface water, blocks drains, leading to less capacity and flooding during large storms (Parkinson, 2002). Without adequate management of waste and efficient service delivery, SuDS is hard to implement in an effective manner.

Further research is required to gain deeper insight on the application of SuDS in low-income countries. Beside the effective technical implementation, there is a need to foster 'buy-in' amongst relevant stakeholders and facilitate quality partnerships with local communities – without which the use of SuDS will be severely limited (Cotterill & Bracken, 2020). Nevertheless, despite the many challenges, if careful consideration of local conditions and proper design is undertaken, SuDS can be installed in such challenging environments as informal settlements and refugee camps (Charlesworth et al., 2017).

2.3 Hydrological modelling and considerations

Hydrologic modelling can be used to predict, analyse and manage urban water quality and pollution (Tuomela, Sillanpää & Koivusalo, 2019). When choosing modelling software, one needs to consider the modelling objectives, availability of the modelling software, availability of software documentation and technical support, compatibility with existing data and cost of the software (Dunsmore *et al*., 2020; Ghonchepour *et al*., 2021). Moreover, it is essential to understand the assumptions and limitations of the program (Armitage *et al*., 2013). Stormwater Best Management Practices (BMP), which include SuDS, are incorporated into most software used to model urban drainage systems (Stuart *et al*., 2020). Examples of modelling tools (Table 2-4) are (Armitage *et al*., 2013):

- The Storm Water Management Model (SWMM)
- The Model for Urban Stormwater Improvement Conceptualisation (MUSIC)
- The Source Loading and Management Model (SLAMM)
- The System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN)

SWMM is a dynamic rainfall-runoff simulation model used for a single event or long-term simulation of runoff quantity and quality (Bahaya, Al-Quraishi & Gruden, 2019). The software consists of routing and runoff components and is suitable for an urban environment (UCT UWM, 2022). It aids in tracking the water quantity and quality of each sub-catchment. It also models water flow rate, depth, and quality at multiple time steps up to a sub-hourly resolution (Elliott & Trowsdale, 2007; UCT UWM, 2022). PCSWMM and HydroSWMM are built around the SWMM engine and offer advantages of analytical tools and GIS representation (Dunsmore *et al*., 2020). Geographic information systems (GIS) are commonly used to collect and manage the spatial data required in models such as SWMM5 (Bahaya, Al-Quraishi & Gruden, 2019).

MUSIC is a stormwater assessment tool developed by the Cooperative Research Centre for Catchment Hydrology (CRCCH) (Wong *et al*., 2002). The software's primary intended use is the conceptual design of drainage systems, with an emphasis on treatment devices (Elliott & Trowsdale, 2007). To undertake this, MUSIC simulates rainfall, stormwater runoff and pollution (Melbourne Water, 2018). The software is suitable for catchment sizes varying between 0.01 km^2 to 100 km^2 with sub-hourly timesteps as small as 6 minutes (UCT UWM, 2022). Popular in cities such as Melbourne, MUSIC has been adopted as a decision support system, aiding in strategic catchment planning and the assessment of urban development applications submitted by land developers (Wong *et al*., 2002).

SLAMM, which has expanded since the 1970s was initially developed by PV & Associates as a planning tool to understand the relationships between urban runoff pollutants and stormwater runoff quality (Pitt & Voorhees, 2002; UCT UWM, 2022). It is suitable for the computation of runoff pollutant loads and flows associated with small storm events (Myllyoja *et al*., 2001).

Furthermore, SLAMM allows interfacing with SWMM for detailed hydraulic system evaluations.

SUSTAIN was developed from research initiated in 2003 by the U.S. Environmental Protection Agency (EPA) to operate as a fully integrated decision support tool for the selection and placement of SuDS, also known as Best Management Practices (BMPs), at strategic locations in urban watersheds (Shoemaker *et al*., 2009). SUSTAIN is inclusive of an optimization module which performs cost estimating and comparatively analyses the performance and cost data of the various BMP options and placement scenarios (Lai *et al*., 2007). The software and related documentation were last updated in 2014 and as a result, are currently out of date and not compatible with a majority of modern machines (UCT UWM, 2022).

Significant site data such as imperviousness, native soil type, land use, elevation, infrastructure dimensions and local rain data are required to create informative water quality models (Bahaya, Al-Quraishi & Gruden, 2019). Key inputs are rainfall, runoff and water quality data (Armitage *et al*., 2013). Other inputs required in modelling are stormwater networks, flow data and temperature. Without adequate data, the design of pollutant mitigation measures will be poorly informed, risking unintended consequences such as increased flooding rather than mitigation (Lindiwe, 2019). However, increased model complexity does not necessarily lead to better reliability, especially where there is significant uncertainty (Lindiwe, 2019). Simplified data-based model representations such as event mean concentrations (EMCs) to simulate diffused pollution have proven efficient in obtaining feasible calibration and validation if the data available is limited (Tuomela, Sillanpää & Koivusalo, 2019).

Table 2-4: Potential uses of selected modelling software (Elliott & Trowsdale, 2007; Wong *et al*., 2002; Myllyoja *et al*., 2001)

Software Potential Use	MUSIC	SLAMM	SWMM
Public education			
Research	✓	✓	✓
Developing sizing rules for devices	✓	✓	✓
Planning of land use in catchments	✓	✓	✓
Preliminary design of regional controls	✓	✓	✓
Preliminary design of subdivision or site	✓	Marginally suited	✓
Detailed design of regional controls			Marginally suited
Detailed design of subdivision or site			Marginally suited
Site layout and materials selection			Marginally suited

3. Site description

3.1 The Swartkops Estuary

The Swartkops catchment is approximately 1360 km^2, with the Chatty River as the largest tributary contributing to the estuary (Nel, 2014). Initially, the main economic activity in the catchment was farming. More recently, rapid urban growth has resulted in the catchment accommodating majority of the residents in Gqeberha (previously known as Port Elizabeth) metropolitan area (Binning & Baird, 2001).

Table 3-1: Economic values provided by the Swartkops Estuary (Pretorious, 2014)

Type of value	The value provided by the estuary
Subsistence	Ranked 1st amongst temperate systems in South Africa with a value of R809 000 per annum
Property	Ranked 19th amongst temperate systems, in South Africa, in terms of property value related to estuaries with a value of R155 million
Tourism	Ranked 7th amongst temperate systems in South Africa in terms of tourism value attributed to estuaries with a value of R50 million per year.
Nursery for fish	Ranked 5th amongst temperate systems in South Africa with a value of R32.8 million per annum.

The estuary is an essential aquatic ecosystem and a valuable recreational and ecological asset (Nel, 2014). Its ecological value is attributed to the presence of key invertebrate species such as mud prawns, fish species in the estuary's nurseries, and birds. It is one of the most important estuaries in South Africa regularly holding approximately 4000 birds (Nel, 2014). Moreover, previous studies have reported the importance of the estuary for various social functions. Table 3-1 summarises some of the estimated economic benefits provided by the Swartkops Estuary in 2014.

The Swartkops catchment supports various land uses such as residential townships, industrial estates and railway systems (Nel, 2014). In the vicinity of the estuary, the primary form of land use is industrial (Nel, 2014). Other anthropogenic activities affecting the estuary are wastewater treatment works (WWTW), saltpans, sand or clay mining, brickworks, the motor industry, the wool industry, extractive processes and the wool industry (Adams, Pretorius & Snow, 2019).

Human activity in the catchment has resulted in the rise of pollution levels since the 1950s (Nel, 2014). As a result, the undertaking of some events has been stopped or altered, for example, the Redhouse River Mile swimming event – which was relocated (Adams, Pretorius & Snow, 2019). Other events that have been altered due to the water quality in the estuary are the traditional healing ceremony and baptisms carried out in the area adjacent to the Motherwell Canal by the Zion Christian Church (Pretorious, 2014). Table 3-3 highlights the various pollutants identified in the Swartkops Estuary in different studies between 1982 and 2011. The Markman canal, Motherwell canal, and the Chatty River are major entry points for diffuse pollution, especially nitrate and ammonia (Pretorious, 2014). The nutrient inputs from these entry points (Table 3-2) have been reported to be significant (Adams, Pretorius & Snow, 2019) with the Motherwell Canal being the most significant nitrogen source, followed by the Markman Canal, Perseverance and Chatty River (Adams, Pretorius & Snow, 2019). Faecal bacteria is coming from the Motherwell Canal (Adams & Riddin, 2019) and urban runoff discharging from the Chatty River (Pretorious, 2014). The Swartkops River is the primary source of phosphorus to the estuary due to the three WWTWs in the riverine reaches (Adams & Riddin, 2019). Untreated municipal wastewater also enters estuaries through stormwater runoff from informal settlement areas (Van Niekerk & Turpie, 2011).

Table 3-2: Pollution at three major entry points into the Swartkops Estuary
(Adams, Pretorius & Snow, 2019)

Entry point	Land Use	Type of pollution
Markman Canal	• Industrial Area • Small peri-urban village • Two sewage pump stations • Road bridge	• Untreated domestic sewage • Industrial wastewater
Motherwell Canal	• Motherwell township • 14 stormwater drains • Illegal dumping	• Litter • Debris • Raw sewage
Chatty River	• Townships	• Stormwater runoff • Raw sewage discharge • Litter

The estuary is currently at a Present Ecological State (PES) of Category D as it is largely modified and with a Recommended Ecological Category (REC) of C (Adams & Riddin, 2019) due to its ecological, economic, and recreational importance. To combat the high pollution levels in the estuary, citizens started the Zwartkops Conservancy in 1968 (Nel, 2014), which was tasked with cleaning the Swartkops river and Motherwell canal (Pretorious, 2014). In 2010, the Nelson Mandela Bay Municipality constructed its first artificial wetland system at the Motherwell Canal which is being impacted by continuous sewage spills from the Motherwell residential area (Nel, 2014). A co-management forum for the Swartkops Estuary has since been formed comprising of The Cape Action for People and the Environment (C.A.P.E), which runs the Estuaries Management Programme, the Subsistence Bait Collectors and Fishermen, the NMU Developmental Studies and the stakeholders mentioned above (Pretorious, 2014).

Table 3-3: Historical record of pollution in areas feeding into the Swartkops Estuary (Pretorious, 2014)

	Watling and Watling (1982)			**Emmerson (1985)**			**Lord and Thompson (1988)**			**Scharler *et al.* (1997)**				**DWS (1995 – 2012)**			**NMBM: SRK Consulting (Pty) Ltd (2011)**		
Parameters	**B**	**M**	**N**	**B**	**M**	**N**	**B**	**M**	**N**	**B**	**M**	**N**	**P**	**B**	**M**	**N**	**B**	**M**	**N**
Settlers bridge				X		X						X	X	X		X	X	X	X
Tippers Creek		X																	
Swartkops Village		X		X		X	X							X		X	X	X	X
Chatty River														X			X	X	X
Markman canal		X																	
Brickfields				X		X	X				X	X	X			X	X	X	X
Motherwell canal		X											X			X	X	X	X
Redhouse Yacht Club		X		X		X	X						X			X	X	X	X
Bar None		X									X	X				X			
Perseverance		X		X		X	X				X	X	X			X	X	X	X
Perseverance Bridge																X			
Frans Claasen Bridge																X	X	X	X
Niven Bridge																X	X	X	X
Key: 'B'-bacteria, 'M'-trace metals, 'N'-Nutrients, 'P'-phytoplankton biomass																			

Issues which require further investigation and monitoring are inflow measurements into the estuary, eutrophication of the river estuary, elevated stormwater and effluent inputs, contamination by toxins such as trace metals and organic compounds, faecal pollution, illegal dumping and littering (Adams, Pretorius & Snow, 2019). Increased levels of stormwater and effluent inputs may contribute to eutrophication through an increased amount of nutrients in the ecosystem. Eutrophication in turn may lead to several negative effects in the estuary such as increased algal blooms which may cause harm to aquatic animals through localized anoxia (Dorgham, 2014). Toxins from trace metals and organic compounds and harmful bacteria from faecal pollution negatively affect the health of the organisms living in the estuary. Illegal dumping not only negatively impacts the appearance of the estuary but also contributes to pollution. Inflow monitoring will aid in the tracking of changes regarding water quality and quantity over time. Extensive research is currently being carried out to improve the estuary's health and that of its environs.

3.2 The Chatty River

The Chatty River is the largest tributary contributing to the Swartkops estuary (Nel, 2014) and is located on the lower reaches of the estuary. The Chatty River Catchment has steep slopes in the upper southern sub-catchments that ease from west to east to more gentle slopes closer to the sea forming low-lying terraced coastal plains as it joins the Swartkops Estuary (Maclear, 1996; SRK Consulting, 2015). The catchment covers an area of approximately 140 km^2 (SRK Consulting, 2015). Figure 3-1 shows the Chatty River and its tributaries.

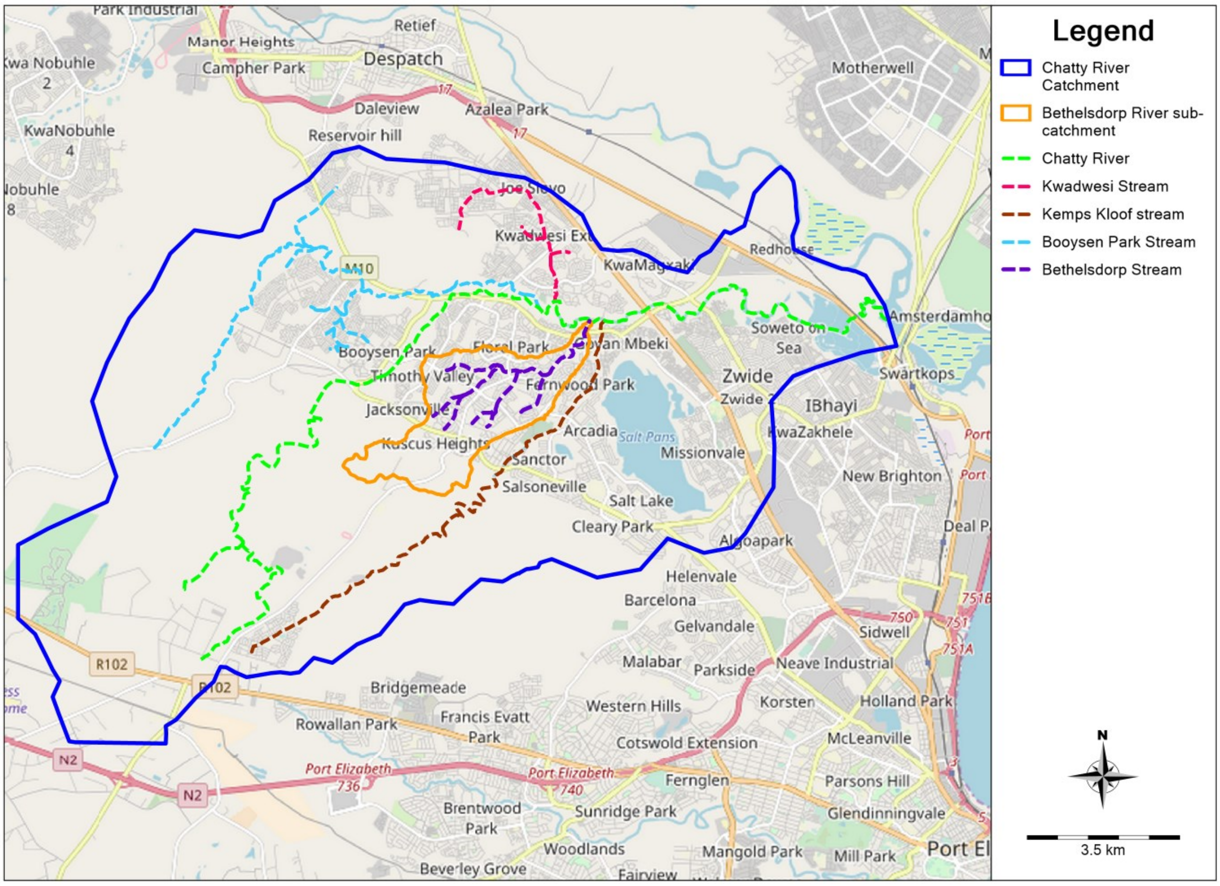


Figure 3-1: Chatty River and its tributaries

The Chatty River Catchment has a subtropical climate, with most rainfall events experienced at the start of spring, from August to September (Figure 3-2). Temperature variations are shown in Figure 3-3.

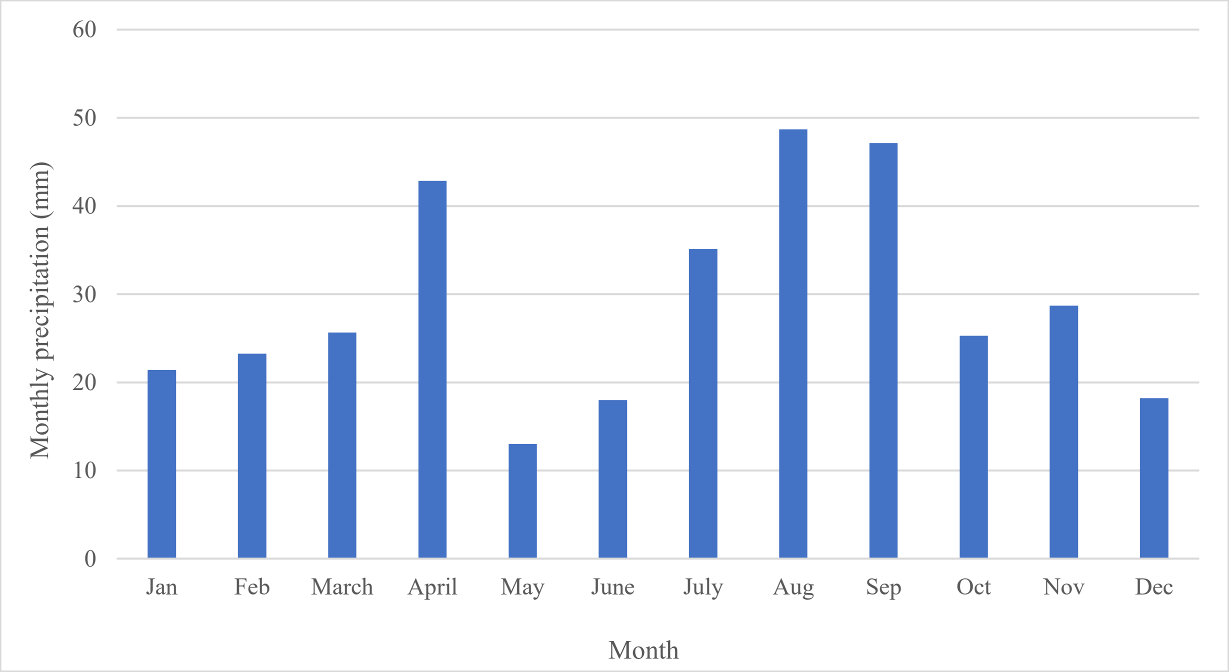


Figure 3-2: Temporal variation of rainfall (2013 - 2019)

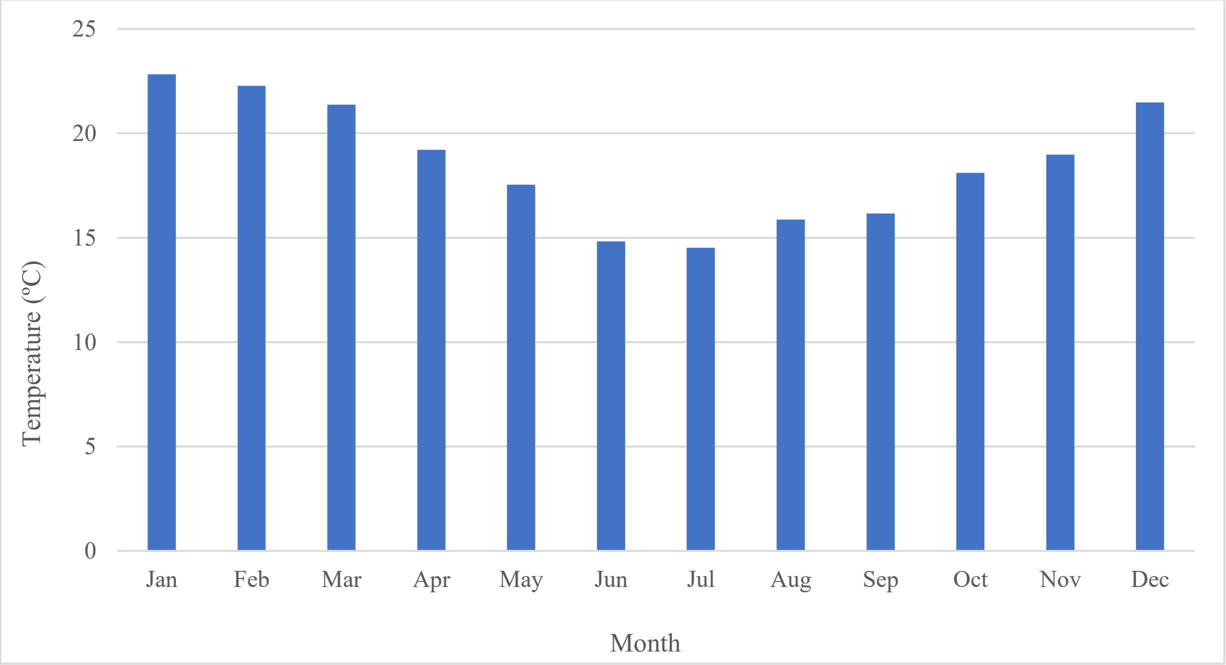


Figure 3-3: Average daily temperature (2013 - 2019)

3.3 Water quality concerns in the Chatty River

The Chatty River Catchment is characterized mainly by low-income residential land use. High-density – and growing – informal settlements, for example, Zwide, New Brighton, Missionvale and Veeplaas (Adams & Riddin, 2020), are located in the catchment. Other notable land uses are livestock grazing in the open spaces, mining in the upper reaches, public open spaces and other forms of agriculture in the upper reaches of the catchment.

There is significant pollution from raw sewage and litter as the river flows through the catchment (Adams, Pretorius & Snow, 2019). Moreover, stormwater and sewerage overflow manholes are located along the watercourse (Vromans, 2016) which, when damaged, negatively impact the water quality of the river. Finally, plastic pollution is evident in the watercourse from litter dumping in the river and on the riverbank, as shown in Figure 3-4.

Figure 3-4: Litter dumping in the river and on the river bank

The watercourse comprises engineered channels, natural streams and culverts with formal and informal urban development within the 1:50-year flood line (SRK Consulting, 2015). The conservation value of the lower and middle reaches of the river and its contributing streams is low due to its highly degraded ecological status leading to the absence of aquatic life and biodiversity (Swanepoel *et al*., 2020). On the other hand, indigenous fish, such as the Cape Kurper (*Sandelia capensis*), may be found in the relatively natural upper reaches of the Chatty River, above urban development (Anton Bok Aquatic Consultants, 2016).

Several wetland areas with salt marsh or salt-tolerant plants may be spotted along the Chatty River and its tributaries (Vromans, 2016), as shown in Figure 3-5. However, polluted stormwater runoff and sewerage overflows have led to the contamination of many wetlands and the deterioration of the overall health of the wetland ecosystem and its biodiversity.

Figure 3-5: Wetland observed on the lower reaches of Bethelsdorp stream

4. Method

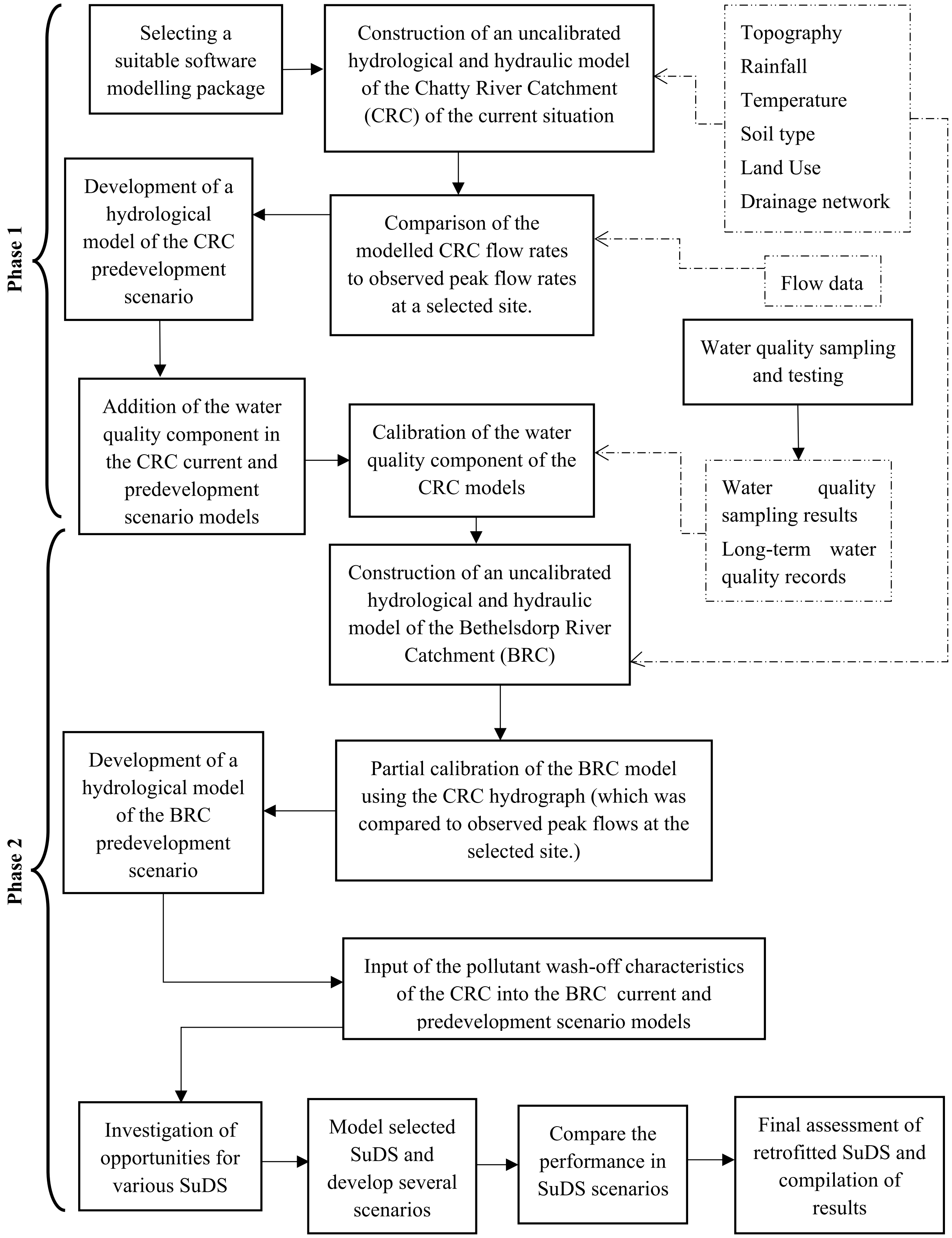


Figure 4-1: Overview of study method

This study aimed to investigate the extent of pollution in the Chatty River draining into the Swartkops Estuary and explore the potential of Sustainable Drainage Systems (SuDS) to improve the water quality in the river using a scenario-based approach. Figure 4-1 outlines the research procedure adopted, following knowledge building through the undertaking of a desktop study of the site and literature review.

The research was divided into two phases, where the initial phase was an investigation of the hydrological and water quality conditions in the Chatty River Catchment (CRC). In the second phase, the investigation of the potential impact of SuDS on water quality in the river was carried out on a representative tributary of the Chatty River. Four major tributaries drain into the Chatty River. They are the Kwadwesi stream, the Kemps Kloof stream, the Bethelsdorp stream and the Booysen Park stream (Section 1.1). The sub-catchment selected for detailed assessment was the Bethelsdorp River Catchment (BRC).

4.1 Modelling software selection

Various software modelling packages were reviewed (Section 2.3) and PCSWMM was selected as the modelling software for this study. PCSWMM is a web-oriented shell designed to facilitate the teaching, learning, design, and research use of the U.S. EPA Stormwater Management Model (SWMM) (James, 2005). The software uses the unadulterated EPA SWMM 5 hydrology and hydraulics engine (James *et al.*, 2010) and links GIS and SWMM to facilitate various functions.

PCSWMM is widely used in South Africa (Dunsmore *et al*., 2020) for example, in Knysna (Lindiwe *et al.*, 2019), Durban (Turpie *et al*., 2017) and Cape Town (Thewlis, 2022). The PCSWMM software was chosen for this study as it substantially improves the usability and functionality of SWMM (Armitage *et al*., 2014). Furthermore, PCSWMM has accompanying tutorials, manuals, user forums and an online, indexed help file which provides extensive information and guidance (James, 2005).

In this project, the latest version of PCSWMM (build 7.5.3406, released in May 2022) was used to extract attributes from GIS databases and edit the data to build the models described in the following sections. Long-term (continuous) simulations were undertaken to generate results and compare the impact of the various scenarios on water quantity and quality in the catchment.

The general steps, outlined in Figure 4-2, were followed in the development of deterministic models in design and problem solving as broken down in the *Rules for responsible modelling* by James (2005).

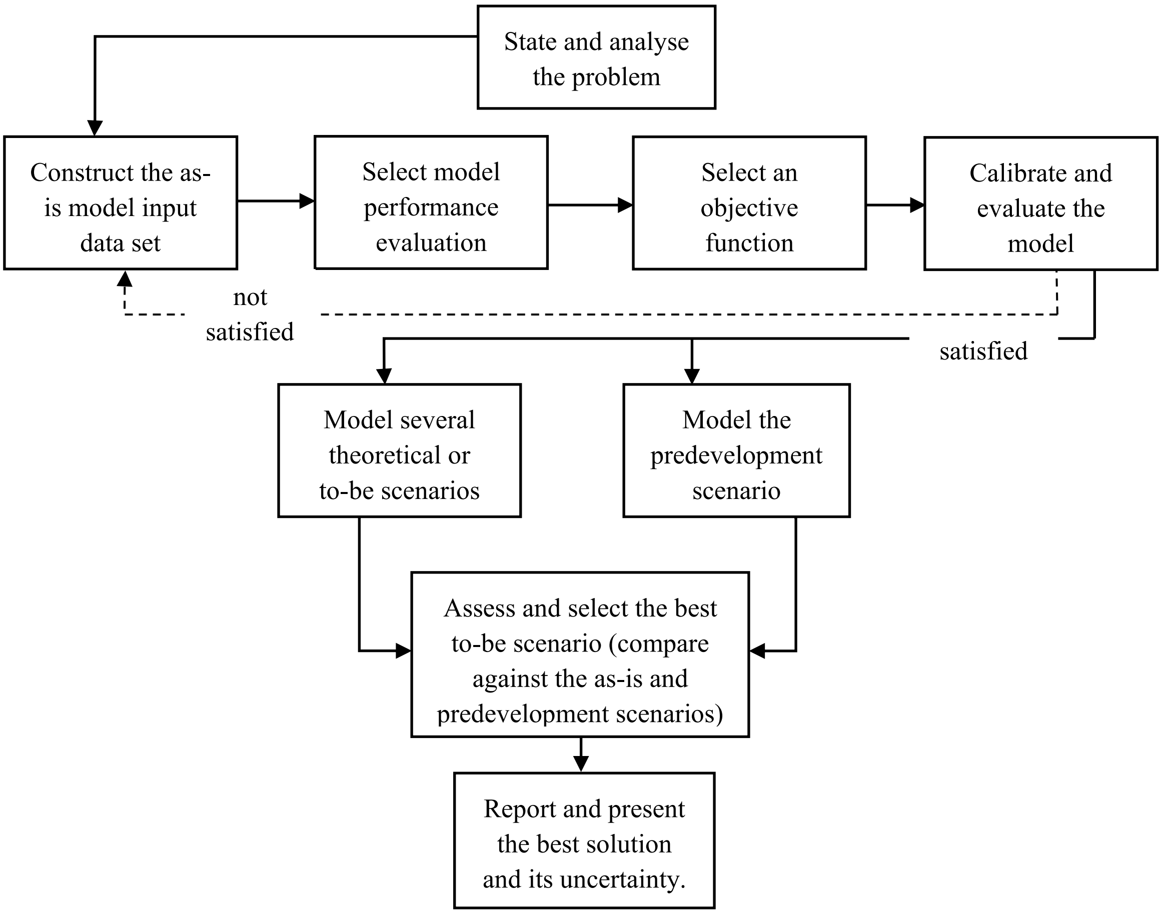


Figure 4-2: Modelling procedure for problem-solving (James, 2005)

4.2 Overview of study approach

A desktop study and literature review were undertaken to provide background knowledge of the project and understand the challenges faced within the study area. Following the background study, an initial site visit was carried out which provided more information on the current conditions in the study area. Moreover, water quality sample collection at the various tributaries of the Chatty River was initiated.

Water Quality grab samples were tested for total suspended solids (TSS), *Escherichia coli* (E.*coli*) dissolved inorganic phosphorus (DIP), dissolved inorganic nitrogen (DIN), salinity, dissolved oxygen (DO), turbidity, electrical conductivity (EC), and pH. Water quality records from the Department of Water and Sanitation (DWS) complemented the results. The water quality test results provided information on the extent of pollution and confirmed the need for mitigation measures. The pollutants tested were limited to these to remain within the budgetary constraints of the project.

Following the investigation of the extent of pollution in the CRC, hydrological models were required to assess the current hydrological conditions in the CRC and the impact of modelled SuDS interventions on water quality using the BRC as a representative catchment. Data collection for the PCSWMM model then commenced.

To understand the current overall hydrological state of the catchment, 'As-is' and Predevelopment models of the CRC were developed. The potential impact of SuDS on water quality in the Chatty River was then investigated through the modelling of the Bethelsdorp River Catchment (BRC), a sub-catchment within the CRC. Scenarios of the various retrofitted SuDS interventions were modelled in the BRC and compared to the 'As-Is and Predevelopment BRC models to assess their potential performance.

Model inputs (Table 4-1) were collected through a desktop study, literature reviews and site inspections. The data were processed to the appropriate format required in PCSWMM. Excel and QGIS were additional software used for the processing and formatting of data where necessary.

Topographical data processed in QGIS was applied in PCSWMM to undertake sub-catchment delineation. Sub-catchment properties, such as drainage and infiltration were determined from the soil type and land cover respectively to help model the rainfall-runoff relationships. Where sub-catchments had several land cover and soil types, the PCSWMM Area Weighted tool was used to aggregate the properties. Topographical data was also useful in the positioning of the drainage network during the delineation process in PCSWMM. The shape file of 1 m conduits was edited and verified using Stormwater network maps and satellite imagery. The PCSWMM transect tool was used to process the natural water course cross-sections. Channel materials and properties were identified through municipality records and geospatial data to define conduit properties such as roughness coefficients.

Meteorological data was processed and inputted into PCSWMM. Temperature data were useful in the processing of potential evapotranspiration data in the catchment through the Hargreaves method. Rainfall data was converted to an acceptable format in Excel and was input into PCSWMM to create a rain gauge. The rain gauge was assigned to each sub-catchment.

Flow data was collected and processed for calibration of the BRC model. Peak flow data from selected storms was collected and processed to partially calibrate the BRC model. Although the BRC model was a sub-catchment within the CRC model, it had an increased discretization. This in turn increased sensitivity to parameter uncertainty. Peak flows observed at the selected flow measurement sites matched peak flows modelled in the 'As-is' CRC model. The CRC hydrographs whose peak flow matched the observed peak flow were extracted from the CRC model and used in the partial calibration of the BRC model.

A water quality component was also inputted into the PCSWMM models to investigate the impact of modelled SuDS on pollution load and concentration. The model simulated pollutant indicators through Event Mean Concentration (EMC) values associated with the defined land cover. The pollutant indicators modelled were total Suspended Solids (TSS) and nutrient concentrations, that is, Dissolved Inorganic Phosphorus (DIP) and Dissolved Inorganic Nitrogen

(DIN). Preliminary EMC values were applied and adjusted in the CRC 'As-Is' model using water quality data from the water quality sampling test results of the Chatty River.

The predevelopment models of the CRC and BRC were developed from the 'As-is' models. The likely properties of the land cover and drainage network associated with the natural conditions in the catchment before development and anthropogenic activities were inputted into PCSWMM The models provided estimated runoff rates and volumes and pollutant loads and concentrations before human intervention.

Table 4-1: Summary of model inputs

Data requirement	Data type	Source	Use
Topography	Contour Map	Nelson Mandela Bay Municipality (NMBM)	Sub-catchment delineation in PCSWMM
Land cover	Land use Map	Department of Environment Forestry Fisheries	Define surface drainage properties and pollutant wash-off Event Mean Concentration (EMC) values of the current situation
	Vegetation Map	South African National Biodiversity Institute (SANBI)	Define associated surface drainage properties and pollutant wash-off EMC values of the predevelopment conditions
Soil data	Soil Map Sieve analysis test results	Water Research Commission (WRC) ISRIC data hub Sieve analysis tests	Define infiltration properties
Stormwater network	Chatty River map Satellite imagery	NMBM Site surveys Google Maps	Define the drainage network's properties such as roughness coefficients, slope and dimensions Verify the positioning of the PCSWMM delineated conveyance network
	Engineered channels and culvert Map		
Meteorological data Rainfall data	Rainfall record	South African Weather Service (SAWS)	Simulation of rainfall in the model
	Temperature record		Apply to Hargreaves method for the computation of potential evapotranspiration in the catchment
Flow data	Peak flow rates	Site measurements	Model calibration
Water Quality data	Water Quality grab sample results	Nelson Mandela University (NMU) South African Environmental Observation Network (SAEON) DWS	Calibration of the water quality model developed through the application of EMC values associated with various land uses

Finally, various SuDS opportunities were investigated and identified. These scenarios were then developed in the BRC PCSWMM model to analyse their likely performance. The process involved site selection, preliminary sizing, SuDS simulation and a comparison to the BRC 'As-is' and predevelopment model outputs in PCSWMM.

5. Hydrological model development

A model is a simplification of reality to a comprehensible form (James, 2005). Various models were developed during this project including the existing state of the catchment (‘As-is’); the likely long-past condition of the catchment (Predevelopment); and the various retrofitted SuDS interventions. Their development was carried out using the Personal Computer Stormwater Management Model (PCSWMM) software, a decision support system (James, 2005) supplied by Computational Hydraulics International (CHI).

The study was divided into two phases as described in Chapter 4. The data obtained in the first phase was consolidated into two models of the CRC. In the second phase, the BRC was modelled in several scenarios to investigate the potential of retrofitted SuDS to improve water quality in the river. This chapter expounds on the various processes undertaken to develop the hydrological models, listed below, of the Chatty River Catchment (CRC) and the Bethelsdorp River Catchment (BRC):

- CRC ‘As-Is’ model
- CRC predevelopment model
- BRC ‘As-Is’ model
- BRC predevelopment model
- BRC retrofit SuDS Scenarios

5.1 Data acquisition and processing

Various data sets were required to determine the inputs for the development of the various hydrological models. This included: topographical data, meteorological data, land cover data, and soil data. As with all hydrological models, there are many sources of uncertainty and observed flow data was therefore necessary to improve them.

5.1.1 Topography

Topographical data was necessary for the development of the hydrological model. Various functions in PCSWMM are undertaken using the topographical data, such as delineating the catchment, discretization into sub-catchments, and characterising the drainage network which was represented by links and nodes in the models.

The Nelson Mandela Bay Municipality (NMBM) supplied a 1 m contour map for Nelson Mandela Bay. The contour map was limited to the Chatty River Catchment using the PCSWMM clip polygon tool. A digital elevation model (DEM) with a 5 m x 5 m resolution was then developed from the clipped contour map using the QGIS Grass plugin.

Despite the limitations, generating a DEM from contours provided a valuable representation of the terrain surface, as higher-resolution elevation data was not available. The potential limitations were on accuracy and resolution as the DEM depended on the quality and density of the input contour data. Errors may have also been introduced from interpolation errors.

5.1.2 Rainfall data

Rainfall data for this project was sought through inquiries amongst the Bethelsdorp locals, South African Weather Service (SAWS), Weather Underground (Wunderground), Agricultural Research Commission (ARC) and the Department of Water and Sanitation (DWS). Table 5-1 lists the rain gauges found in the study area). Figure 5-1 shows the location of the rain gauges managed by SAWS and DWS.

Table 5-1: SAWS rain gauge information

Station name	Period	Resolution
PORT	January 2013 – August 2016 and April 2019 – May 2022	5 minutes
Chatty AWS	August 2013 – February 2019	Daily and hourly
Swartkops Power Station	January 2001 – August 2009	Daily and hourly
Ngqura Coega	March 2003 – December 2021	Daily, hourly and 5 minutes

For modelling purposes, it is necessary to have a shorter rainfall time-step increment than the catchment's response time to rainfall. This response time is influenced by the topography, size and imperviousness of the catchment. The time of concentration, T_c, for a defined watercourse (SANRAL, 2013) was thus used to estimate the response time of the CRC and the BRC (Equation 5-1).

$$T_c = (\frac{0.87L^2}{1000S_{av}})^{0.385} \tag{5-1}$$

where T_c= Time of concentration (hours); L = hydraulic length of the catchment measured along the flow path from the catchment boundary to the point where the flood needs to be determined (km); and S_{av} = average slope (m/m).

The CRC has a response time of approximately 50 minutes while the BRC has a response time of approximately 10 minutes. The alternative runoff methods (ARM), a tool in SWMM was used to simulate the runoff response. With the data available, the SCS method was chosen and the time to peak was 15 minutes for the CRC and 3 minutes for the BRC. Since the rainfall data was provided in daily, hourly and/or 5-minute resolutions, the 5-minute resolution was thus preferred.

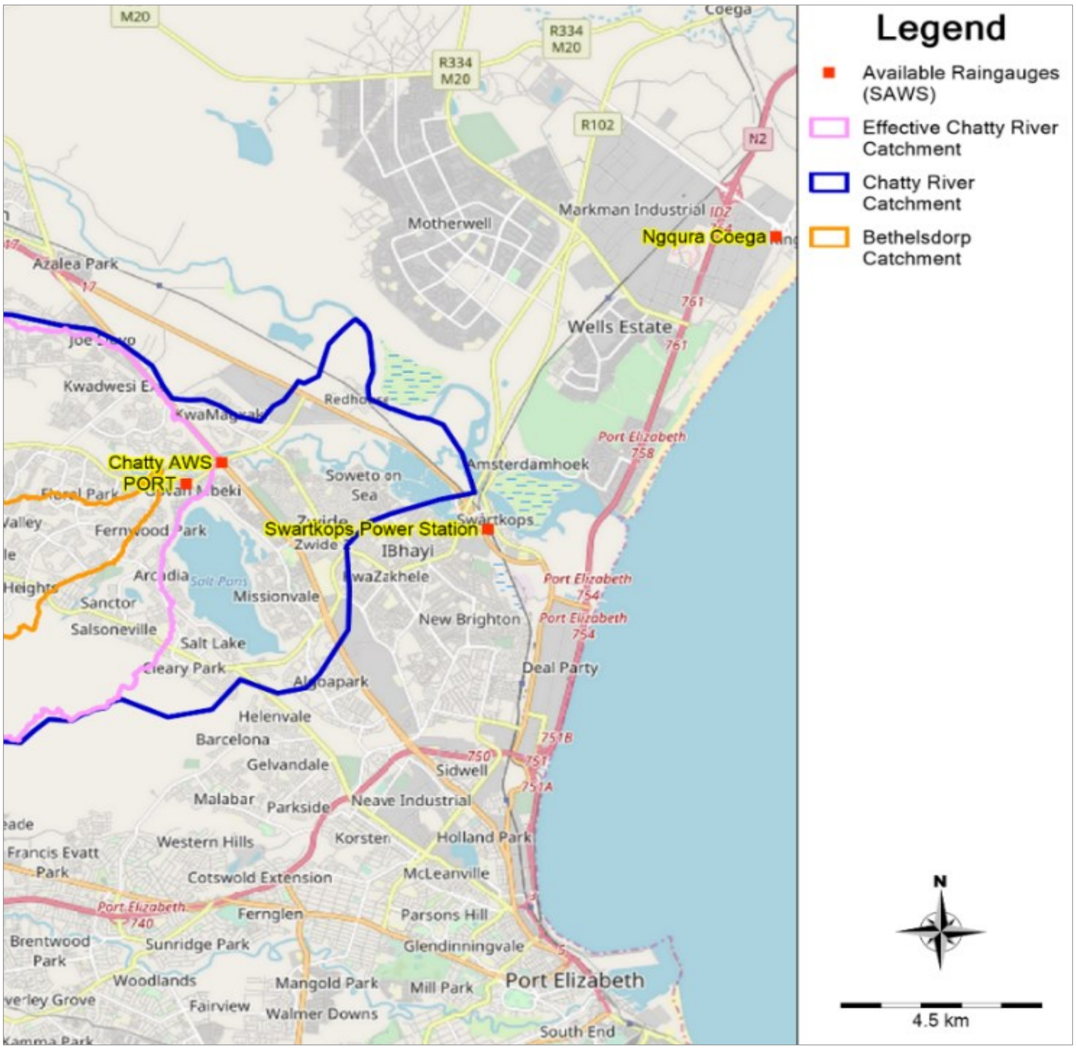


Figure 5-1: SAWS and DWS rain gauge locations in the Chatty Catchment vicinity

No data was collected for the Chatty AWS rain gauge in 2022. Rainfall data for 2022 was required to calibrate the PCSWMM model against observed flow measured during the study (in 2022) therefore, the Port rain gauge was ideal. Disaggregated Chatty AWS data was therefore used in place of the missing data from the Port rain gauge dataset, that is, from August 2016 to April 2019. The annual rainfall data was compared between the rain gauges on Excel to confirm the overlap between Chatty AWS and Port rain gauge. Seeing it is unlikely that there would be significant differences in the data from rain gauges so close to each other with no topographic features that might make a difference, the Ngqura Coega rain gauge was identified as suitable for disaggregating the Chatty AWS rain gauge from hourly data to 5-minute data for the period August 2016 to April 2019. Disaggregation was done through the freely accessible software, NetSTORM, a rainfall disaggregation tool developed by CDM Smith. The NetSTORM disaggregation tool applies the continuous disaggregation algorithm developed by Ormsbee (1989) to produce synthetic high-frequency data from hourly precipitation data (CDM, 2008). Some minor edits to the algorithm, such as introducing a spiking factor, may be used for datasets in different rainfall zones.

5.1.3 Evapotranspiration and temperature data

Monthly evapotranspiration data was calculated using the Hargreaves formula (Hargreaves & Allen, 2003) (Equation 5-2), the method adopted in SWMM. Maximum, minimum, and mean daily temperature data were acquired from SAWS from 2013 to 2017. Due to missing temperature data from 2017 to 2022, monthly means of daily data were calculated in Excel using a pivot table and applied to the simulation period. Unfortunately, there were no weather stations with evaporation data to validate the results. The summary of values is in Appendix B.1.

$$ET_o = 0.0023\, R_a\, (T_C + 17.8)\, {T_R}^{0.5} \tag{5-2}$$

where ET_o= Evapotranspiration rate (mm/day); R_a = extra-terrestrial solar terrestrial radiation ($\mathrm{MJm^{-2}d^{-1}}$); T_C = mean daily temperature (°C); and $T_R = T_{max} - T_{min}$ where T_{max} is the mean daily maximum temperature and T_{min} is the mean daily minimum temperature (°C).

Monthly extra-terrestrial radiation values, R_a, were calculated from the monthly solar radiation factors, R_s, for the Eastern Cape published by the Council for Scientific and Industrial Research (CSIR). The Clemence (1992) equation for the estimation of solar radiation over Southern Africa (5-3) was manipulated to find R_a, as shown in Equation 5-4.

$$R_s = 0.04184(1.233 R_a T_r + 10.593\, T_{max} - 0.713 T_{max}\, T_r + 16.548) \tag{5-3}$$

$$R_a = \frac{(R_s/0.04184) - 10.593\, T_{max} + 0.713 T_{max}\, T_r - 16.548}{(1.233 T_r)} \tag{5-4}$$

where R_s = solar terrestrial radiation on a horizontal surface ($\mathrm{MJm^{-2}d^{-1}}$); R_a = extra-terrestrial solar terrestrial radiation ($\mathrm{MJm^{-2}d^{-1}}$); T_{max} = daily maximum temperature (°C); T_r = daily temperature range (°C).

5.1.4 Soil type and infiltration data

Soil data was acquired from the Water Research Commission (WRC) regional soil map developed in 1990 (soilwr90) and the Soils and Terrain Digital Database of the International Soil Reference and Information Centre (ISRIC).

A sieve soil analysis of soil samples collected from the locations within the study area indicated in Figure 5-2 validated the soil maps. The samples, collected in airtight plastic containers, were analysed through the following steps (British Standards Institution, 1990):

- The soil samples were placed on drying pans and dried in a drying oven maintained at 105°C for 24 hours.
- The weight of each sieve, ranging from 4.75 mm to 0.75 mm, and the bottom pan, were noted.
- The weight of each dry soil sample was measured and noted.
- A brush was used to clean the sieves assembled in ascending order. The pan was placed below the 0.075mm sieve.
- After carefully pouring the soil sample into the top sieve and placing a cover over it, the sieve stack was placed into a mechanical shaker for 10 minutes.
- The stack was removed from the shaker. The weight of each sieve, and the pan, with its retained soil, were carefully measured and noted.
- The cumulative percentage of the soil material passing the sieve was determined.
- The grading curve of the percentage passing each sieve against the sieve size was plotted for each sample.
- The Coefficient of Curvature, C_c and Coefficient of Uniformity, C_u (Appendix C.1), were calculated, although the sample was relatively small.
- Finally, the gradation was determined for each sample and the soil classified based on the grading curve and using the Unified Soil Classification System (USCS). A summary of the calculations can be found in Appendix C.

The modified Green-Ampt method was used to simulate infiltration in the model. The Green-Ampt infiltration parameters were determined from the soil texture properties. The soil maps and sample tests show that sand is the dominant soil type in the study area. The sandy loam description from the soilwr90 map refers to soil texture that mostly contains sand with a smaller amount of silt and clay, whereas the ISRIC soil percentages and soil tests showed that sand was of a higher percentage. The percentage of sand and clay from the ISRIC data set was processed in the Soil Hydraulic Properties Calculator by CMD Smith based on research carried out by Saxton et al. (1986) to determine the saturated hydraulic conductivity of the soil (Table 5-2). The sandy loam classification from the WRC database was used to determine the porosity or initial moisture deficit and suction head factors from literature (Dickinson et al., 1992 & Brakensiek et al., 1983) (Table 5-2).

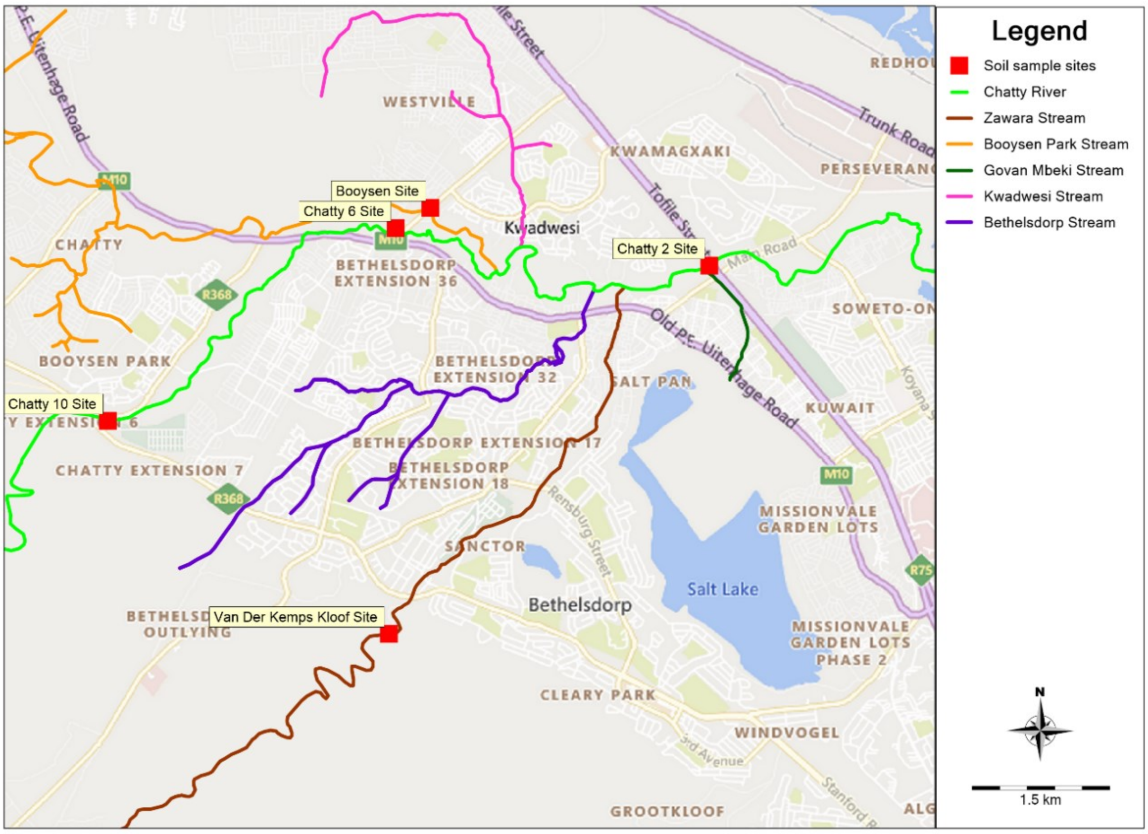


Figure 5-2: Map showing soil sample sites

Table 5-2: Infiltration parameters

(Dickinson *et al.*, 1992; Saxton *et al.*,1986 & Brakensiek *et al.*, 1983)

Zone	Soil Type	Sand (%)	Clay (%)	Saturated Hydraulic Conductivity, K (mm/hr)	Suction Head, Ψ (mm)	Initial Moisture Deficit, Φ (fraction)
1	Sandy Loam	54	24	4.901	109.98	0.33
2	Sandy Loam	65	16	7.903	109.98	0.33
3	Sandy Loam	58	16	11.961	109.98	0.33

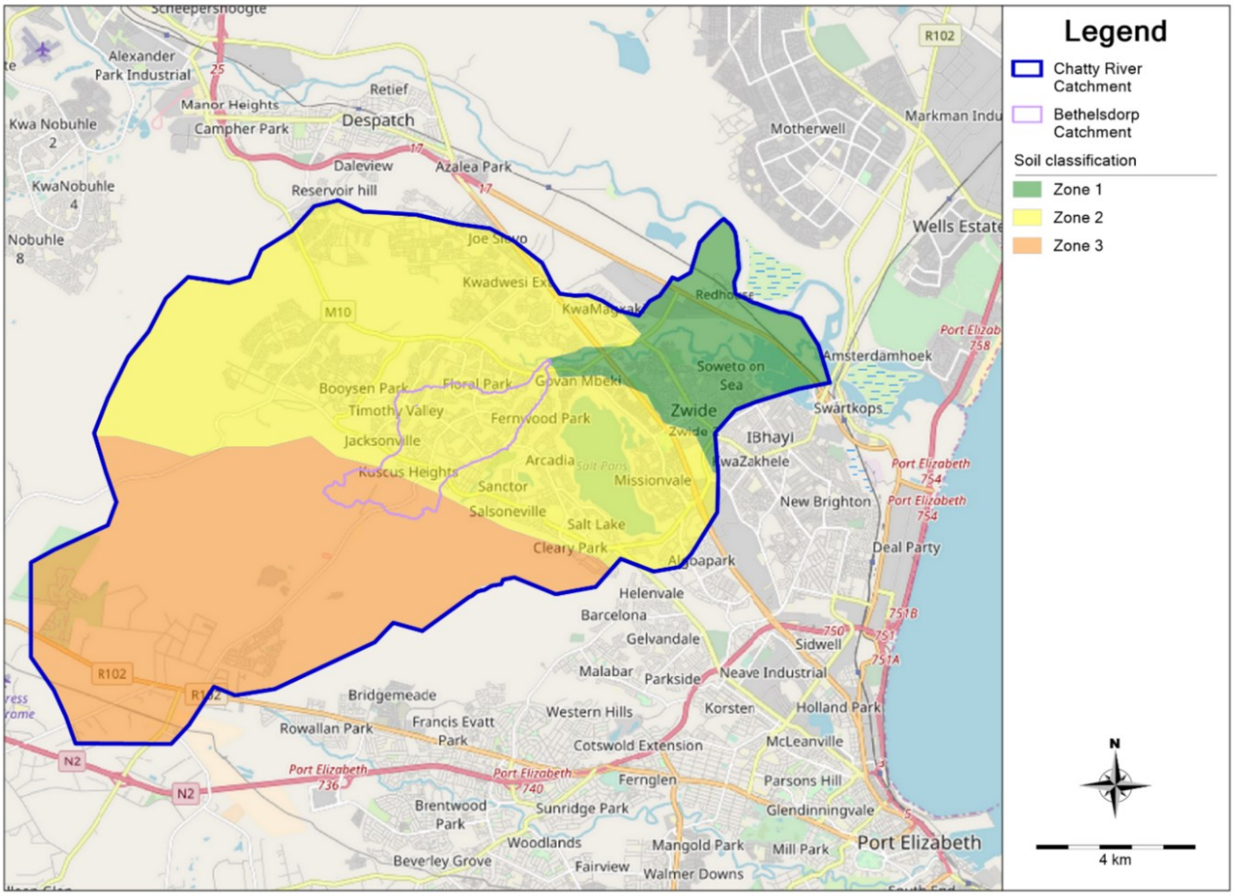


Figure 5-3:Chatty River Catchment soil map

5.1.5 Land use

Land use data was essential for the modelling of runoff and stormwater quality. Parameters such as imperviousness, flow roughness and depression storage characteristics were defined to reflect hydrological properties in the model's sub-catchments (Gregory, 2014). Event Mean Concentration (EMC) factors based on land use were used to indicate pollutant wash-off.

The land use data were extracted from the Department of forestry fisheries and the environment South African National Land Cover (SANLC) 2018 GIS dataset. The land use types were updated and edited by interpreting satellite imagery from Google Maps (Google Maps, n.d.). Table 5-3 lists the final land use categories chosen for the runoff analysis and simplified for the estimation of the EMC factors. The land uses are mapped in Figure 5-6.

Undocumented land uses, identified during the site visits, took place in the catchment, for example, informal settlements (Figure 5-4) and grazing in open spaces (Figure 5-5). Furthermore, there was extensive dumping of litter and rubble by the riverbanks in open spaces (Figure 5-7) which influenced the hydrological and wash-off parameters applied to the model as the open spaces were not only covered by soil and vegetation.

The South African National Biodiversity Institute Biome GIS dataset for the Nelson Mandela Bay Area formed the basis of the biome classification. As shown in Figure 5-8, Albany thicket and fynbos biomes were the predominant land covers before urban development.

Table 5-3: Land cover categories

Land cover for runoff	Land cover for water quality
Urban formal	Urban formal
Urban informal	Urban informal
Dams	Dams
Mine	Mine
Agriculture	Agriculture
High-density alien plants	Open Space
Recreational Open Space	
Unused Open Space	
Dumping site	
Roads	Roads
Thicket Biome	Rural
Fynbos Biome	

Figure 5-4: Urban informal land use

Figure 5-5: Undocumented cattle grazing

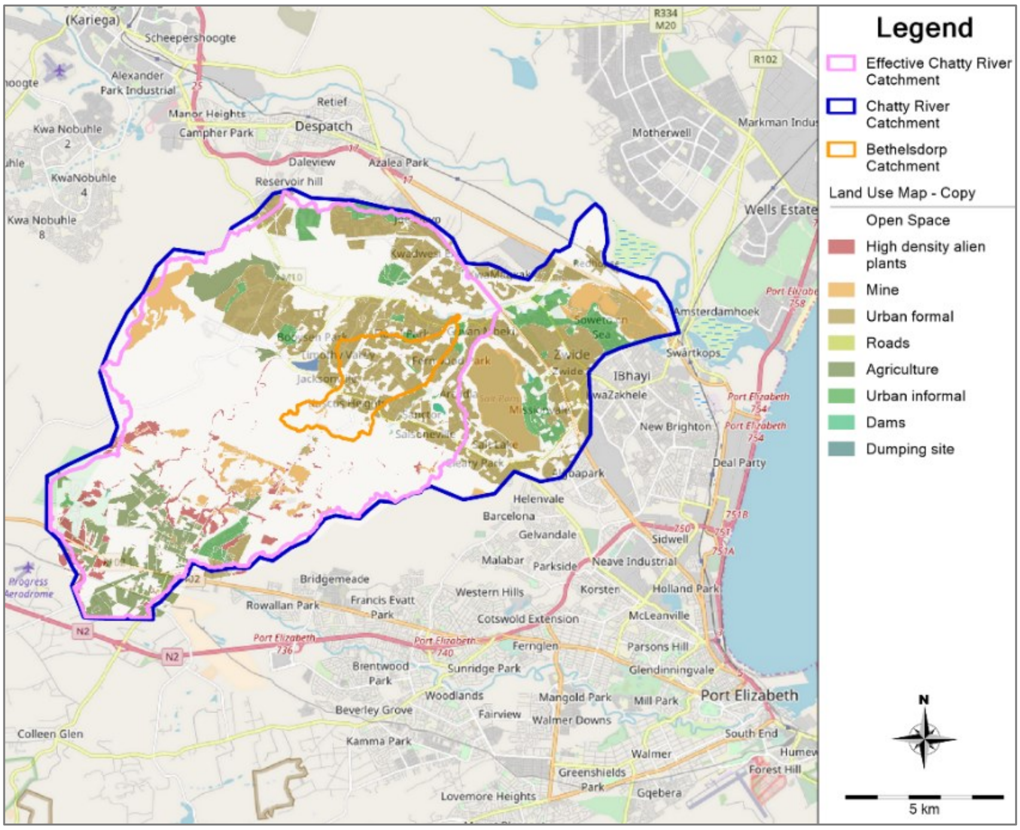


Figure 5-6: Land use map for the Chatty River Catchment

Figure 5-7: Litter in open spaces

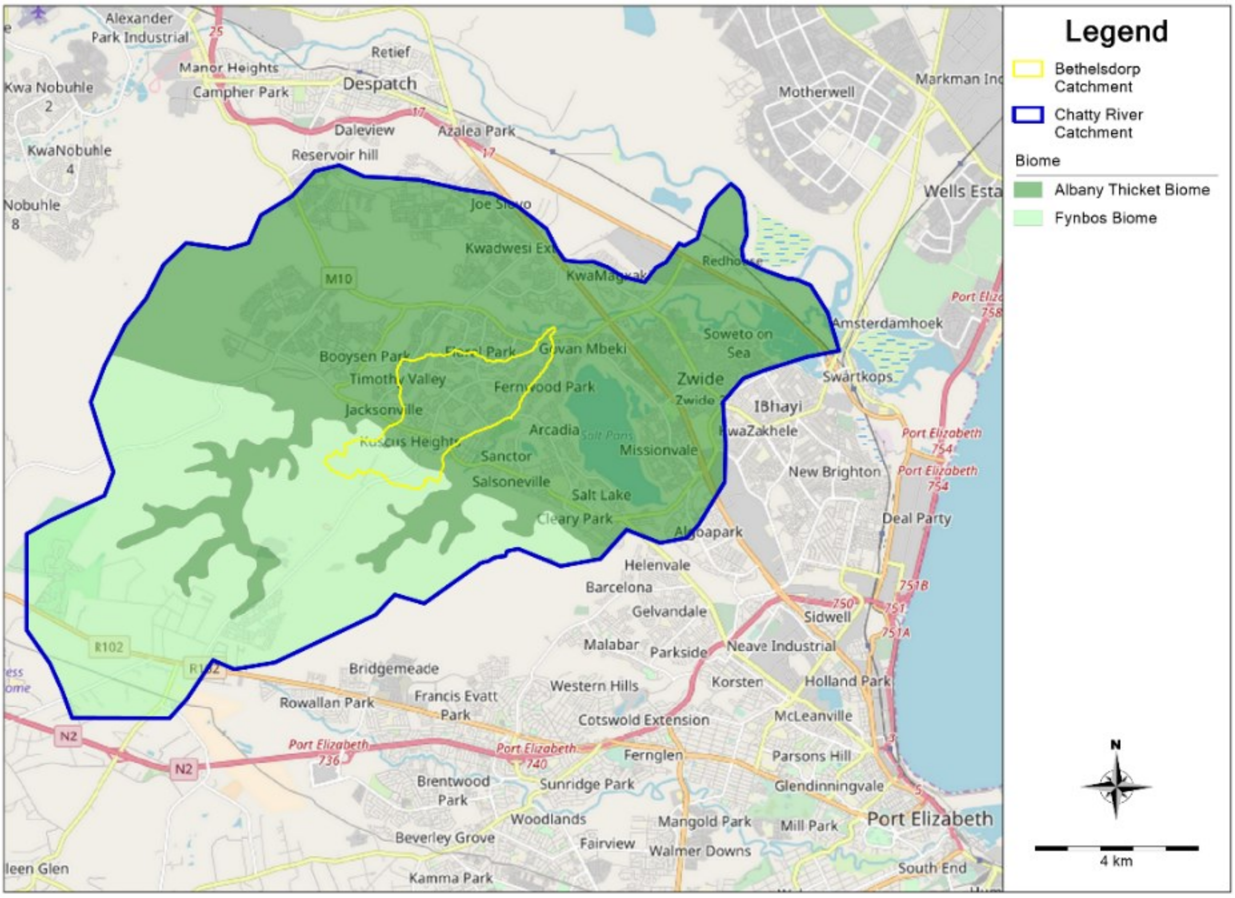


Figure 5-8: Vegetation map for the Chatty River Catchment

Overland roughness factors were expressed through the use of Mannings *n* values. Depression storage, an initial abstraction, for the impervious and pervious areas in the various land uses was based on literature and the observed conditions from the site visits and desktop study. The percentage of impervious area with no depression storage accounts for immediate runoff occurring at the start of rainfall before depression storage is satisfied for example new pavement that may not have surface ponding and pitched roofs draining directly to street gutters (CHI, 2022). Preliminary impervious percentages and the percentage of impervious area with no depression storage for different land use categories were obtained from literature (ASCE, 1992; Brabec *et al.*, 2002; McCuen *et al.*, 1996; Gregory, 2014; Turpie *et al.*, 2017). Satellite imagery (Google Maps, n.d.) underlying the land use map and site visits were used to inform and adjust the preliminary parameters. Finally, all impervious surfaces were modelled as directly connected impervious areas (DCIA). The key hydrological properties of the Chatty Catchment are presented in Table 5-4.

Table 5-4: Summary of the Chatty River Catchment hydrological properties (by land use properties)

(ASCE, 1992; Brabec *et al.*, 2002; McCuen *et al.*, 1996; Gregory, 2014; Turpie *et al.*, 2017)

	Manning's n		Depression storage (mm)		Imperviousness (%)	Impervious without storage (%)
Land Use	Impervious	Pervious	Impervious	Pervious		
Urban formal	0.013	0.15	1.875	3.75	65	20
Urban informal	0.013	0.15	1.875	3.75	50	20
Dams	0.015	0.015	0	0	100	0
Mine	0.024	0.15	1.25	2.5	70	20
Agriculture	0.013	0.17	2.5	5	30	10
High-density alien plants	0.024	0.15	2.5	5	5	15
Recreational Open Space	0.024	0.15	2.5	5	5	10
Unused Open Space	0.024	0.15	2.5	5	5	15
Dumping site	0.024	0.15	1.875	2.5	40	15
Roads	0.011	0.15	1.25	2.5	90	20
Albany Thicket Biome	0.05	0.15	2.5	5	5	10
Fynbos Biome	0.05	0.4	2.5	5	5	10

5.1.6 Flow data

Observed flow data was required to calibrate the hydrological models developed in PCSWMM. Flow data collection is a process that should be planned at the initial stages of a project due to the variable rainfall patterns throughout the year and unpredictable changes in the weather forecast. Planning allows for maximum utilisation of opportunities available for the collection of calibration data during a time-sensitive project such as this one.

Discharge was determined using the slope-area method where the Manning equation (Equation 5-5) was applied to express the volumetric flow rate (Rossman & Huber, 2016a) during storm events. The sites chosen were reasonably uniform, with regular cross-sections that could be expected to have a steady uniform flow to apply the slope-area method. Measurements of geometric properties used to calculate the area and hydraulic radius, that is, the length of the sides, base, and vertical height of the channels, were surveyed on-site. A dumpy level survey (Figure 5-10) was conducted at each site to determine the channels' approximate slope.

$$\mathrm{Q} = \frac{AR^{\frac{2}{3}}S^{\frac{1}{2}}}{n} \tag{5-5}$$

where Q = flow (m^3/s); A = cross-sectional flow area (m^2); R = Hydraulic radius (m) = $\frac{A}{P}$; S = slope (m/m); P = wetted perimeter (m).

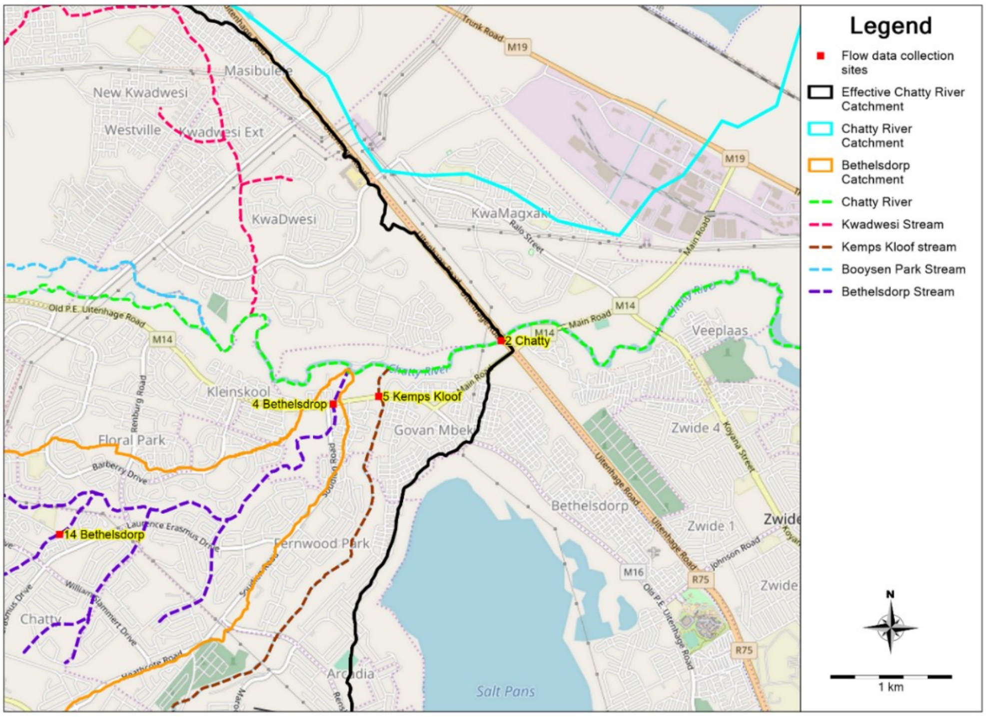


Figure 5-9: Flow data collection sites

Several attempts were made to collect the flow depths at the measurement locations. The methods attempted included: i) the use of chalk sticks, ii) a Solinst levelogger and iii) a stencilled measurement scale at selected sites (Figure 5-9). The chalk stick method (Kolsky, 1998) is a relatively low-cost and simple method to measure peak flow depths using wooden sticks, with increments, coated in chalk and housed in PVC trunking with perforations to obtain the highest flow depth during a storm (Appendix D.1). The Solinst levelogger collects continuous flow depth data through pressor transducers (Appendix D.2). There was no flow gauging site along the stream with recent or historical flow data.

Attempts made to use the chalk sticks and Solinst levelogger were unsuccessful due to theft of the instruments placed on site, however, the use of the stencilled measurement scale was successful and peak flows obtained were used for event-based partial calibration of the Bethelsdorp River Catchment (BRC) As-Is model.

Figure 5-10: Taking slope measurements at Site 5 (Kemps Kloof) using a dumpy level

5.1.6.1 Flow measurements

Peak flow depths were measured at Site 14 (Bethelsdorp), shown in Figure 5-11. The channel was a long reasonably uniform, trapezoidal, concrete cross-section that could be expected to have a steady uniform flow. A stencil was sprayed on the trapezoidal channel's slope, as shown in Figure 5-12. When the water depth increased during peak rainfall, the relative roughness of the channel reduced, and the impact of the channel's roughness elements (e.g., irregularities and vegetation) on flow velocity diminished. This reduction in roughness effects was assumed to allow the flow to stabilise and become uniform.

Initially, a collaboration with a neighbouring school was attempted for the recording of the daily water levels and the high-water marks left on the surface after large storms. Unfortunately, the primary contact person fell ill with COVID-19 and the plan fell through after inconsistent communication with the school.

Figure 5-11: Trapezoidal channel at Site 14 (Bethelsdorp)

Several rainfall depths were simulated in PCSWMM to establish a storm event with sufficient intensity to produce a measurable flow response at Site 14 (Bethelsdorp). Rainfall depths greater than 5 mm were seen to produce a measurable flow response and targeted for peak flow depth measurements to be recorded.

Windy.com, a weather forecasting service, was used to predict the occurrence of the desired rainfall depth. With the aid of the NMU team, available between 8 am and 5 pm on weekdays, the associated high-water mark was recorded during the targeted storm event. The peak flow depth, that is, from the high-water mark, was used in the Manning Equation (Equation 5-5) to convert flow depths to flow rates. The peak flow rate was then used in the partial calibration of the BRC As-is model.

Figure 5-12: Stencil placement on the slope of the trapezoidal channel

5.2 Hydrological model construction

5.2.1 Sub-catchment development

In the model, a sub-catchment is a land parcel that receives precipitation from an associated rain gauge and generates runoff that flows into a drainage system node or another sub-catchment (Rossman & Huber, 2016a). In SWMM, a collection of sub-catchments receive precipitation and generate runoff and pollutant loads in the runoff component (James & Rossman, 2010). SWMM allows users to enter an extensive list of variables, however, the modelling process focused on surface water management.

The catchments were delineated into sub-catchments using the Watershed Delineation Tool (WDT) and DEM provided (Section 5.1.1) in PCSWMM. Each sub-catchment is defined as a hydrological unit in the system (Gregory, 2014). Representative sub-catchment surface cover parameters, imperviousness, roughness, depression storage and infiltration were extracted from the underlying GIS land use (Section 5.1.5) and soil (Section 5.1.4) databases (James, 2005) using look-up tables. The Spatial Weighting tool in PCSWMM defined the weighted average parameter values based on the area fraction for each sub-catchment.

The slope and length of each sub-catchment were also established using the WDT. The determined flow path lengths were divided into the sub-catchment area (Gregory, 2014) to establish the sub-catchment width, an input parameter in PCSWMM. Different rain gauges can be used for different sub-catchments; however, in this investigation, the PORT rain gauge (Section 5.1.2) was used for the entire catchment due to the limited available data.

PCSWMM allows the user to choose among several infiltration methods: Horton's method, the Green-Ampt method, a modified Horton's method, a modified Green-Ampt method and the Curve Number method (Rossman & Simon, 2022).

The modified Green-Ampt method was applied to the sub-catchments. Unlike the Green-Ampt method, the modified Green-Ampt method retains moisture deficit in the topsoil layer during initial periods of low rainfall (Rossman & Simon, 2022). It assumes a sharp wetting front exists in the soil column separating the soil at some initial moisture content below from the saturated soil above (Rossman, 2010). Finally, the Green-Ampt method requires that the rainfall intensity is always greater than the infiltration capacity of the soil (Almedeij & Esen, 2014) while the modified Green-Ampt method enables the software to model more representative infiltration when rainfall intensity is less than the soil’s saturated hydraulic conductivity.

Runoff that is not infiltrated was directed at the lowest point into an outlet. Dynamic wave routing, also known as indirect routing, was applied during modelling. The lowest point can be a junction or another sub-catchment. Multiple sub-catchments can be directed into a singular outlet provided they have diverging flow paths and make up the same contributing area. Due to the absence of stormwater network maps of the study area, the sub-catchments were reviewed and edited based on existing delineated catchment maps provided by the NMBM that had been developed for a review of the 1:50 and 1:100-year flood lines in the Chatty River (SRK Consulting, 2015).

Not all of the Chatty River Catchment was modelled in this project. This study was focused on the mitigation of water quality in the Chatty River but the lower section where it enters the Swartkops estuary is subject to tidal influences that transport pollutants from other catchments feeding the estuary up the river and raising its salinity. The effective area of the modelled Chatty River Catchment was approximately 114 km^{2,} with an effective outlet at Site 2 (Chatty) (Figure 5-13). It was then delineated into 61 sub-catchments with an average area of 2 km^2.

The Bethelsdorp River Catchment in Figure 5-14 had a total area of 8.9 km^2 with 75 sub-catchments. It was delineated with an average target area of 0.1 km^2.

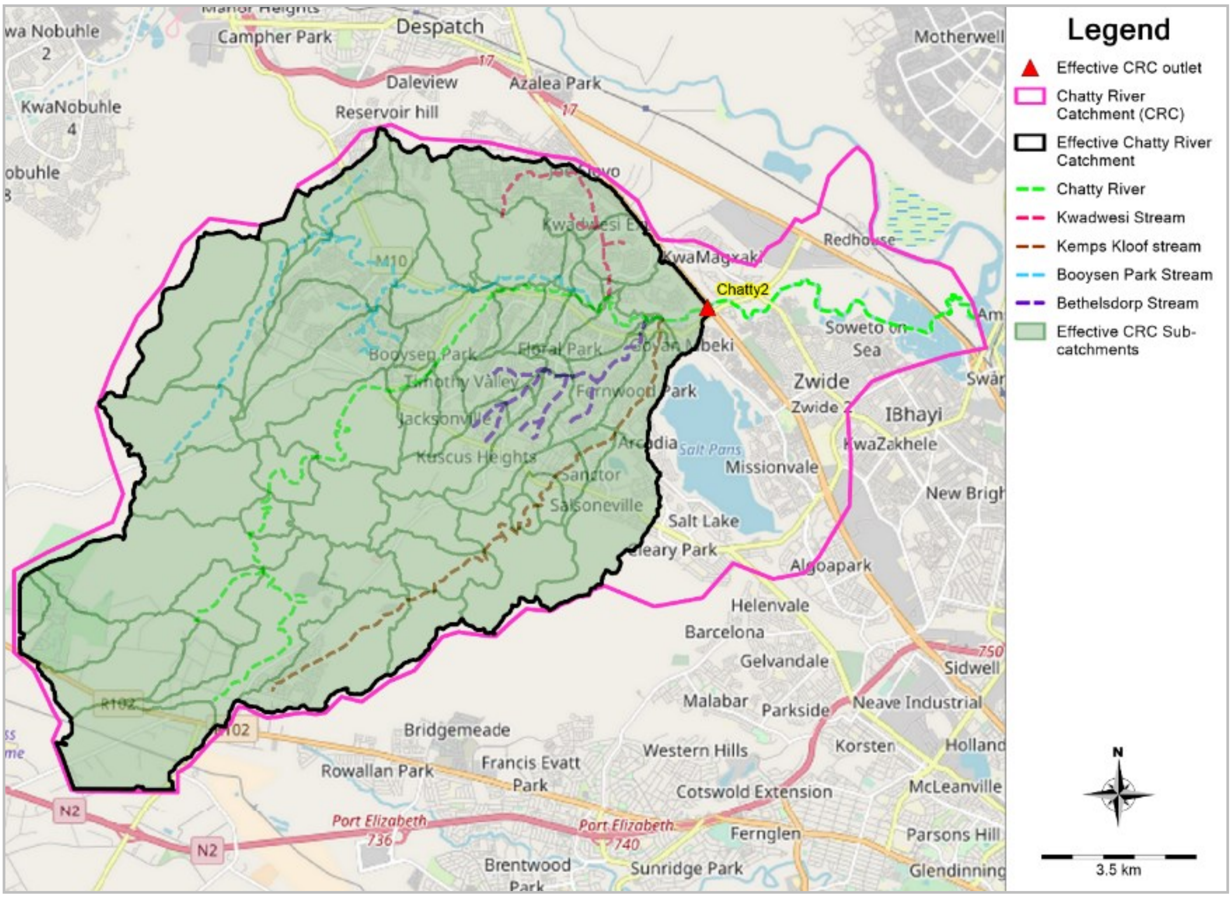


Figure 5-13: Modelled Chatty River Catchment sub-catchment delineation

5.2.2 Conveyance network

The routing component, transporting runoff and pollutant loads, was simulated in PCSWMM through a drainage network of pipes, culverts, and channels represented as conduits (Rossman & Huber, 2016a). The conveyance network was modelled using the Watershed Delineation Tool (WDT) supplied with topographical data in the form of a DEM, field surveys, and satellite imagery of the study area. The sub-catchments and conduits fed directly into inlets at their lowest point, represented by junctions.

Flow routing through a conduit in PCSWMM is governed by the gradually varied, unsteady flow, conservation of mass and momentum equations (Rossman & Simon, 2022). Users can choose between Steady Flow Routing, Kinematic Wave Routing, and Dynamic Wave Routing. Dynamic Wave Routing was chosen for this project as it caters to systems with flow regulation via weirs and orifices, elements used in SuDS modelling. Furthermore, this routing option produces the most theoretically accurate results as it solves the complete one-dimensional Saint Venant flow equation (Rossman & Simon, 2022).

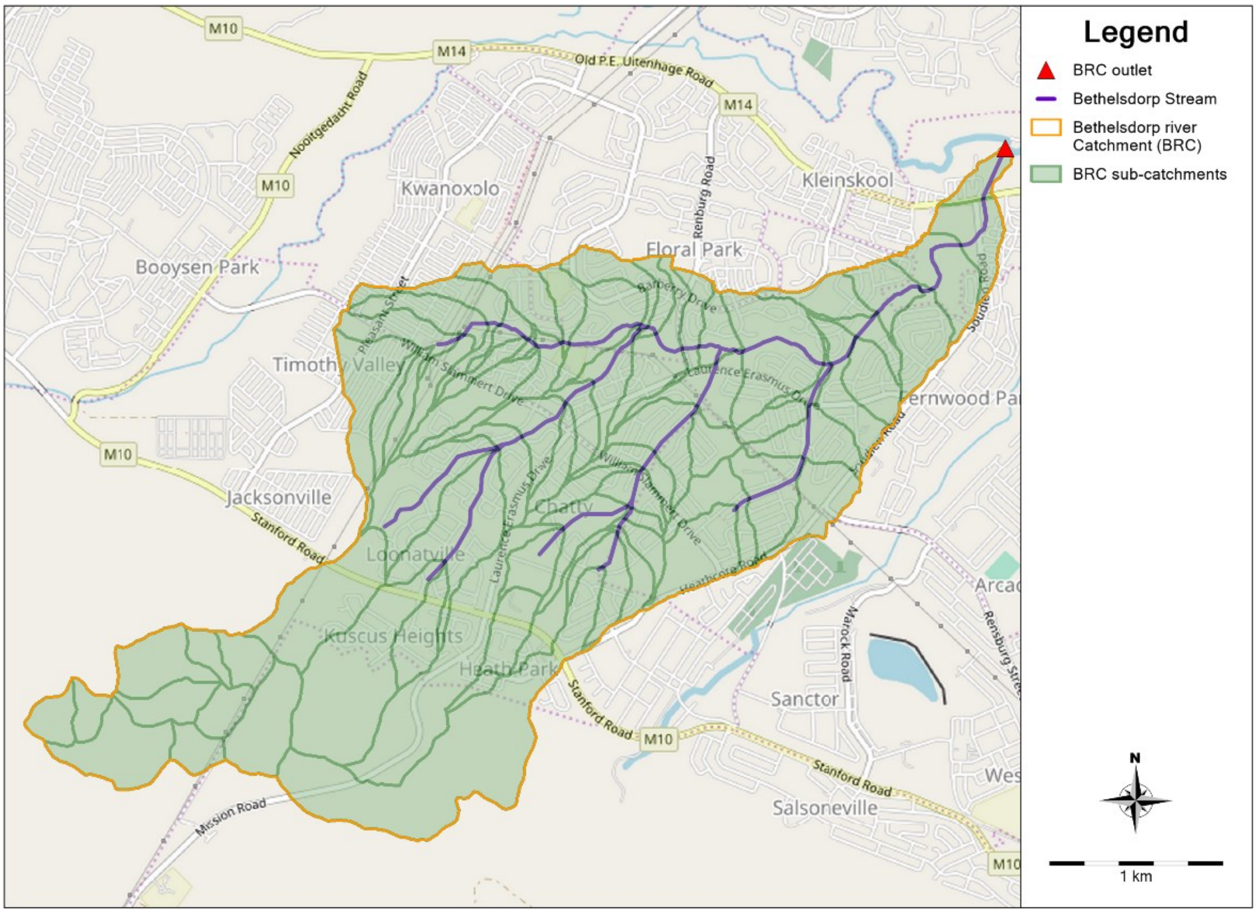


Figure 5-14: Bethelsdorp river Catchment sub-catchment delineation

Dynamic wave routing methods require smaller hydraulic time steps than other routing methods to maintain numerical stability resulting in longer run times (CHI, 2022). The routing time step applied was 5 seconds. The hydrological time steps, the 'wet weather' and 'dry weather' time steps, were also carefully considered. A 'wet weather' time step, applicable during periods of precipitation or overland flow, was thus defined as 1 minute. This timestep should be less than or equal to the rainfall interval and was determined as a fraction of the 5-minute rainfall interval to capture changes in flow with changes in rainfall intensity. SWMM uses linear interpolation to compute the flow that falls in between the times at which the input rainfall time series was recorded (CHI, 2022). The 'dry weather' time step, when there is no precipitation and depression storage, should be equal to or greater than the wet weather time step for long-term continuous simulations (James & Rossman, 2010). It was chosen to be 15 minutes to reduce the run time in PCSWMM which may have been caused by a smaller time step of 5 minutes and reduce the risk of a coarser representation of the recession limb which may have been caused by a larger time step for example, 1 hour. The dry weather time step was essential to update infiltration parameters and provide hydrograph continuity or inflow to channels and conduits when there is no rainfall in the area (Rossman & Huber, 2016a).

A Manning’s roughness coefficient, *n*, was assigned to all conduits as detailed in Table 5-5 using reference tables in ACSE (1982).

Table 5-5: Manning's roughness coefficient for conduits (ASCE, 1982)

Conduit type	Roughness coefficient
Natural channel	0.04
Concrete engineered channel	0.0115
Closed rectangular culvert	0.016
Circular culvert	0.013

5.2.2.1 Chatty River Catchment

Delineation using the Watershed Delineation Tool and DEM led to the generation of 1 m circular conduits on the simulated flow paths. The spatial positioning of the flow paths was compared and edited using the most recent satellite imagery at the time of the study (Google Maps, 2022) underlying the conduit layer. The natural open channels in the Chatty River and its tributaries were estimated by converting the circular conduits to irregular cross-sections using the Transect Creator tool and topographical data in PCSWMM. Survey data of engineered trapezoidal, semi-circular, and rectangular channels collected during the project were also added. Figure 5-15 shows the conduits used for the study.

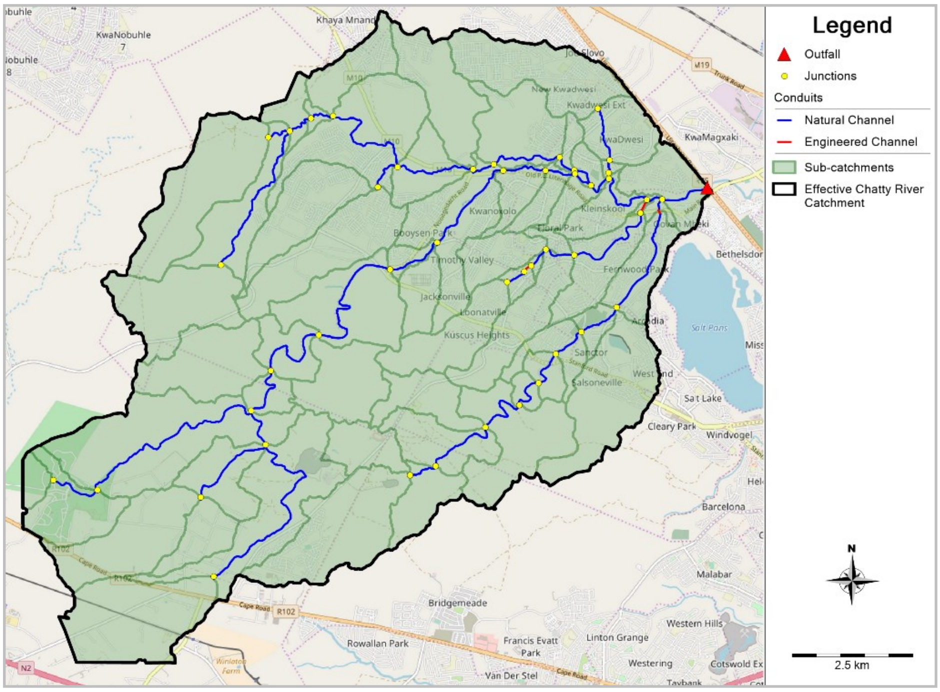


Figure 5-15: Drainage network in the modelled Chatty River Catchment

5.2.2.2 Bethelsdorp River Catchment

As with the Chatty River Catchment, circular conduits initially generated in the delineation process by PCSWMM were converted into irregular cross-sections using the Transect Creator tool. Engineered channels surveyed during site visits were also added to this model. Field survey data of some rectangular and circular culvert sections at road crossings in the study area, undertaken by SRK Consulting, was provided by the NMBM and added to the model, as shown in Figure 5-16. These culverts were modelled as closed conduits in PCSWMM.

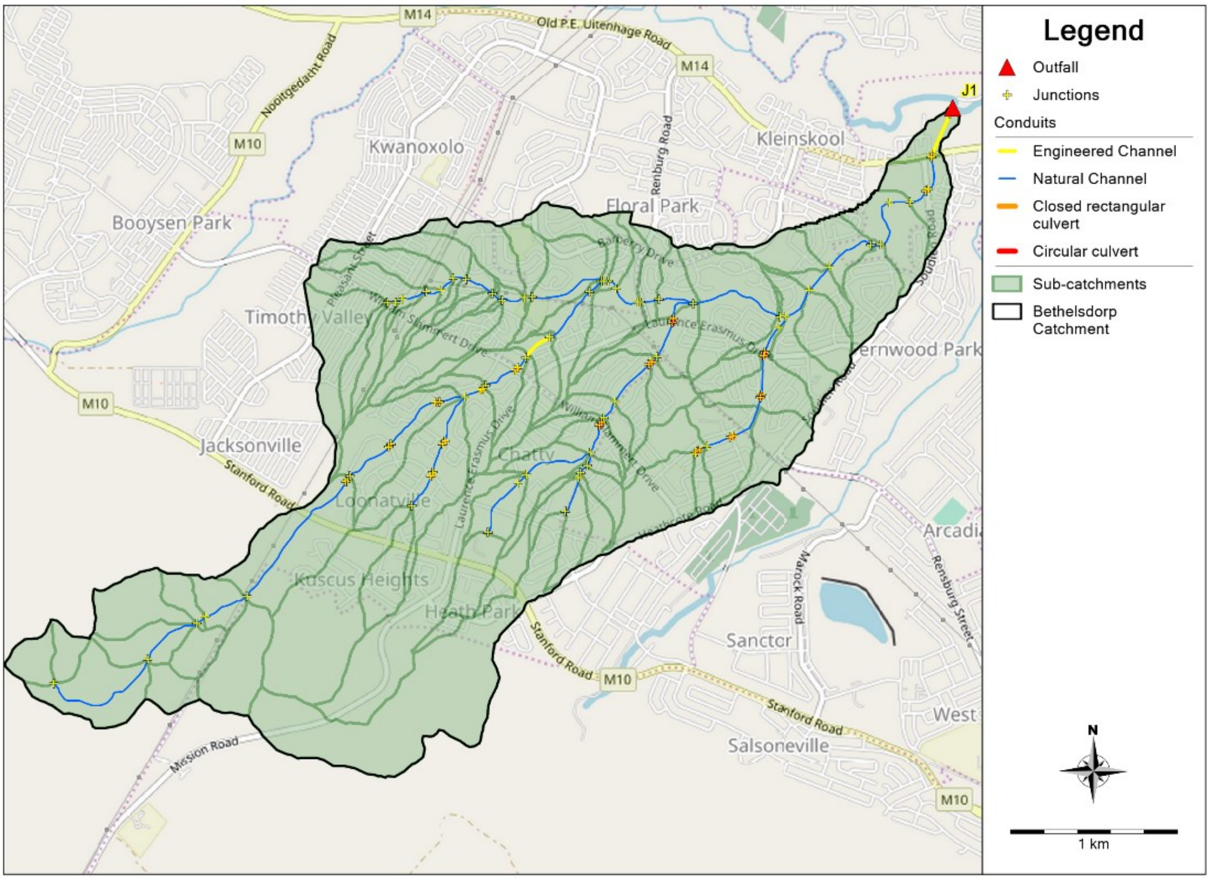


Figure 5-16: Drainage network in the Bethelsdorp River Catchment

5.2.3 Calibration and sensitivity analysis

Calibration is an integral part of engineering modelling. Sensitivity analysis, although less computer-intensive (James, 2005), is necessary to complement the calibration process, especially where the collection of observed flow data has been challenging. Overall, the sensitivity analysis and calibration process is carried out during modelling to optimise estimated parameters (James, 2005). This section outlined the process undertaken to conduct a sensitivity analysis and model calibration as required in the As-is models.

5.2.3.1 Sensitivity analysis

A sensitivity analysis clarifies which processes were the most significant on the 'As-Is' model results and which data was most significant to the study. The sub-catchment parameters influencing surface runoff volume were chosen for the sensitivity analysis as they were determined from previously published data, watershed delineation and field observations.

Table 5-6 highlights the likely impact of surface runoff parameters on runoff volume and peak. The parameters considered were sub-catchment width, slope, imperviousness, roughness, and depression storage. The Green-Ampt infiltration parameters obtained from literature, suction head, saturated hydraulic conductivity, and initial moisture deficit were also included in the sensitivity analysis.

Table 5-6: Sensitivity of runoff volume and peak flow to surface runoff parameters
(Rossman & Huber, 2016a)

Parameter	**Typical effect on hydrograph**	**Effect on increase of runoff volume**	**Effect on increase of runoff peak**	**Comments**
Imperviousness	Significant	Increase	Increase	Less effect when pervious areas have low infiltration capacity.
Width	Affects shape	Decrease	Increase	Increasing the width for storms of varying intensity tends to produce higher and earlier hydrograph peaks and a generally faster response. It only affects volume to the extent that reduced width on pervious areas provides more time for infiltration.
Slope	Affects shape	Decrease	Increase	Same as for width but less sensitive since flow is proportional to the square root of slope.
Roughness	Affects shape	Increase	Decrease	Inverse effect as for width.
Depression storage	Moderate	Decrease	Decrease	Significant effect only for low-depth storms.

An event-based sensitivity analysis was undertaken, as done in previous studies, for example, Lindiwe *et al*. (2019) and (Xu, Xiong, *et al*., 2019), and several storms were considered. The analysis was undertaken for the Kroneberg Drive monitoring station, Site 14 (Bethelsdorp).

The events were auto selected using the Events Tool on PCSWMM. The smallest storm event was 4.8 mm (31/03/2013, 14.17 hrs), others included: 7.2 mm (19/05/2022, 17.67 hours) and finally 24 mm (21/07/2021, 18.92 hrs). The variation of rainfall depth, that is 4.8 mm, 7.2 mm and 24 mm, facilitated the analysis of the variation of parameter sensitivity with rainfall depth.

The Sensitivity Radio Tuning Calibration (SRTC) tool was used to conduct a sensitivity analysis based on selected parameters whose uncertainty was assigned. The influence of the change of each parameter, while the other parameters remained unchanged, was then assessed. Uncertainty estimates were set using upper and lower bounds to ensure that the parameters remained within their physically meaningful limits. A default bound of +50%/-50% of the initial value, as proposed by Liong, Shreeram and Ibrahim (1995), was applied. The computational runs were carried out in parallel to save time.

5.2.3.2 Chatty River Catchment sensitivity analysis results

Due to the influence of total rainfall on runoff (Xu *et al*., 2019), three storms with varying depths were analysed for the Kroneberg Drive monitoring station, represented by C22_2 in PCSWMM. The changes in peak flow and volume were analysed for the effect of changes in runoff and Green-Ampt parameter values within +50%/-50% bounds. A sensitivity analysis was carried out as described in Section 5.2.3.1.

The sensitivity analysis of peak flow with a maximum change of parameter values for the variable rainfall depths is presented in Figure 5-17 and Figure 5-18. Peak flows were most sensitive to changes in the percentage of impervious area (Imperv). This was in line with investigations carried out by Lindiwe *et al.* (2019) and Turpie *et al.* (2017). The Manning's coefficient for impervious areas also has a noticeable influence on peak flows. This is because Manning's coefficient mainly affects convergence time, which determines the flow peak time (Xu, Xiong, *et al*., 2019).

The peak flows were insensitive to changes in pervious runoff parameter values, similar to Lindiwe *et al.* (2019) findings, as the pervious areas may have generated no runoff due to infiltration in these storms. Similarly, peak flows were insensitive to the increase or decrease of Green-Ampt parameter values, saturated hydraulic conductivity, initial deficit, and suction head. This is similar to Fisher-Jeffes (2015) findings, where the Green-Ampt parameters were the least sensitive and Mancipe-Munoz *et al.* (2014), where the parameters were insensitive in areas where imperviousness was between 20% and 50%. The uncalibrated area contributing to the monitoring site had an imperviousness of 24%. With an increase in flow length, the peak runoff is reduced due to the increased infiltration time in pervious areas. Peak flow was sensitive to changes in slope. However, the sensitivity was less than with the length as flow is proportional to the square root of the slope (Rossman & Huber, 2016a).

The impact of depression storage was slightly sensitive for small storms, as highlighted by (Rossman & Huber, 2016a) and shown in a study by Lindiwe (2019). Changing the depression storage parameters for impervious areas (DSImperv and ZeroImperv) slightly influenced peak flow for the smaller storms, that is, 4.8 mm and 7.2 mm, as it becomes a smaller component of the water budget as depth increases (Rossman & Simon, 2022). Furthermore, as shown in Figure 5-19 and Figure 5-20, the sensitivity of depression storage reduced with time as depression storage filled up during the storm. During the July 2021 storm, the peak flow occurred in the second half of the storm, as shown in Figure 5-20, while in the May 2013 storm, the peak flow occurred in the first half of the storm, as shown in Figure 5-19.

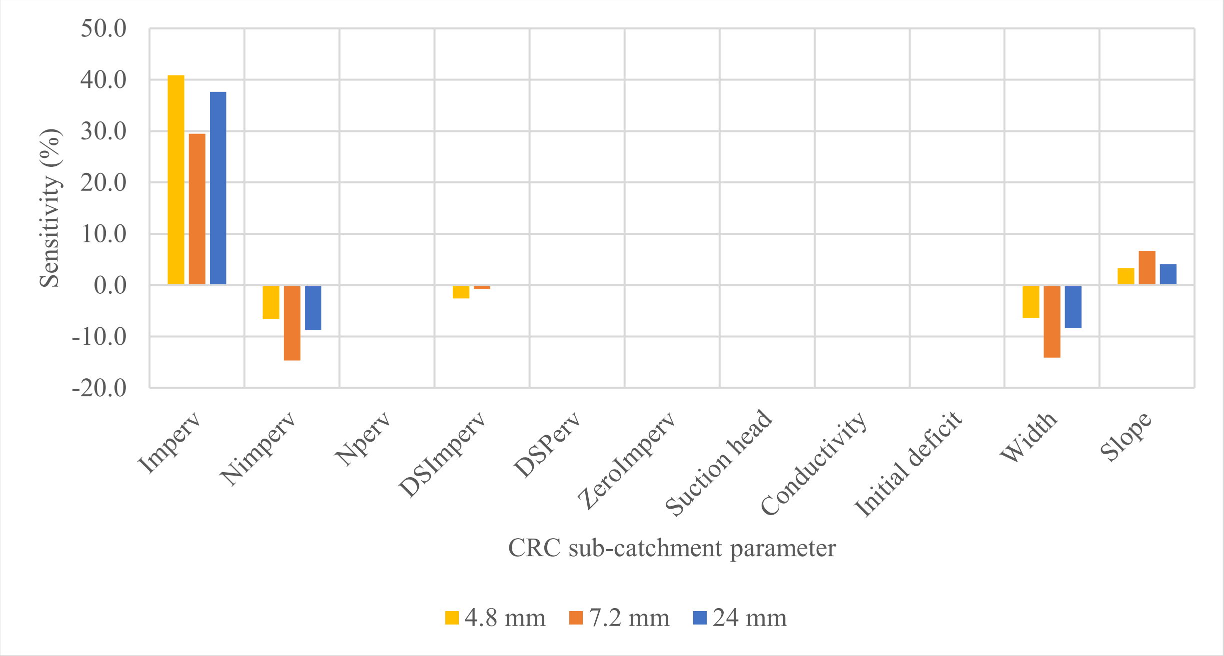


Figure 5-17: Peak flow changes with a maximum increase of parameter values by 50%

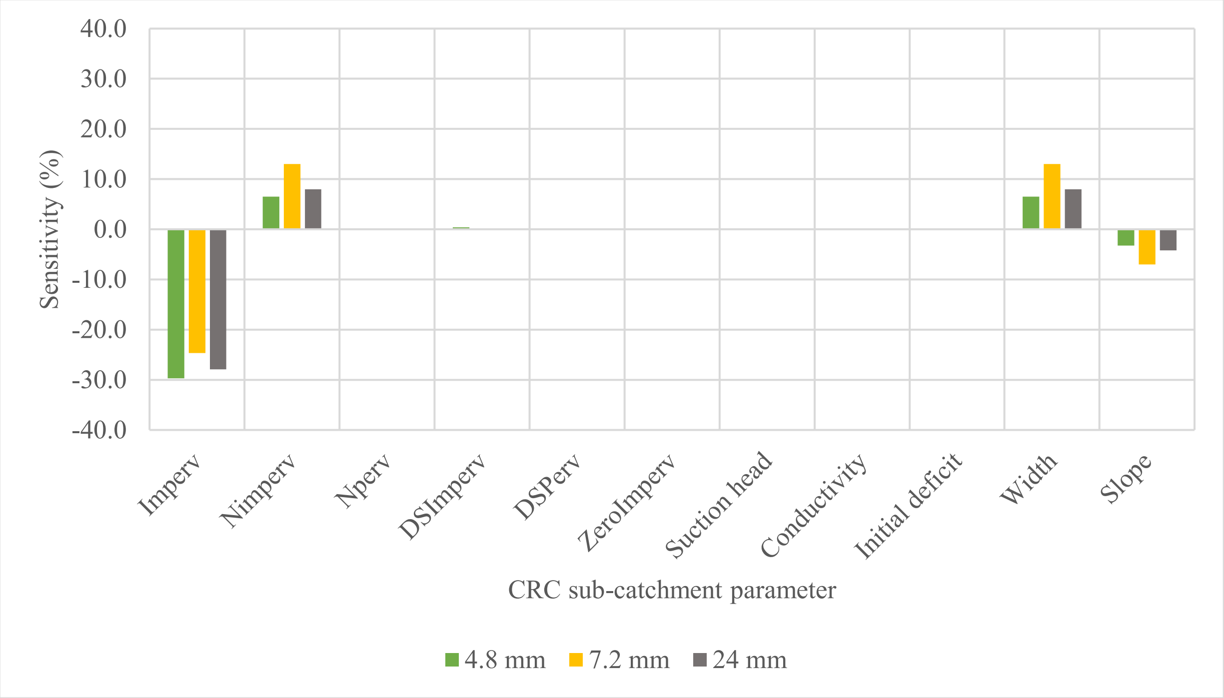


Figure 5-18: Peak flow changes with a maximum decrease of parameter values by 50%

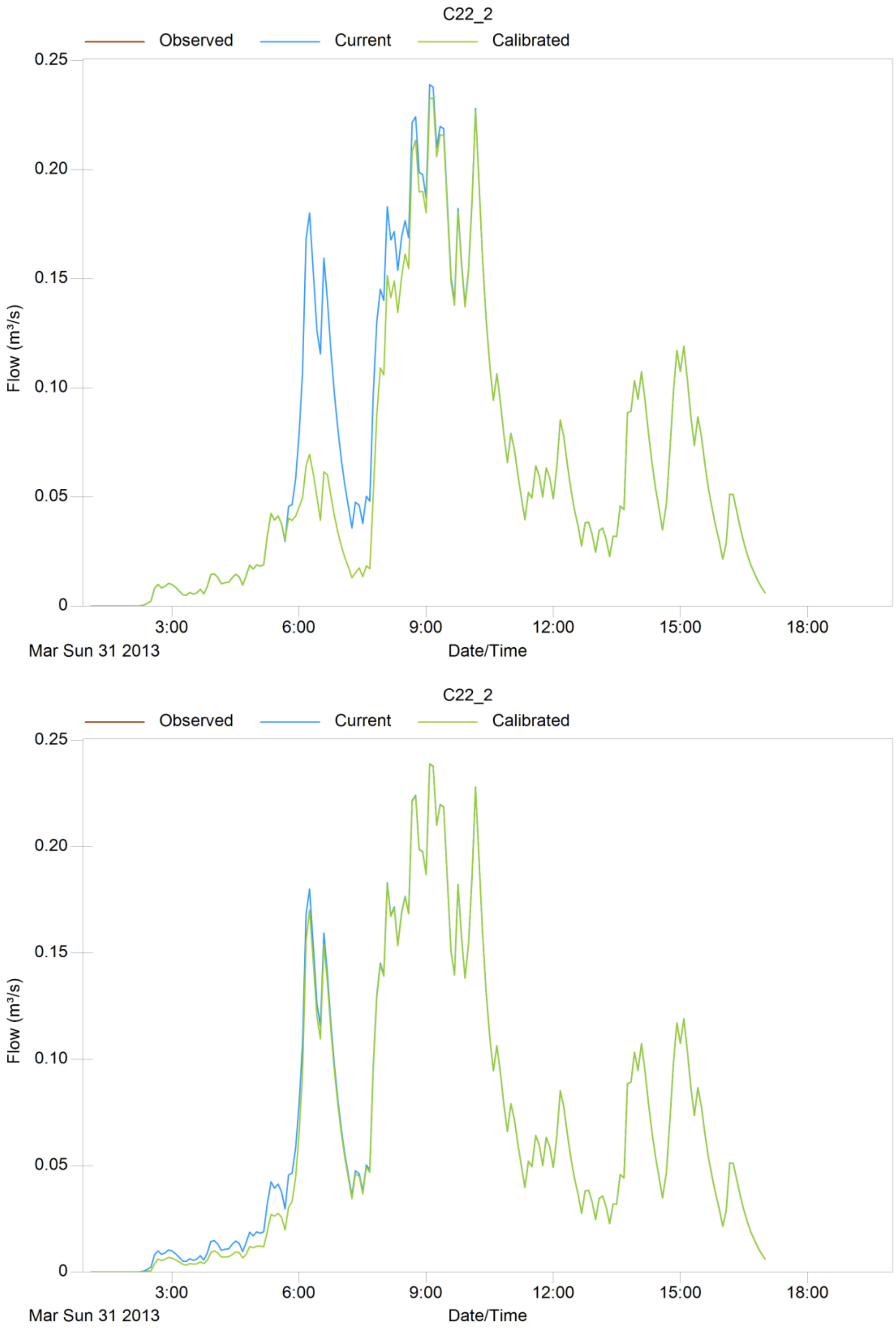


Figure 5-19: Variable influence of the change in depression storage parameters with time (4.8 mm rainfall depth)

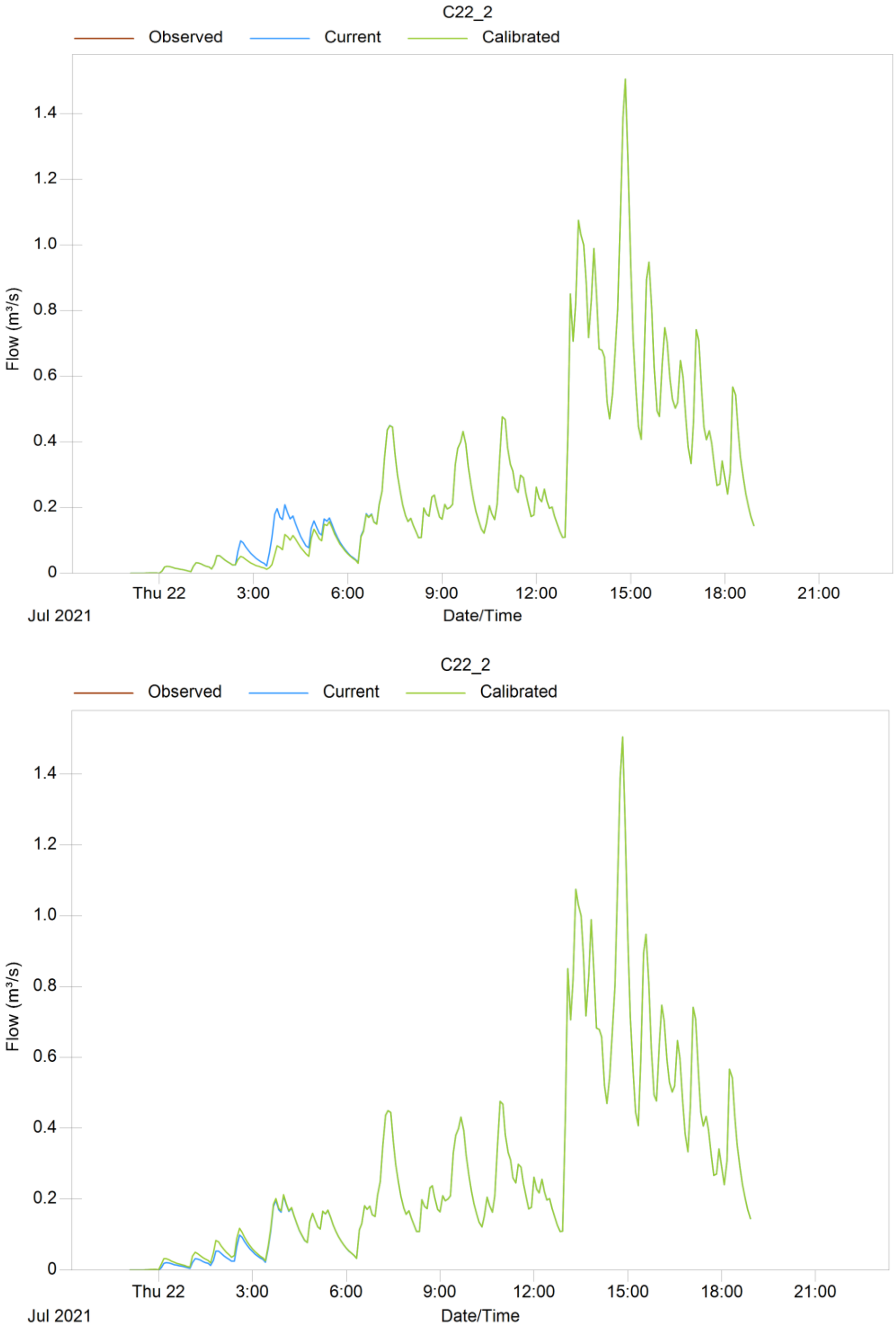


Figure 5-20: Variable influence of the change in depression storage parameters with time (24 mm rainfall depth)

Flow volume was highly sensitive to the percentage of impervious area in relation to the other parameters. The catchment’s impervious areas were modelled and assumed to be directly connected to the drainage system in the development of the 'As-is' model and this may have contributed to the high sensitivity. Although changes in Manning's coefficient for the impervious area influenced total flow volume, it was less than peak flow as it mainly impacted convergence time. As with peak flow, the Green-Ampt and pervious area parameters had an insignificant impact on the total flow volume. The depression storage parameters were more sensitive for total flow volume than peak flow rate as the amount of storage available changed. Sensitivity reduced with increased rainfall depth as depression storage became a minor water budget component.

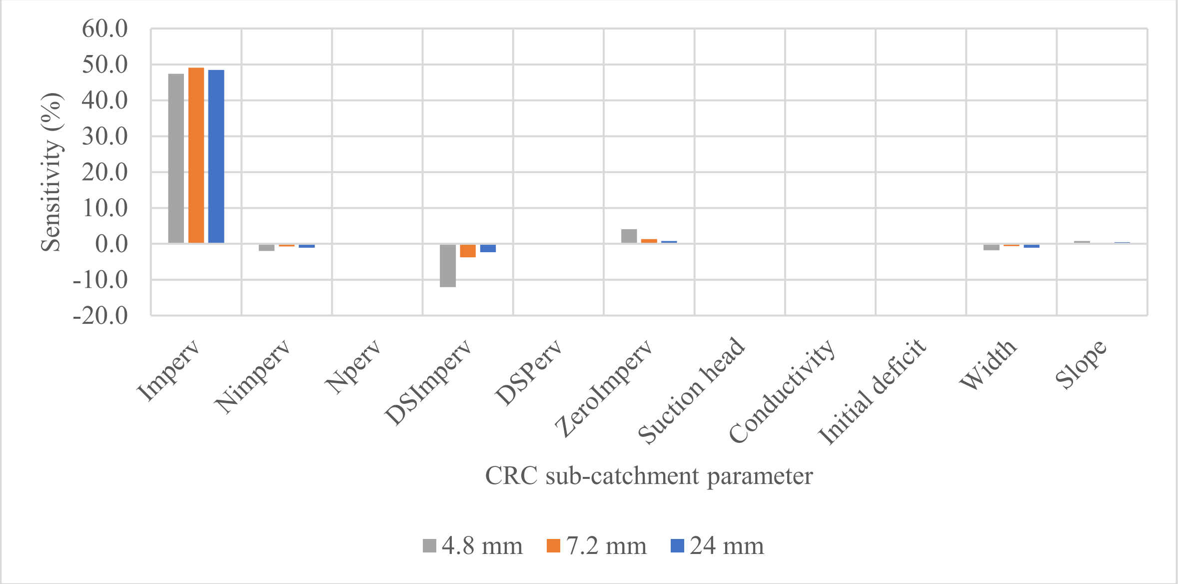


Figure 5-21: Peak volume changes with a maximum increase of parameter values by 50%

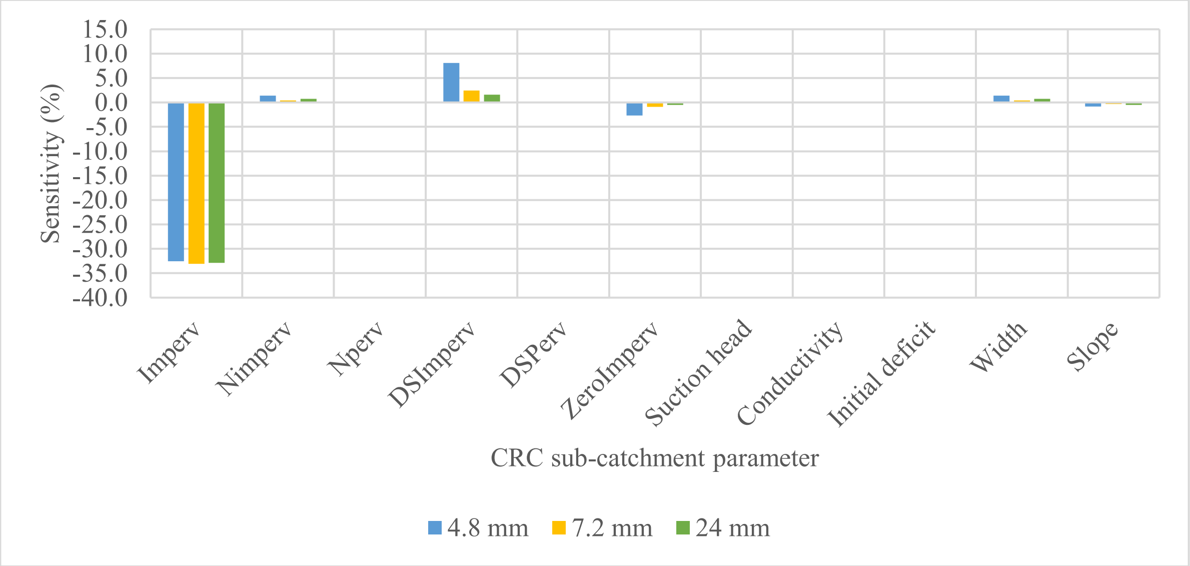


Figure 5-22: Peak volume changes with a maximum decrease of parameter values by 50%

5.2.3.3 Bethelsdorp River Catchment sensitivity analysis results

A sensitivity analysis similar to the one carried out in the Chatty River Catchment (Section 5.2.3.1) was carried out for the Bethelsdorp River sub-catchment. This aimed to assess the influence of sub-catchment runoff and infiltration parameters on peak flow and volume. It was an essential step in the modelling process as only a partial calibration of the catchment, as described in Section 5.2.3.4, could be carried out in this study. As the smaller Bethelsdorp River Catchment had a higher spatial resolution and more refined land use map; this step was repeated for the Kroneberg monitoring station, C22_2.

As with the Chatty River Catchment, the peak flows were most sensitive to the percentage of impervious area (Imperv) which was modelled as directly connected to the drainage system. This is highlighted in Figure 5-23 and Figure 5-24. In addition, the peak flow was insensitive to changes in pervious parameters (Nperv and DSPerv) and infiltration parameters, that is, suction head, saturated hydraulic conductivity, and initial soil moisture deficit. The sensitivity as a result of changes in Manning's coefficient for impervious area and sub-catchment length was relatively small, however, reduced with a reduction in rainfall depth.

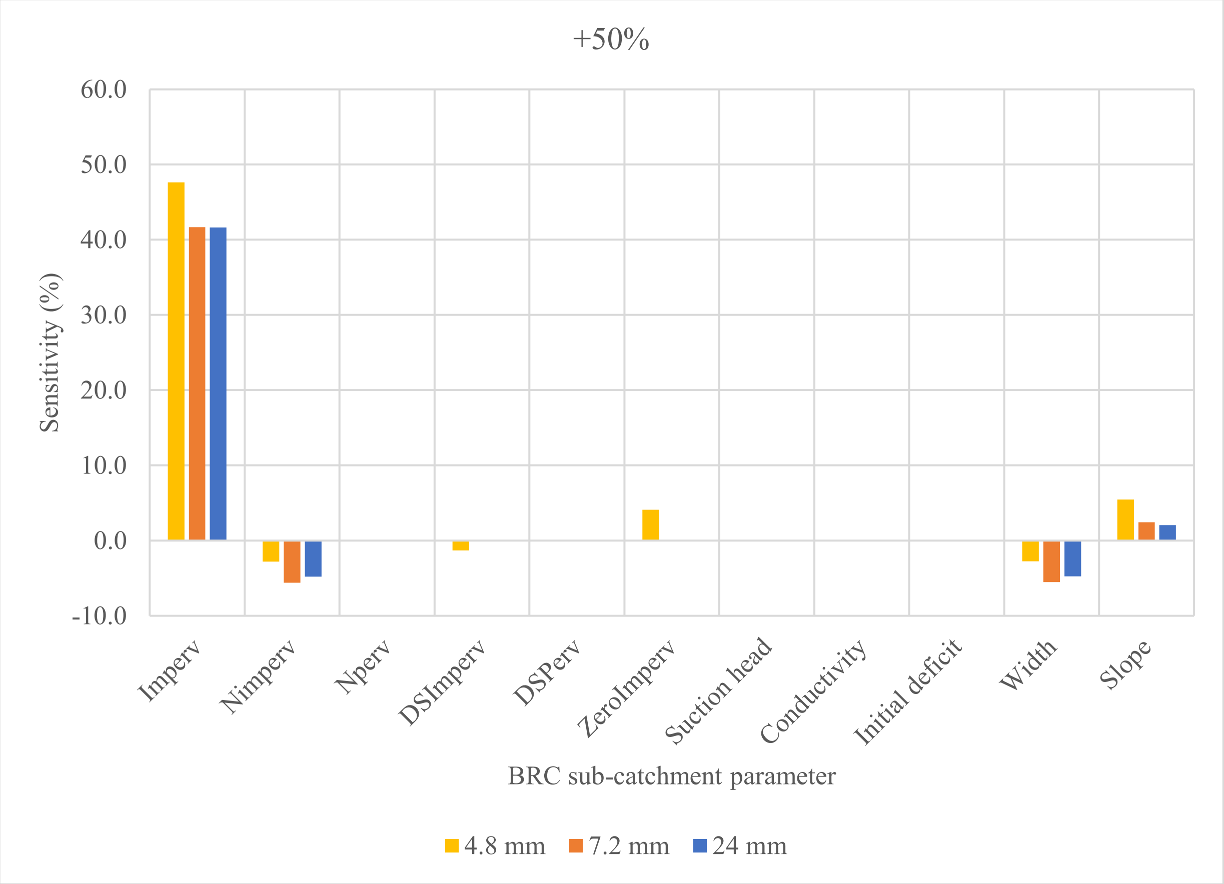


Figure 5-23: Peak flow changes with a maximum increase of parameter values by 50% in BRC

The peak flow sensitivity to depression storage parameters, DSImperv and ZeroImperv, was highest in the smallest storm, 4.8 mm. This is because the rainfall peak times for the larger storms occurred in the second half of the storm. Furthermore, changes in DSImperv led to a distinct alteration of the 4.8 mm hydrograph shape as shown in Figure 5-24.

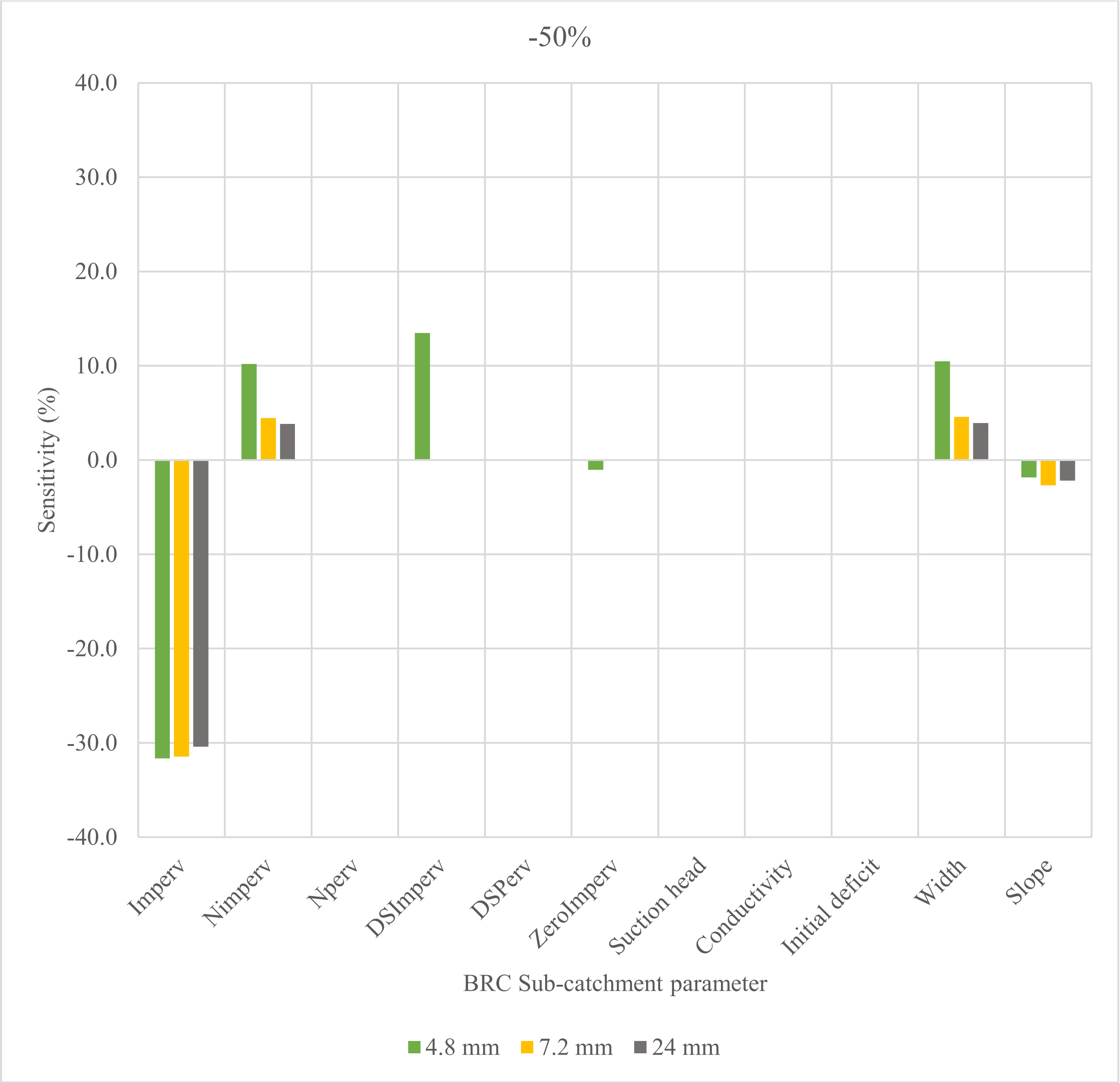


Figure 5-24: Peak flow changes with a maximum decrease of parameter values by 50% in BRC

The percentage sensitivity of the 11 sub-catchment parameters evaluated is shown in Figure 5-26 and Figure 5-27. Runoff volume was less sensitive to runoff parameter changes than peak flow for all parameters except DSImperv. Despite no change to peak flow, depression storage for impervious areas and the percentage of impervious areas with no depression storage altered the initial flow values, changing the total flow volume. As with previous studies (e.g., Krebs *et al.*, 2013; Mancipe-Munoz *et al.*, 2014; Xu *et al.*, 2019), the impervious area percentage was the most sensitive parameter. Flow volume had a relatively low response to changes in sub-catchment slope, length, and Manning's coefficient for the impervious area.

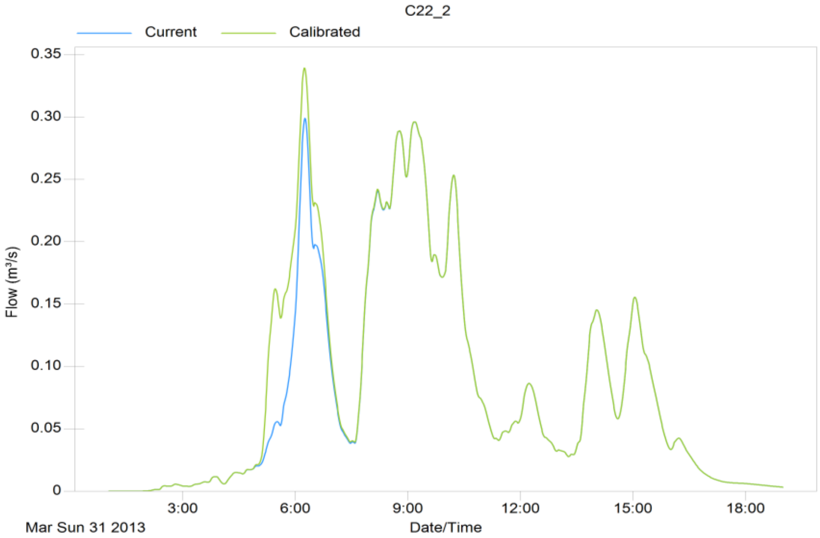


Figure 5-25: Altered hydrograph in calibrated hydrograph due to changes in DSImperv

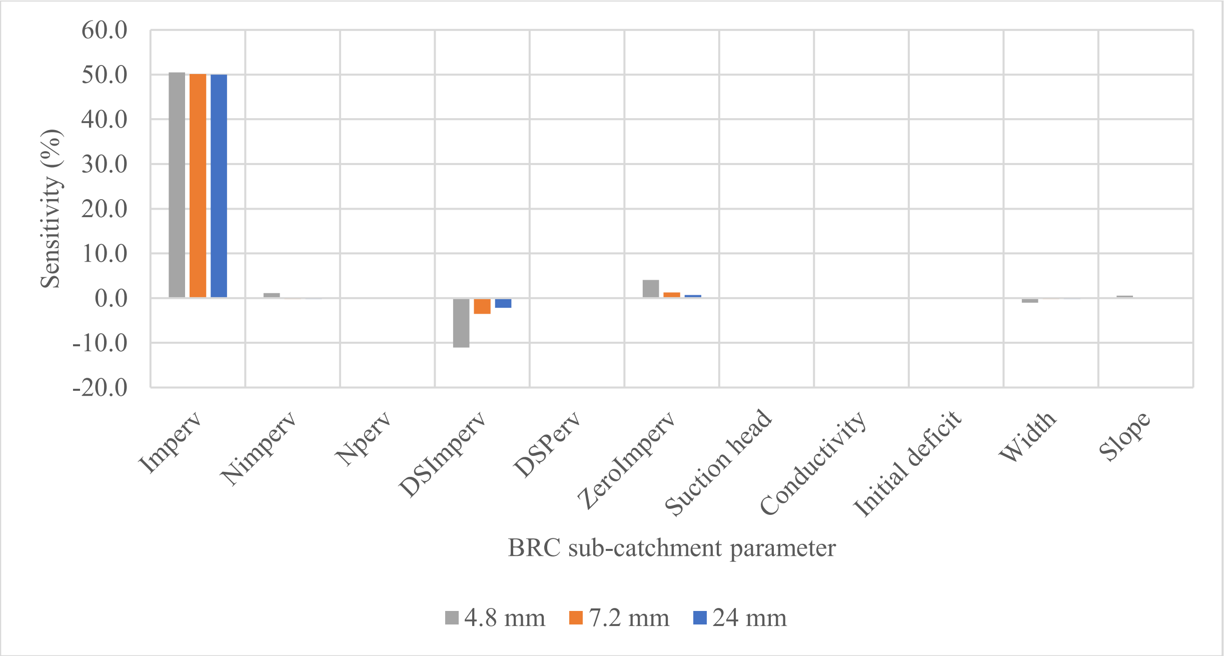


Figure 5-26: Peak volume changes with a maximum increase of parameter values by 50% (BRC)

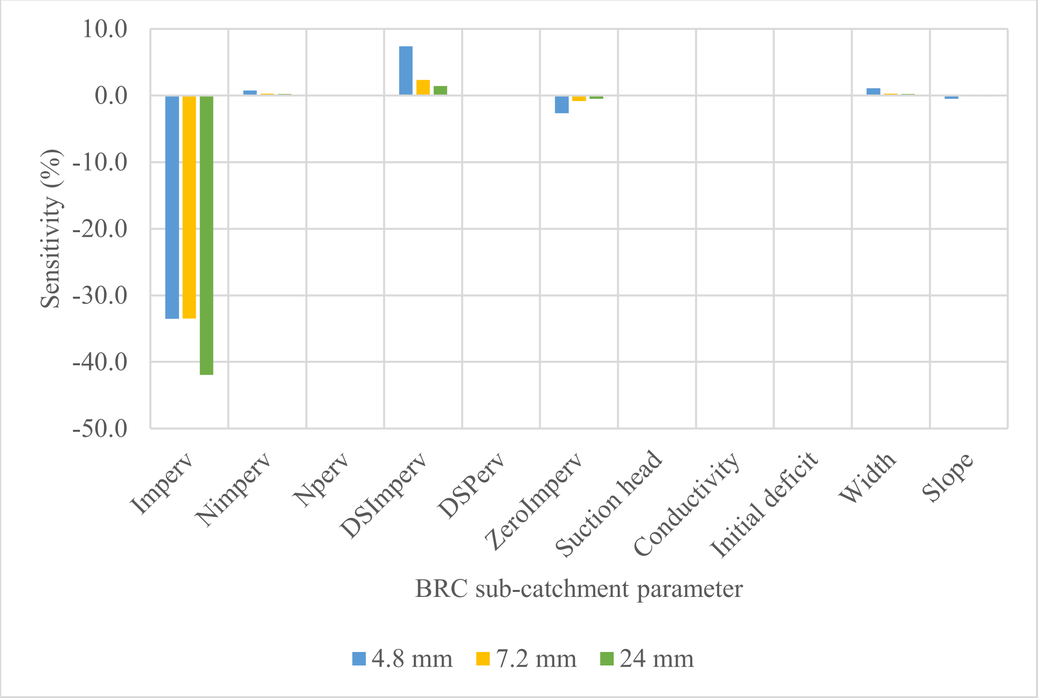


Figure 5-27: Peak volume changes with a maximum decrease of parameter values by 50% (BRC)

5.2.3.4 Calibration

Calibration is a process carried out in PCSWMM to optimise the parameters used in the model so that the simulated results best match the observed response (James & Rossman, 2010). It is an essential step in continuous hydrological modelling for developing a representative model of the study area.

The collection of observed flow data in the study area faced several obstacles. Although continuous events are shown to be more effective as they take account of initial conditions (Tan *et al*., 2008) only a limited number of observed peak flows were available for calibration. Furthermore, an independent set of data excluded during calibration is required for model validation, an extension of calibration (James, 2005) to test the optimum parameters against the field observations. The models developed in this project were not validated due to the lack of flow data to undertake validation.

Data from the Kroneberg Drive monitoring site, Site 14 (Bethelsdorp) (Figure 5-9), was used to collect flow data for calibration. The observed peak flow was 0.767 m^3/s, whereas the uncalibrated Chatty River Catchment-modelled peak flow was 0.726 m^3/s. The observed flow at the time of data collection, 20/05/2022, at 8:00 am, after the storm, was 0 m^3/s and was used to check the modelled recession limb. This was similar to the modelled Chatty River Catchment flow shown in Figure 5-28.

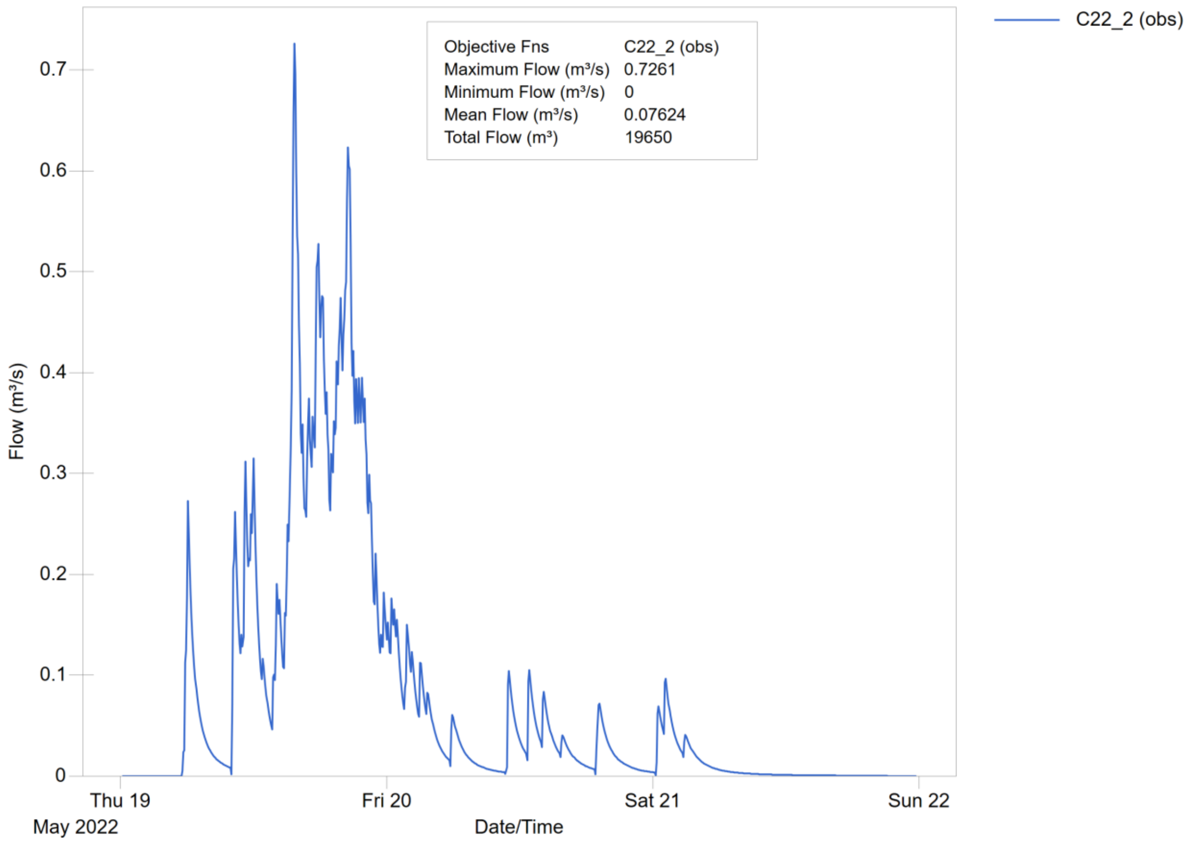


Figure 5-28: Chatty River Catchment flow time series for partial calibration (19/05/2022)

Despite having a larger scale, the CRC model had a better match with the observed peak data than the BRC model. This may indicate that a model with more complexity may not be necessary. Complexity can be measured by the number of uncertain parameters in the model. Increasing the number of parameters in a bid to obtain a more realistic model also increases the complexity and data uncertainty (Elert *et al.*, 1999). Elert *et al.* (1999) suggest that the quality of the input data is more important than the choice of model. Hence calibration is a critical step in modelling. Due to the closely related flow values and the absence of an observed continuous flow time series for calibration, the Chatty River Catchment As-Is model time series for the storm event (19/05/2022, 7.2 mm, 17.67 hrs) was chosen for the partial event-based calibration of the Bethelsdorp River Catchment As-Is model.

The parameters targeted for calibration depended on the results from the sensitivity analysis. The parameters identified to have a significant influence on peak flow and total flow volume from the sensitivity analysis were chosen for calibration. Sub-catchment area has a high sensitivity to the model, as highlighted in previous studies (Krebs *et al.*, 2016; Lindiwe *et al.*, 2019; Xu, Xiong, *et al.*, 2019). However, James (2005) states that the area is considered a parameter measured with almost total certainty hence it was excluded during calibration.

PCSWMM supports the creation of 4, 6 or 8 sensitivity points for each parameter assigned an uncertainty. Using eight sensitivity points allows for better production of nonlinear parameter sensitivities thus eight sensitivity points were simulated in the model with each point assigned a potential uncertainty range. They included the time-to-peak, peak flow, runoff volume and overall shape of the hydrograph (Tan *et al*., 2008).

The goodness-of-fit was evaluated using various error functions provided on PCSWMM, that is, the Integral Square Error (ISE), Nash-Sutcliffe efficiency (NSE) and the coefficient of determination (R^2). The error statistics were computed on the visible portion of the time series. The ISE rating varied from “Excellent” to “Poor”, NSE values ranged between $-\infty$ and 1, while R^2 ranged between 0 and 1. Finally, once calibration was complete, the verify button in the SRTC tool was used to validate the SRTC prediction.

5.2.3.5 Bethelsdorp River Catchment partial calibration

A partial calibration was undertaken due to several limitations during flow data collection, highlighted in Section 5.1.6. The six calibration parameters used for calibration were chosen from the eleven sub-catchment properties used in the sensitivity analysis carried out on PCSWMM. These were parameters to which peak flow and flow volume were sensitive. They were sub-catchment length, slope, percentage imperviousness, manning’s coefficient for the impervious area, depression storage for the impervious area and percentage impervious area with no depression storage.

The depression storage for the impervious area (DSImperv) and impervious area with no depression storage ZeroImperv were used to calibrate the flow at the initial period of the storm. In the uncalibrated model, the flow path was modelled to follow topography. However, this is not the case in an urban setting due to obstructions such as buildings and street curbs (Smith & Vidmar, 1994), which may increase the flow length. The sub-catchment width was, therefore, increased. The Manning’s coefficient for the impervious area, followed by the sub-catchment slope and finally, the percentage imperviousness parameters were altered until the goodness of fit, shown in Table 5-7 error functions, were within an acceptable range specified in Section 5.2.3.4. After the run, the verified hydrograph was slightly different from the calibrated hydrograph, as many equations used in SWMM are non-linear (Rossman & Simon, 2022). The final verified hydrograph is shown in Figure 5-29.

The goodness of fit was assessed using the Integral Square Error (ISE), Nash-Sutcliffe efficiency (NSE) and the coefficient of determination (R^2) error functions. According to Niazi *et al*. (2017), error function ratings, NSE and R^2, are typically above 0.6. Shamsi & Koran (2017) recommended an ‘Excellent’ ISE rating for final design, a ‘Good’ rating for preliminary design, and a ‘Fair’ rating for planning. Furthermore, Shamsi & Koran (2017) suggested an NSE of 0.5 – 1 as sufficient for models used in planning, preliminary design and final design. The partial calibration was therefore considered acceptable based on the error function values listed in Table 5-7.

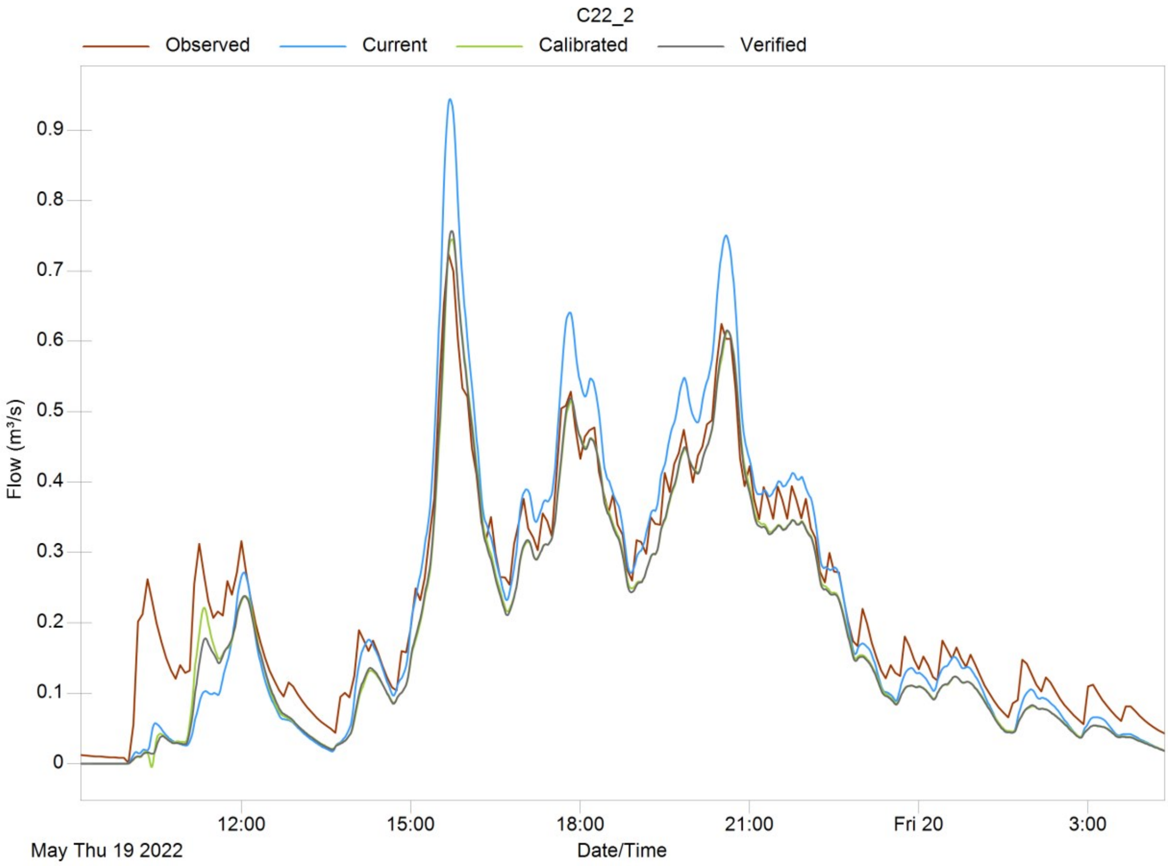


Figure 5-29: Hydrograph of observed, modelled, and calibrated flow data

Table 5-7: Error functions

Parameter	Error function	Calibrated	Validated
Runoff volume	ISE rating	Fair	Fair
	NSE	0.942	0.94
	R^2	0.979	0.979
Runoff peak	ISE rating	Fair	Fair
	NSE	0.978	0.977
	R^2	0.978	0.978
The shape of the hydrograph	ISE rating	Excellent	Excellent
	NSE	0.91	0.905
	R^2	0.937	0.933

5.2.4 Predevelopment model development

The predevelopment scenario of the Chatty River Catchment was used to estimate the hydrological patterns and pollutant loads in the catchment before urban development. The sub-catchment parameters were defined using the vegetation and soil data retrieved for the area reflecting the catchment's natural state, as described in Sections 5.1.4 and 5.1.5. Although the As-is and predevelopment models had the same drainage network length and size, several changes were made. The drainage network consisted of natural channels developed using the available DEM, as the engineered channels were converted to natural channels. As a result of development, the course of the river and its tributaries may have changed. The current shape of the river and its tributaries, adapted from satellite imagery, was used in the predevelopment model as there was very little data regarding the river and its tributaries prior to development. Due to the absence of historical flow data for calibration when the catchment was in its natural and rural state, the results obtained are only a rough estimation of flow patterns.

6. Water Quality model development

Water quality data was required to understand the extent of pollution in the Chatty River, investigate the water quality hotspots in the study area by analysing the pollutants mentioned in this section, and confirm the need for water quality mitigation measures. The water quality investigation commenced with a review of the historical and current state of the Chatty River Catchment through literature and site visits (Section 3.3). Water quality sampling and testing were subsequently undertaken to acquire experimental knowledge of the current state of the river.

6.1 Preliminary water quality sampling and testing

The first water quality sampling occasion was undertaken during the first site visit to gain a better understanding of the spatial variability of water quality in the Chatty River Catchment. It included water sample collection at eleven sites. Each sample site was chosen to represent part of the catchment. Furthermore, the sites were chosen based on the accessibility. Figure 6-1 shows the preliminary sample sites, and the numbering system indicates the route followed by the researcher.

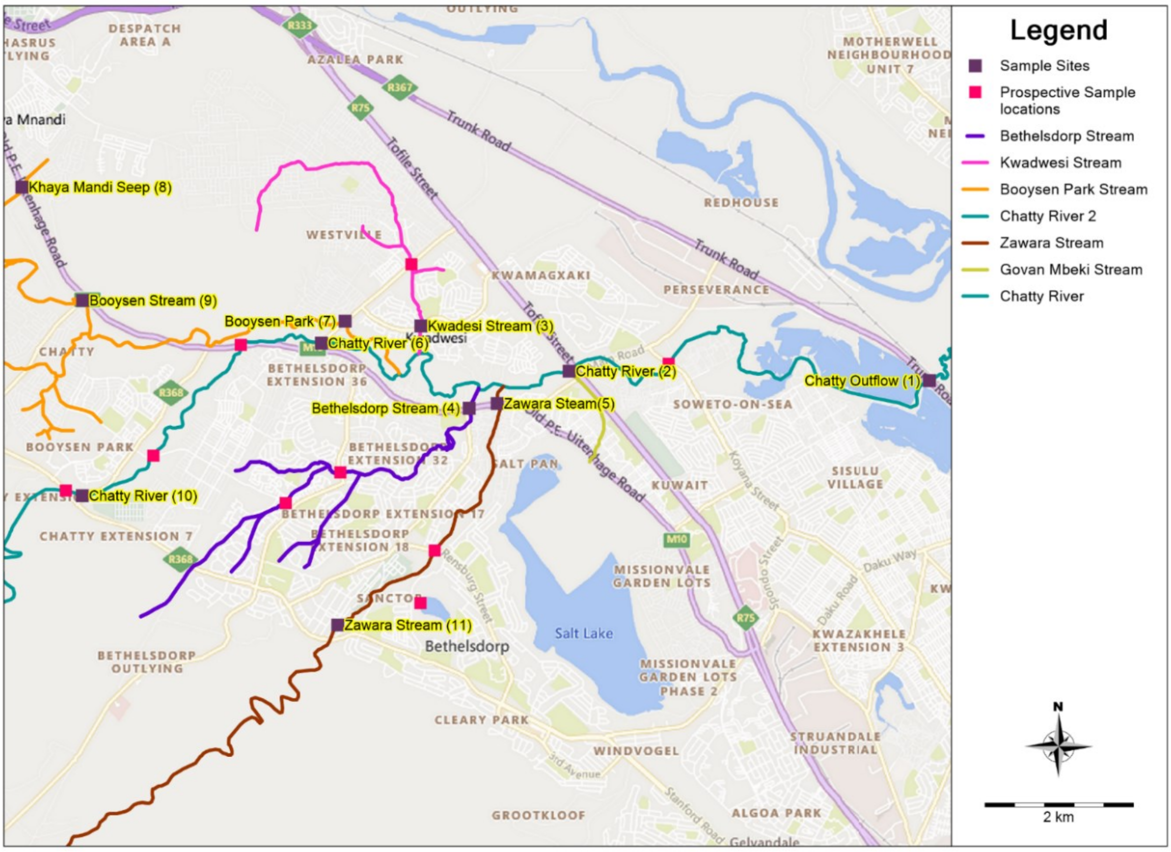


Figure 6-1: Preliminary sample sites and prospective sample sites

Insitu testing was undertaken at each site for Electrical conductivity (EC), pH, total dissolved solids (TDS) and salinity. TDS and EC readings are useful indicators of ion concentrations (DWS, 1996). Additionally, a favourable pH is essential as it determines the undertaking of biological functions such as organism metabolic processes (Matowanyika, 2010).

OHAUS handheld probes were used to measure the water quality variables (Table 6-1). The water samples were collected and measured from plastic cups due to the instabilities within the river due to flow. Each of the handheld probes was calibrated before use. The Electrical conductivity (EC) pen meter was calibrated using a calibration standard of 1413 µS/cm, while the pH pen meter was calibrated using standard buffer solutions of pH 4, 7 and 10. The pH pen was rinsed with distilled water before submerging it in the buffer solution. The total dissolved solids (TDS) pen was calibrated using a calibration standard of 147 mg L^{-1}. The salinity pen was factory calibrated. Table 6-1 lists the equipment used for sample collection and probe tests.

Table 6-1: Equipment used for sample collection and probe tests

Item	Method
pH ST20 OHAUS® handheld probe	Test the pH level in each sample
Total Dissolved Solids (TDS) ST20T-A OHAUS® handheld probe	Test the TDS level in each sample
Electrical Conductivity (EC) ST20C-B OHAUS® handheld probe	Test the EC in each sample
Salinity OHAUS® handheld probe	Test the salinity level in each sample
11 bottles and jars	Collect samples for testing
Distilled water	Rinsing pens, beakers, and jars to enable optimum results.
pH pen buffer powder (pH 4,7 and 10)	Calibrate the pH pen
Paper cups	Collect samples for measuring temperature
EC calibration fluid	Calibrate the EC pen
TDS calibration fluid	Calibrate the TDS pen
1 jar	Testing each sample
1 beaker	Mixing the pH buffer fluid
Gloves	To prevent direct contact with the polluted water
Labels	Labelling of sampling jars and plastic bottles

6.1.1 Measurement of pH

The procedure in the instruction manual (OHAUS, n.d.):

- Remove the protection cap, rinse the pH electrode glass bulb with pure water (distilled water), and wipe clean.
- Press the button (On/Off) to turn on the meter.
- Dip the electrode 2 to 3cm into the test solution (at least 20 ml). Stir and wait until the reading stabilizes.
- Clean the electrode with pure water after each measurement.

6.1.2 Measurement of salinity, TDS, and EC level

The procedure in the instruction manual (OHAUS, n.d.):

- Remove the protection cap, rinse the electrode with pure water (distilled water), and wipe clean.
- Press the button-On/Off- turn on the meter.
- Dip the electrode about 2 to 3cm into the test solution (at least 20ml)
- Wait until the reading stabilizes.
- Clean the electrode with pure water after each measurement.

The preliminary water quality testing results are presented in Appendix Preliminary testing indicated that there were relatively higher levels of pollution in the lower parts of the catchment, that is, at Site 4 (Bethelsdorp), Site 7 (Booysen), Site 3 (Kwadwesi), Site 2 (Chatty) and Site 1 (Chatty). A sampling regime was then developed.

6.2 Biweekly water quality sampling and testing

Water samples collection was organised and samples were collected biweekly between July 2021 and February 2022 with the aid of the NMU team. The testing period was thus representative of the late winter, spring, and summer seasons. The final sample collection sites were chosen based on the site's relevance, the study area's representation, and relative security and accessibility, as informed by the first site visit. The sites were named according to the tributary they were on. Figure 6-2 shows where they were located while Table 6-2 gives their coordinates. Due to concerns regarding personnel safety during sample collection and equipment operation, the study was limited to biweekly monitoring, and the assumption of diffused pollution made.

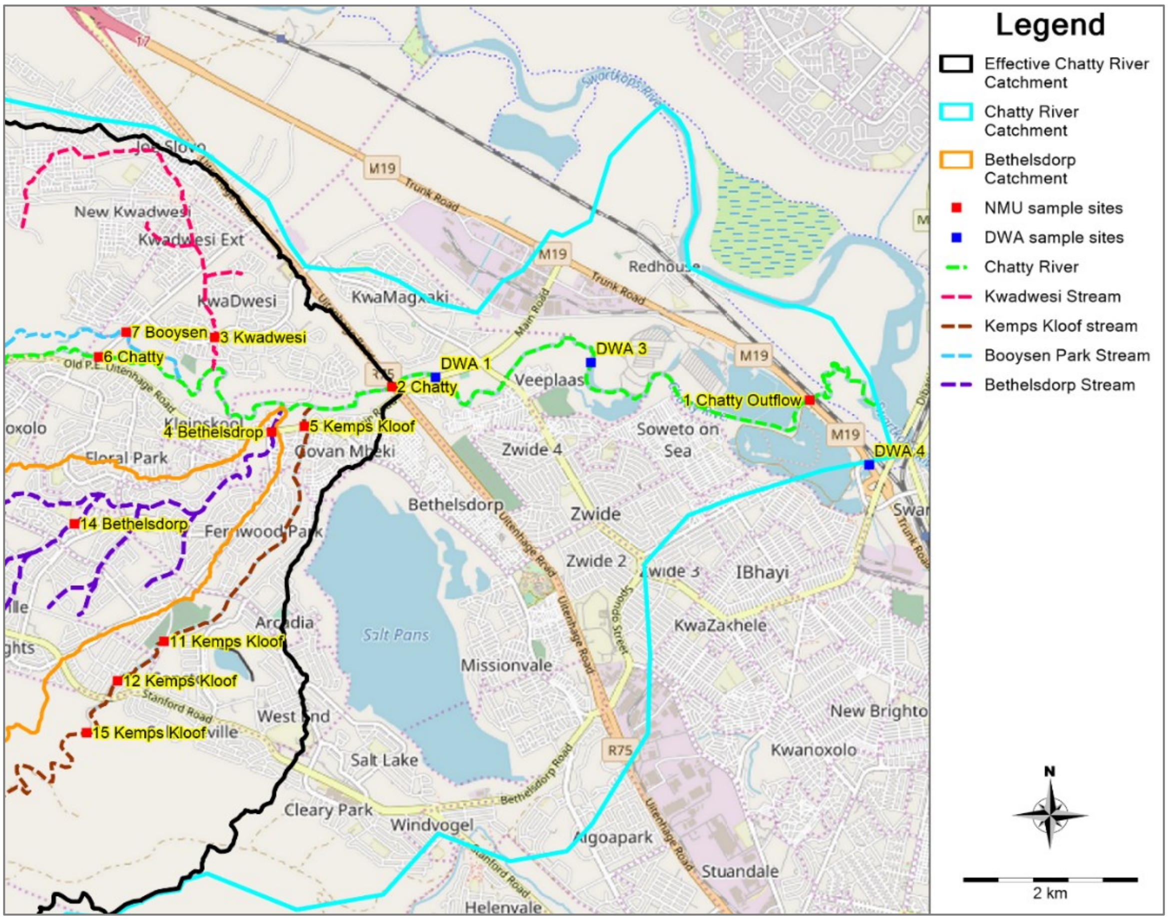


Figure 6-2: Map of the finalised water quality sites

Table 6-2: Location of NMU sample sites in the study area

Sample site	Tributary	GPS coordinates
Site 1	Chatty	33°51'11"S, 25°35'11"E
Site 2	Chatty	33°51'06"S, 25°32'05"E
Site 3	Kwadwesi	33°50'47"S, 25°30'45"E
Site 4	Bethelsdorp	33°51'23"S, 25°31'11"E
Site 5	Kemps Kloof	33°51'21"S, 25°31'26"E
Site 6	Chatty	33°50'54"S, 25°29'54"E
Site 7	Booysen Park	33°50'45"S, 25°30'06"E
Site 10	Chatty	33°52'00"S, 25°27'48"E
Site 11	Kemps Kloof	33°52'42"S, 25°30'23"E
Site 12	Kemps Kloof	33°52'57"S, 25°30'04"E
Site 14	Bethelsdorp	33°51'57"S, 25°29'43"E
Site 15	Kemps Kloof	33°53'16"S, 25°29'49"E

6.2.1 Sampling and testing procedures

A YSI ProDSS Multiparameter Digital Water Quality Meter was used to measure temperature, pH, salinity, turbidity, electric conductivity (EC) and dissolved oxygen (DO) on-site by the NMU research team. Two grab samples were taken from each site during each site visit. One sample was delivered to a registered water quality laboratory for *Escherichia coli* (E. *coli*) for tests. The South African Environmental Observation Network (SAEON) a research facility of the National Research Foundation (NRF) analysed the second sample for inorganic nutrients (i.e., phosphates, nitrites, nitrates, and ammonium) and the NMU research team for total suspended solids (TSS). The datasets are in Appendix A.2.

Microsoft Excel was used to analyse the water quality results and produce time-series graphs. The Target Water Quality Range (TWQR) for aquatic systems and recreation, where applicable, was used to analyse possible risks associated with the extent of pollution in the Chatty River Catchment. Spatial and seasonal variations are also discussed in this chapter.

Figure 6-3: Calibration and in situ testing using the YSI ProDSS Multiparameter Digital Water Quality Meter

6.2.2 Nutrient analysis from sampling

6.2.2.1 Dissolved Inorganic Nitrogen (DIN)

Dissolved inorganic nitrogen (DIN), the sum of the Nitrate (NO_3), Nitrite (NO_2), and ammonium (NH_4) concentrations, measured by SAEON, fell within the eutrophic and hypertrophic range as indicated in the aquatic ecosystem guide by the DWS (1996). This range of values results in a low level of species diversity and potentially the growth of blue-green algae (DWS, 1996). Table 6-3 shows the lowest to highest DIN-polluted sample sites based on the mean concentration. The test results highlighted in Table 6-3 and Figure 6-4 indicate that sections of the stream are highly enriched, above 2.5 mg L^{-1} (DWS, 1996).

Table 6-3: Spatial comparison of DIN concentration using mean

NMU sample site	Tributary	Mean (mg L^{-1})
Site 7	Booysen Park	5.57 ± 5.03
Site 6	Chatty	2.89 ± 1.34
Site 1	Chatty	2.73 ± 1.41
Site 5	Kemps Kloof	2.45 ± 0.67
Site 3	Kwadwesi	2.33 ± 0.61
Site 2	Chatty	2.31 ± 0.62
Site 4	Bethelsdorp	2.28 ± 0.72
Site 10	Chatty	2.23 ± 0.4
Site 12	Kemps Kloof	2.18 ± 0.66
Site 14	Bethelsdorp	2.17 ± 0.86
Site 11	Kemps Kloof	2.11 ±0 .53
Site 15	Kemps Kloof	2.02 ± 0.82

The water quality at Site 7 (Booysen Park), Site 6 (Chatty), and Site 1 (Chatty Outflow) had the highest DIN concentrations (Figure 6-4). This indicates a possible pattern and aggregation of nutrients in the system, upstream to downstream, along the Bethelsdorp stream.

There is a reduction in DIN concentration along the Kemps Kloof stream, that is, from Site 12 to Site 11. This may be attributed to the natural wetland found between the two sites.

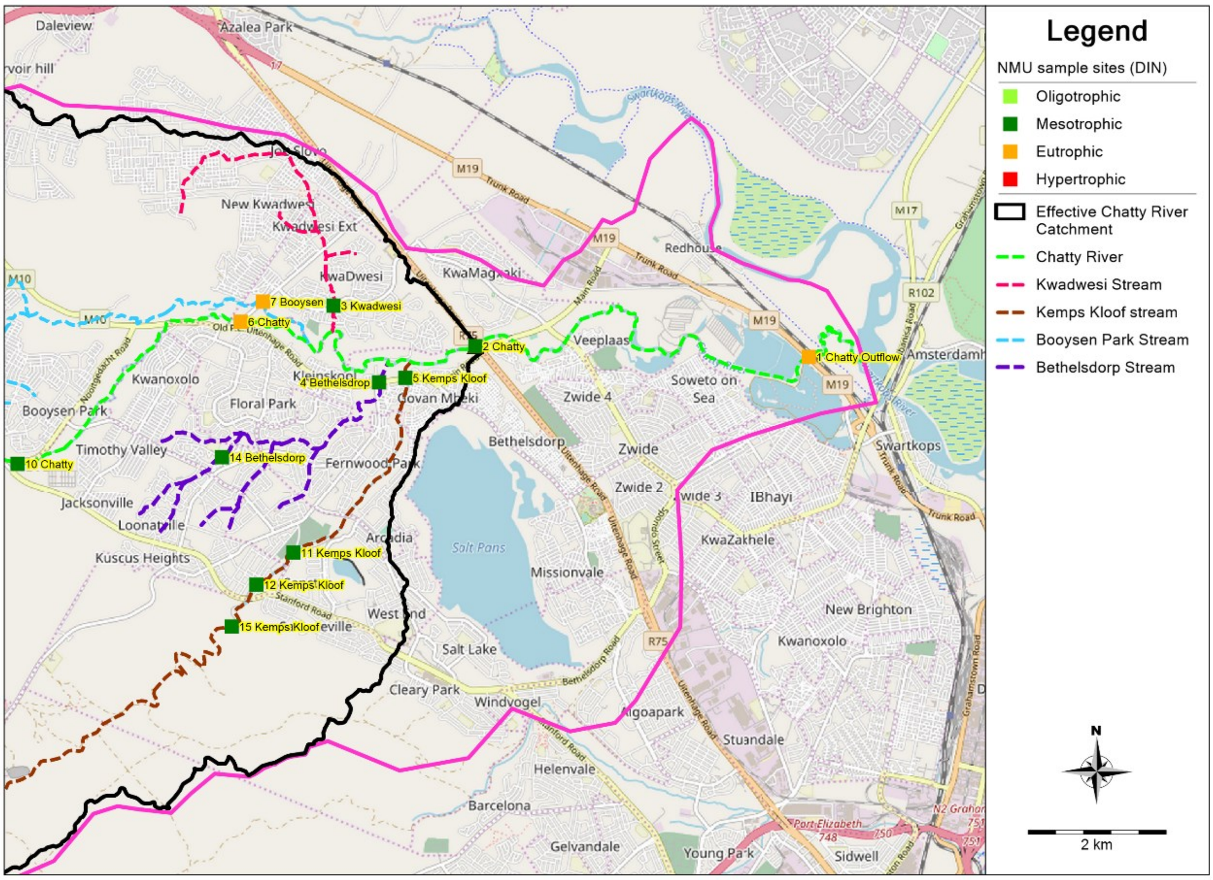


Figure 6-4: Spatial variation of mean DIN concentration at the NMU sample sites

Figure 6-5: Cattle grazing in the open space downstream of Site 4 (Bethelsdorp)

As suggested by Figure 6-4, there is a risk of eutrophic conditions in the drainage network. During the site visits, cattle grazing was seen taking place in the open spaces surrounding Site 4, Site 5, and Site 7 as shown in Figure 6-5. The animal excrement may have increased the risk of DIN pollution build-up (DWS, 1996). Figure 6-6 further highlights the spatial variation of DIN at the sample sites. As shown in Figure 6-7, DIN concentration measurements were higher in summer than in spring and winter.

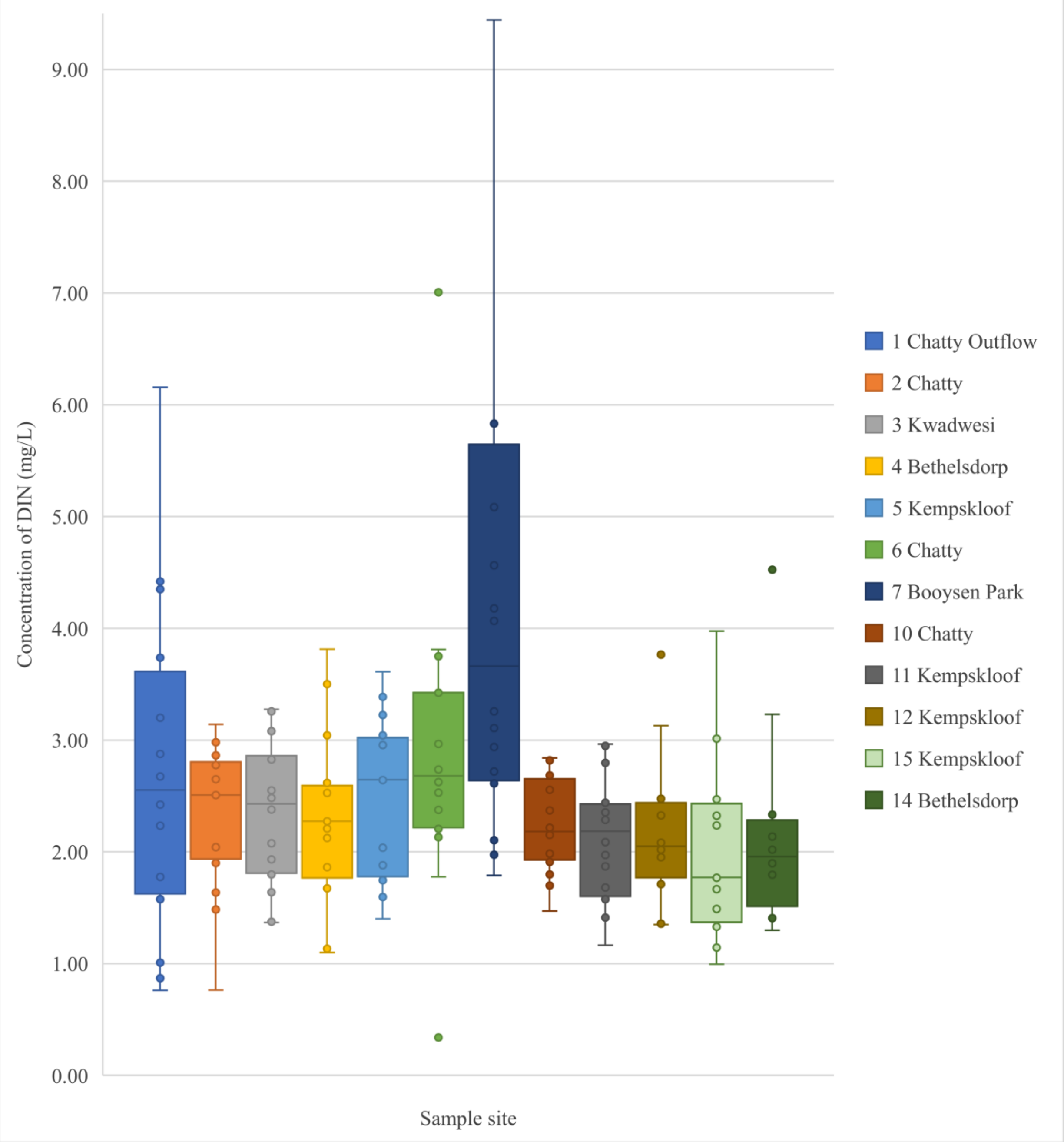


Figure 6-6: Variations in the DIN concentration (mg L^{-1}) at different locations

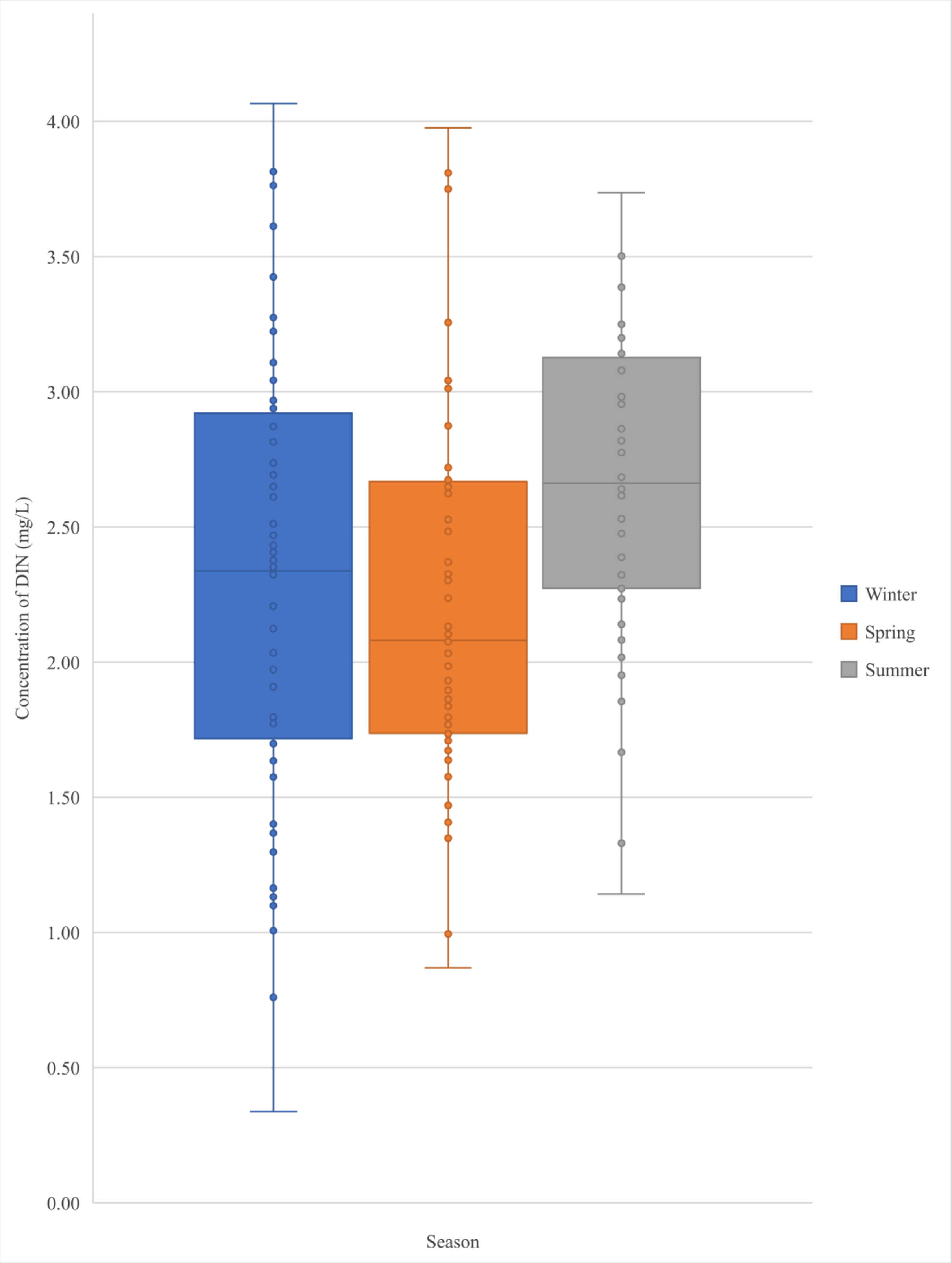


Figure 6-7: Seasonal variation of DIN from all sites (mg L^{-1})

6.2.2.2 Dissolved Inorganic Phosphorus (DIP)

The high levels of measured orthophosphate concentrations (equates to dissolved inorganic phosphorus, i.e., DIP) may be attributed to the untreated domestic waste from residents using the bucket system and agricultural activity observed in the study area. While the municipality significantly reduced the bucket system in 2017, it is still used in the Chatty River Catchment (NMBM Integrated Development Plan, 2018). The agricultural activity involves using fertilizers that may flow into the river system through runoff and faeces from animals grazing in the open spaces.

Table 6-4: Spatial comparison of DIP mean concentration

NMU sample site	Tributary	Mean (mg L^{-1})
Site 5	Kemps Kloof	0.64 ± 0.23
Site 4	Bethelsdorp	0.61 ± 0.31
Site 3	Kwadwesi	0.57 ± 0.14
Site 2	Chatty	0.56 ± 0.19
Site 6	Chatty	0.45 ± 0.19
Site 1	Chatty	0.44 ± 0.17
Site 11	Kemps Kloof	0.38 ± 0.11
Site 7	Booysen Park	0.31 ± 0.15
Site 15	Kemps Kloof	0.20 ± 0.15
Site 12	Kemps Kloof	0.14 ± 0.13
Site 14	Bethelsdorp	0.08 ± 0.13
Site 10	Chatty	0.02 ± 0.01

There was an increase in DIP concentrations in the downstream direction in the Chatty River and its tributaries; however, there were points where this pattern changed for example, at Site 1 (Chatty) and Site 12 (Kemps Kloof) where there was a decrease in DIP concentration compared to the corresponding sites immediately upstream. The highest levels of DIP mean concentration were at Site 5 (Kemps Kloof) and Site 4 (Bethelsdorp). As mentioned in the previous section, animal excrement may be contributing to the nutrient concentration levels at these locations. Additionally, at Site 4 (Bethelsdorp), an overflowing manhole was observed upstream of the sample site. The drainage network is at a high risk of hypertrophic and eutrophic conditions (Figure 6-8).

The concentrations of DIP and their respective means and medians reduce from winter to spring and finally summer. In summer, the mean DIP concentrations were greater than 0.25 mg L^{-1} indicating hypertrophic conditions in the river network with a potential to cause nuisance growth of aquatic plants and blooms of blue-green algae (DWS, 1996).

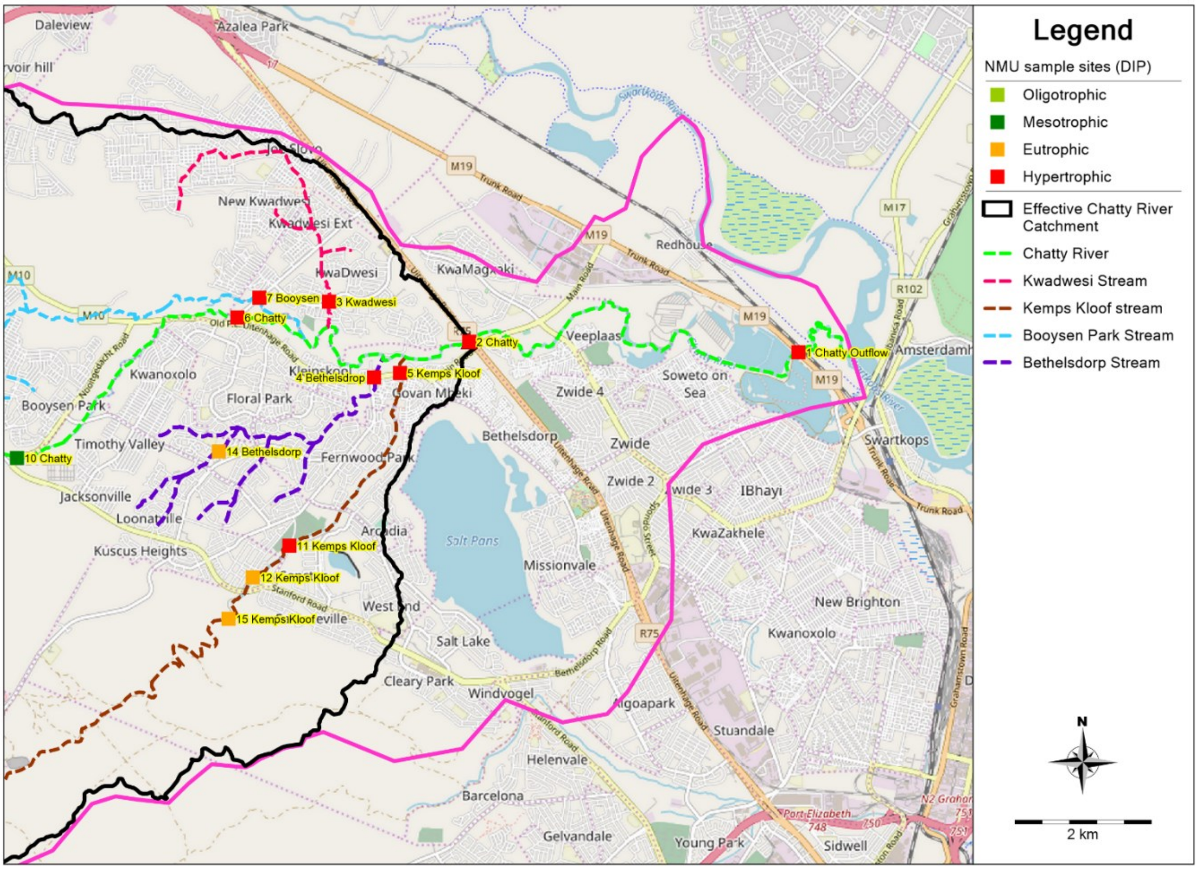


Figure 6-8: Spatial variation of mean DIP concentration at the NMU sample sites

Figure 6-9: Damaged manhole

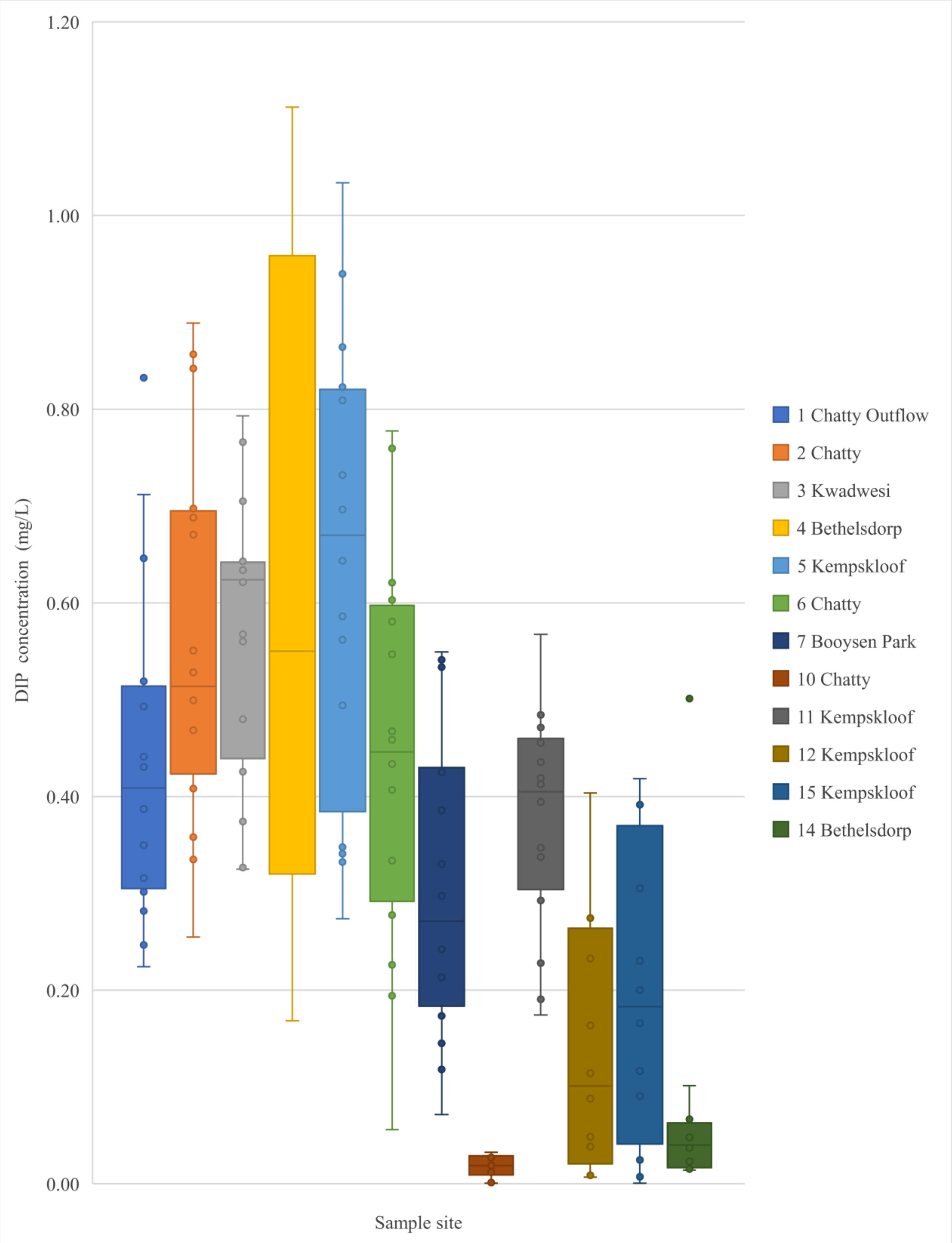


Figure 6-10: Variations in the DIP concentration (mg L^{-1}) at different locations

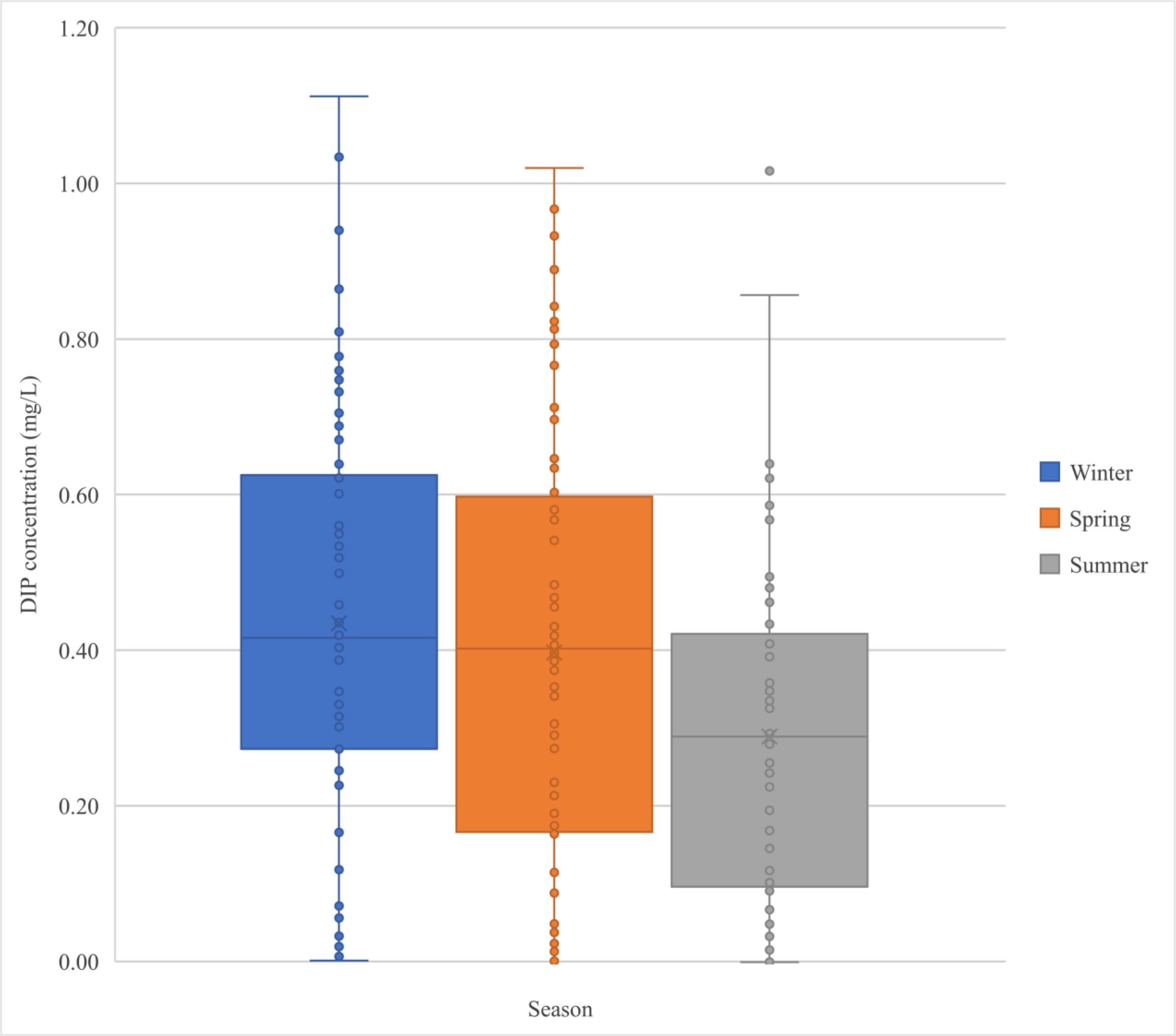


Figure 6-11: Seasonal variation of DIP from all sites (mg L^{-1})

6.2.3 Physical characteristics from sampling

6.2.3.1 Total suspended solids

TSS levels in a stream increase due to wind and rain erosion of soil particles. In the study area, it may be exacerbated by overgrazing in open spaces and reduced riparian vegetation leading to an increased erosion rate. Furthermore, the mining of aggregate in the upper reaches of the Chatty River, unregulated discharge of domestic sewage, and dumping of construction debris at various locations within the study area (Figure 6-13) may further contribute to the raised TSS. Ideally, all TSS values should be below the Target Water Quality Range (TWQR) for aquatic systems of 100 mg L^{-1}; however, the test results presented in Appendix NMU sample results highlight that Site 7, Site 1 and Site 4 were all above the desired threshold.

Table 6-5: Spatial comparison of TSS mean concentration

NMU sample site	Tributary	Mean (mg L^{-1})
Site 4	Bethelsdorp	87.66 ± 84.59
Site 1	Chatty	73.54 ± 58.65
Site 7	Booysen Park	55.27 ± 25.61
Site 3	Kwadwesi	29.36 ± 15.11
Site 10	Chatty	25.21 ± 25.65
Site 2	Chatty	19.16 ± 10.07
Site 12	Kemps Kloof	17.35 ± 8.12
Site 5	Kemps Kloof	16.86 ± 13.84
Site 15	Kemps Kloof	15.77 ± 7.44
Site 14	Bethelsdorp	14.35 ± 6.64
Site 6	Chatty	14.23 ± 8.46
Site 11	Kemps Kloof	12.75 ± 6.61

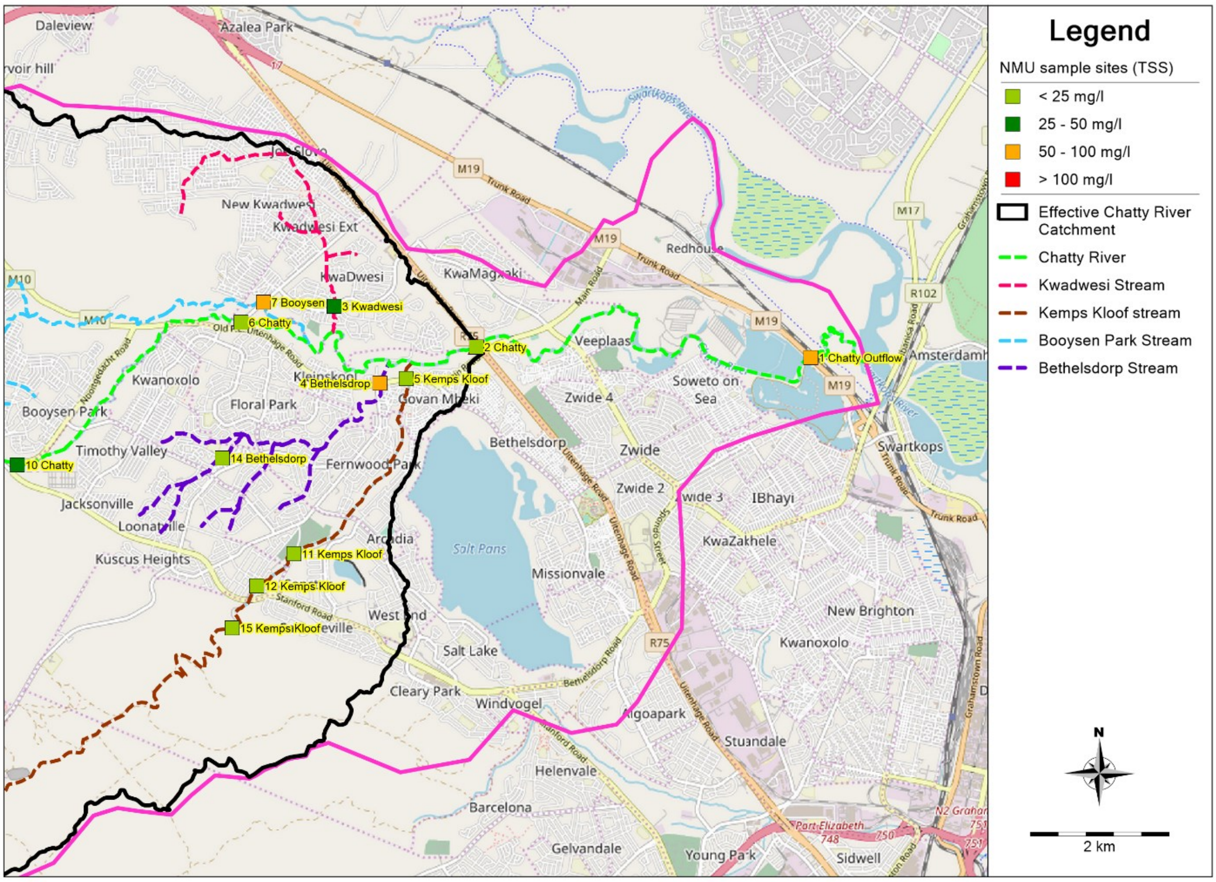
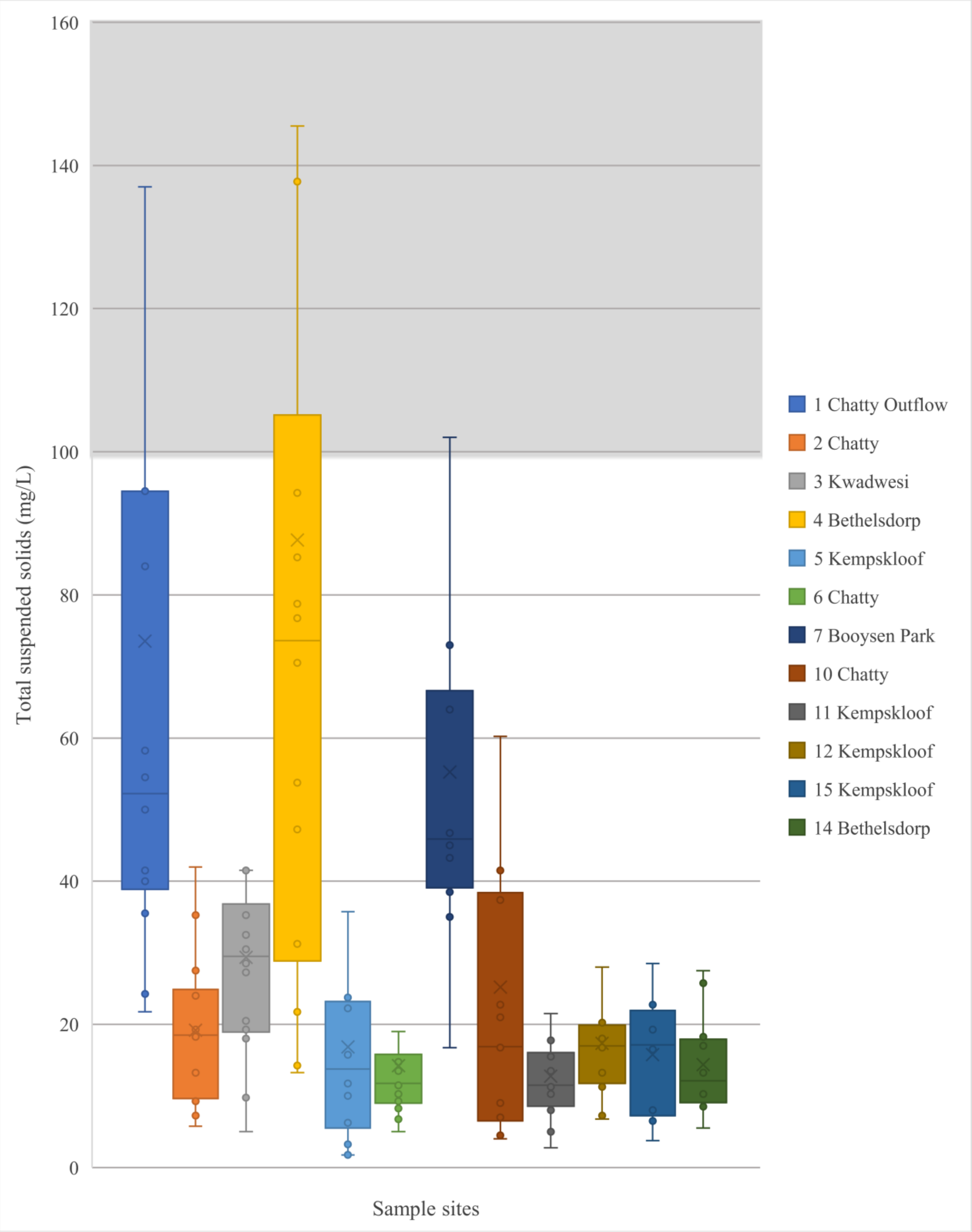


Figure 6-12: Spatial variation of TSS mean concentration at the NMU sample sites

Figure 6-13: Litter and debris beside and inside sample site (11) Kemps Kloof

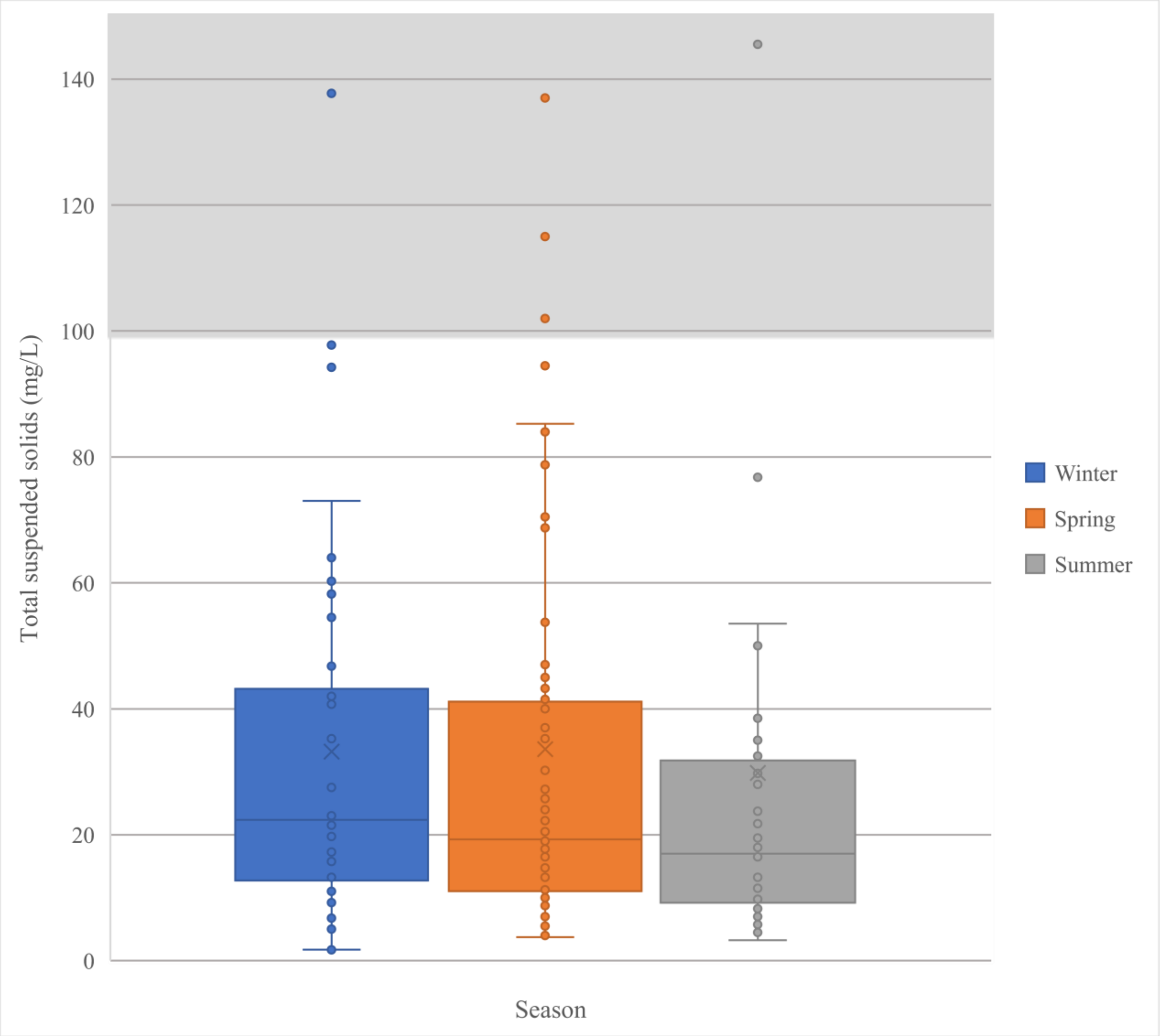
Site 4 (Bethelsdorp) had the highest TSS mean concentration which may be caused by the overflowing manhole upstream. The mean salinity measurements were highest at Site 1 (Chatty Outflow), 6.67 ± 4.00 ppt, indicating that the TSS concentration may be attributed to the marine water that flows into the river during high tides.

A TSS and turbidity (Appendix NMU sample results correlation was not established. This may have been because TSS was tested from the collected samples while turbidity was tested in situ. Turbidity is determined by particles' size, shape, and refractive index (DWS, 1996). As highlighted in Figure 6-15, the TSS pollution was greater in winter than in summer.



*Grey bands represent background TWQR of TSS in aquatic ecosystems

Figure 6-14: Variations in the TSS concentration (mg L^{-1}) at different locations



*Grey bands represent background TWQR of TSS in aquatic ecosystems

Figure 6-15: Seasonal variation in the TSS (mg L^{-1}) concentrations

6.2.3.2 Dissolved oxygen and salinity

The dissolved oxygen (DO) concentration on the site was measured as a percentage of the saturation concentration. The results (Figure 6-18) indicate continuous exposure to concentrations of less than 80% of saturation which could have adverse effects on aquatic life (DWS, 1996). Other sites, such as Site 14 (Bethelsdorp) and Site 1 (Chatty Outflow), consistently had measurements of supersaturation – above 100% - indicating possible eutrophication and dense vegetation in the water which was shown in Figure 6-16 and Figure 6-17.

Figure 6-16: Overgrown channel and illegal litter dumping at Site 14 (Bethelsdorp) (September 2022)

Figure 6-17: Channel with dense vegetation at Site 1 (Chatty Outflow) (20th October 2021)

Site 1 (Chatty Outflow) had the highest salinity levels, as shown in Figure 6-19. This is likely due to the salty marine water from the estuary. The complete dataset can be found in Appendix NMU sample results

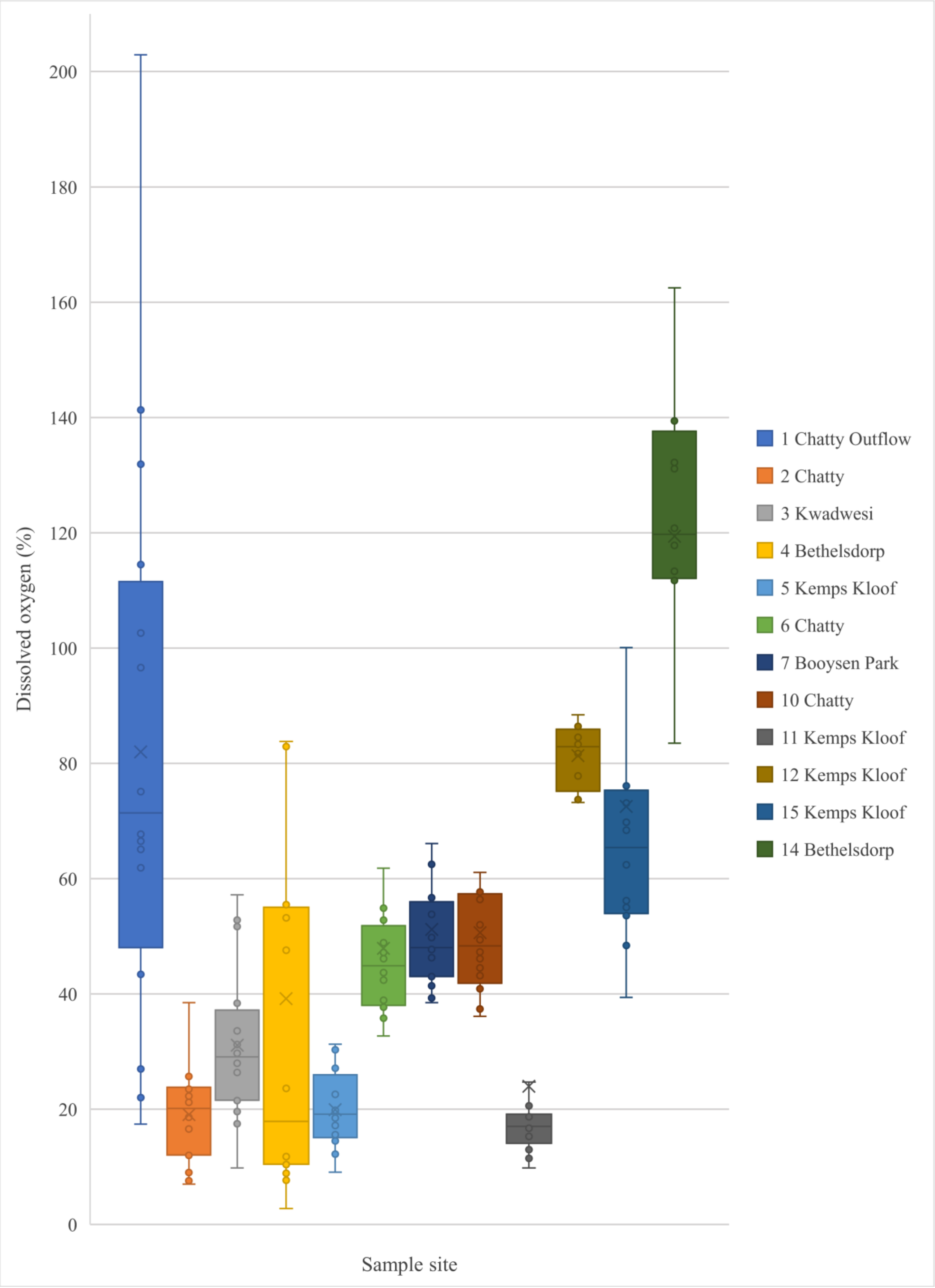


Figure 6-18: Spatial variation of DO (%)

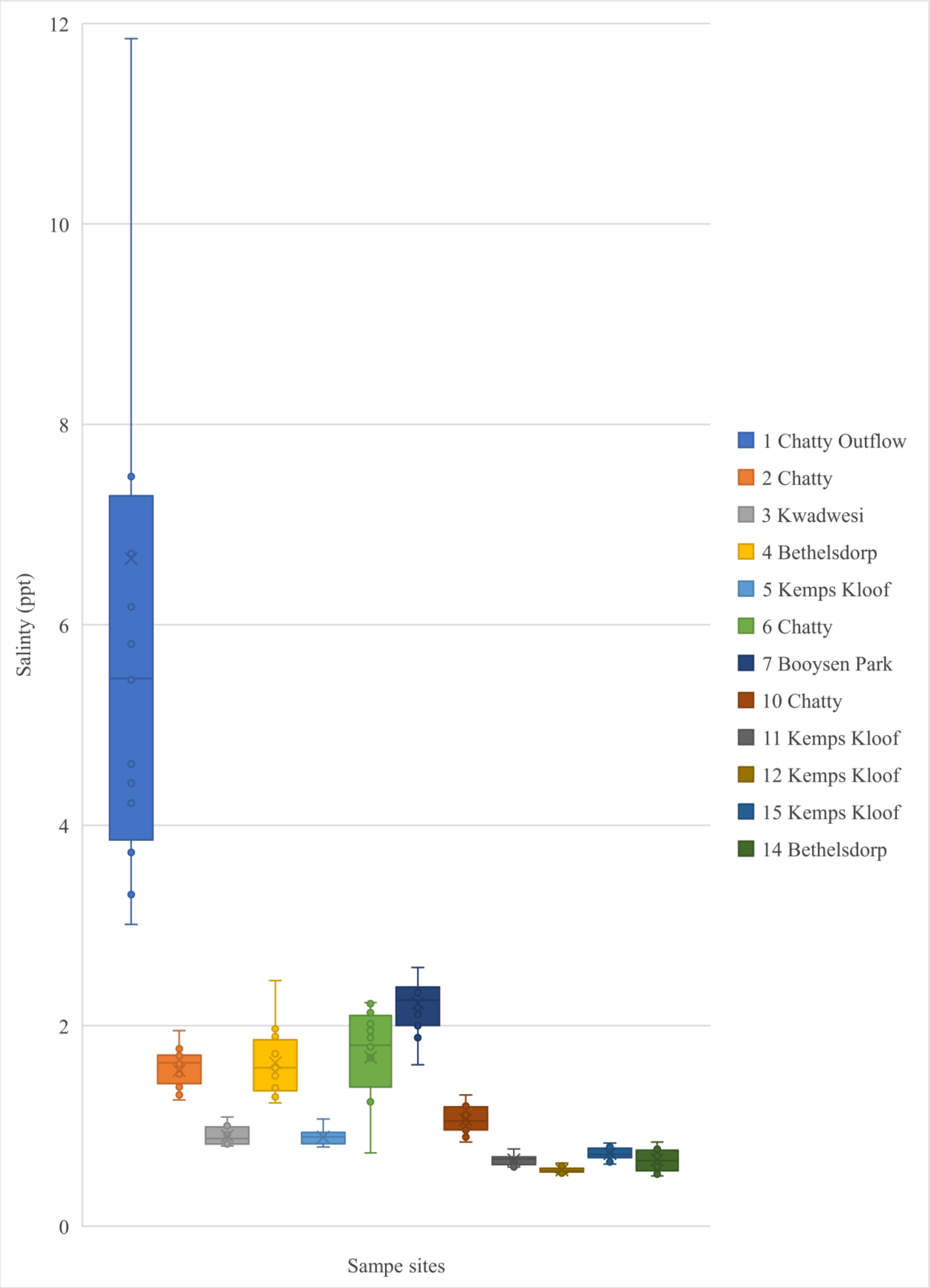


Figure 6-19: Spatial variation of salinity in the study area

6.2.4 Microbiological analysis from sampling

Escherichia coli (E. *coli*) concentrations in the study area varied substantially as shown in Table 6-6. Site 15 (Kemps Kloof), the furthest site from the Swartkops Estuary, in the Van Der Kemps Kloof reserve, had the lowest concentration of E. *coli* contamination. There was an inconsistent increase of *E. coli* upstream to downstream of the river and its tributaries indicating point pollution, for example, at Site 11 (Kemps Kloof). The high concentration recorded at Site 4 (Bethelsdorp) may be attributed to the overflowing manhole upstream of the sample site shown in Figure 6-9. The continued use of the bucket system, the growing informal settlements, and other unreported issues may cause the varied E. *coli* concentrations along the river network.

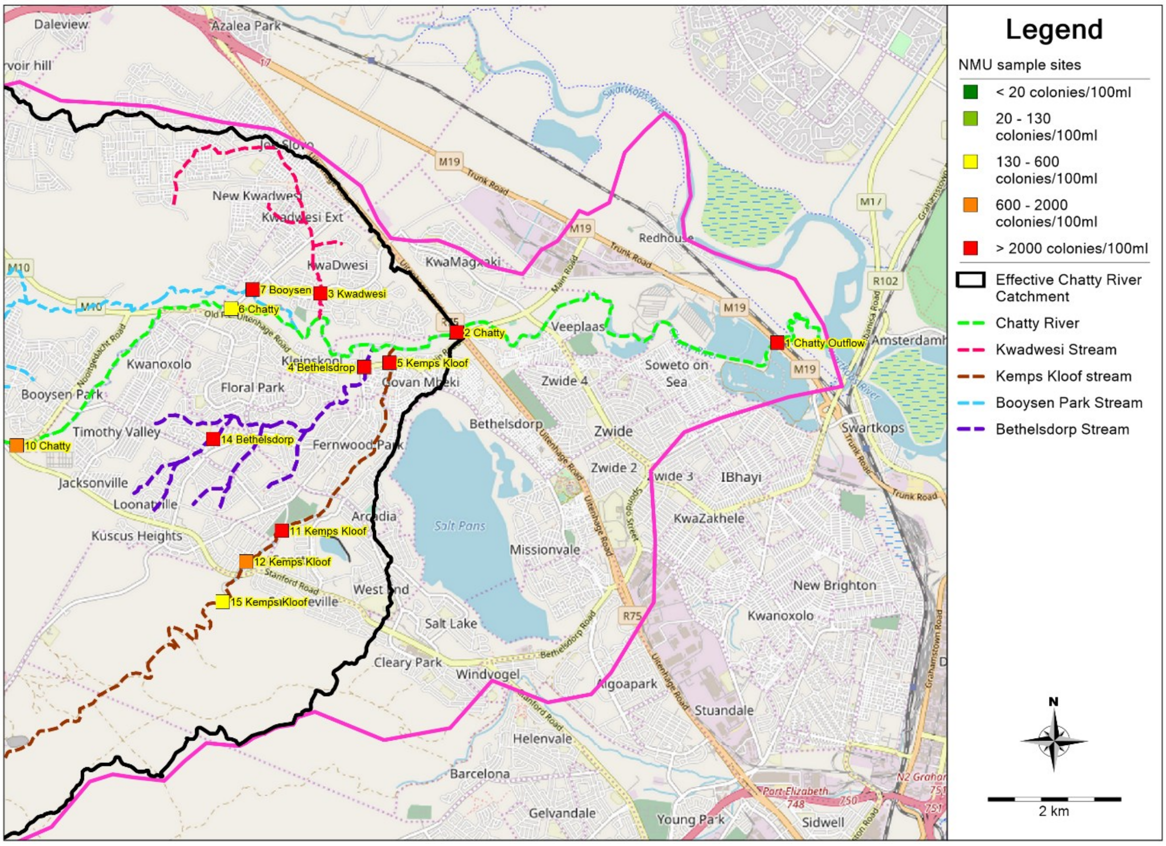


Figure 6-20: Spatial variation of E. *coli* in the study area

Despite the high concentration of faecal coliforms in the river network, residents were seen fetching water for domestic use on several occasions at Site 12 (Kemps Kloof) (Figure 6-21). The highest TWQR for recreational use is 2000 counts/100 mL, while that for domestic use is 20 counts/100 mL. Values above these limits suggest the water poses a risk of waterborne diseases such as cholera, dysentery, and gastroenteritis if ingested by residents. However, most sites measured *E. coli* concentrations above these limits.

Figure 6-20 illustrates the variable risk of noticeable gastrointestinal health effects to the residents in the catchment due to mean E.*coli* concentration levels greater than 2000 colonies/ 100 mL. Seasonal variation was not assessed as the results were limited to 2000 colonies/ 100 mL during the winter period. This was corrected for future sample dates.

Table 6-6: Spatial comparison of E. *coli* mean concentration

NMU sample site	Tributary	Mean (colonies/100 mL)
4	Bethelsdorp	11×10^6
3	Kwadwesi	6.2×10^6
11	Kemps Kloof	5.3×10^6
2	Chatty	50×10^4
7	Booysen Park	16×10^4
5	Kemps Kloof	66×10^3
14	Bethelsdorp	2500
1	Chatty	2200
12	Kemps Kloof	840
10	Chatty	760
6	Chatty	480
15	Kemps Kloof	240

Figure 6-21: Residents fetching water at Site 12 (Kemps Kloof)

6.3 Long-term water quality data

Water quality data was collected by The Department of Water and Sanitation, DWS, from 2010 to 2019 at various times throughout each year. The sample sites (Figure 6-22 and Table 6-7), were downstream of the NMU sample sites. Draining into the drainage network from DWA 1 to DWA 3 is Soweto on the Sea, a low-income suburb in the Chatty River Catchment.

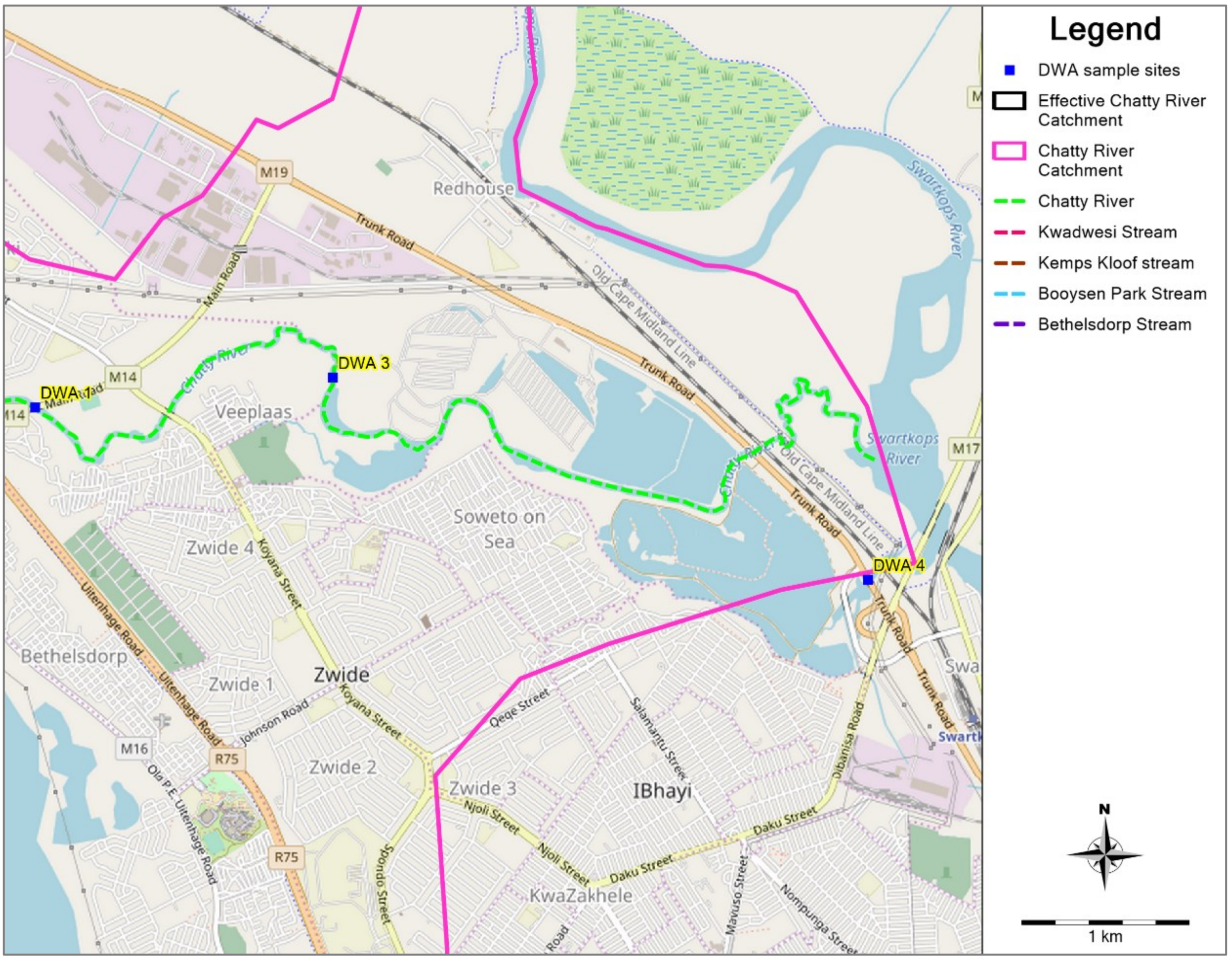


Figure 6-22: DWS sample sites

Table 6-7: Location of DWS sample sites analysed in this study

Sample site	GPS coordinates
DWA 1	33°50'58"S, 25°33'33"E
DWA 3	33°51'03"S, 25°32'25"E

The variables measured in the dataset were Chemical Oxygen Demand (COD), E. *coli*, EC, Faecal coliform, ammonia, ammonium, nitrates, nitrites, orthophosphates, and pH. DWS conducted water sample testing from 2013 – 2019 at the sites. The frequency of sample collection varied from 1 to 8 times a year.

6.3.1 Nutrient analysis

The DIN concentration increased downstream from DWA 1 to DWA 3, with a mean concentration of 3.6 ± 2.9 mgL^{-1} and 6.0 ± 3.9 mgL^{-1} respectively. These results fall within the eutrophic range of 2.5 – 10 mgL^{-1}, stipulated in the '*South African Water Quality Guidelines for Aquatic Ecosystems'* (DWS, 1996). Although the mean concentrations lie within the eutrophic range, some DIN concentrations signalled the risk of hypertrophic conditions, that is, above 10 mg L^{-1}.

The mean DIP concentration increased from DWA 1 (1.3 ± 1.01 mg L^{-1}) to DWA 3 (1.6 ± 1.3 mg L^{-1}). The mean concentration at both sites, that is, greater than 0.25 mg L^{-1}, indicate hypertrophic conditions due to phosphorus. Furthermore, the majority of the sample results lie above the hypertrophic range.

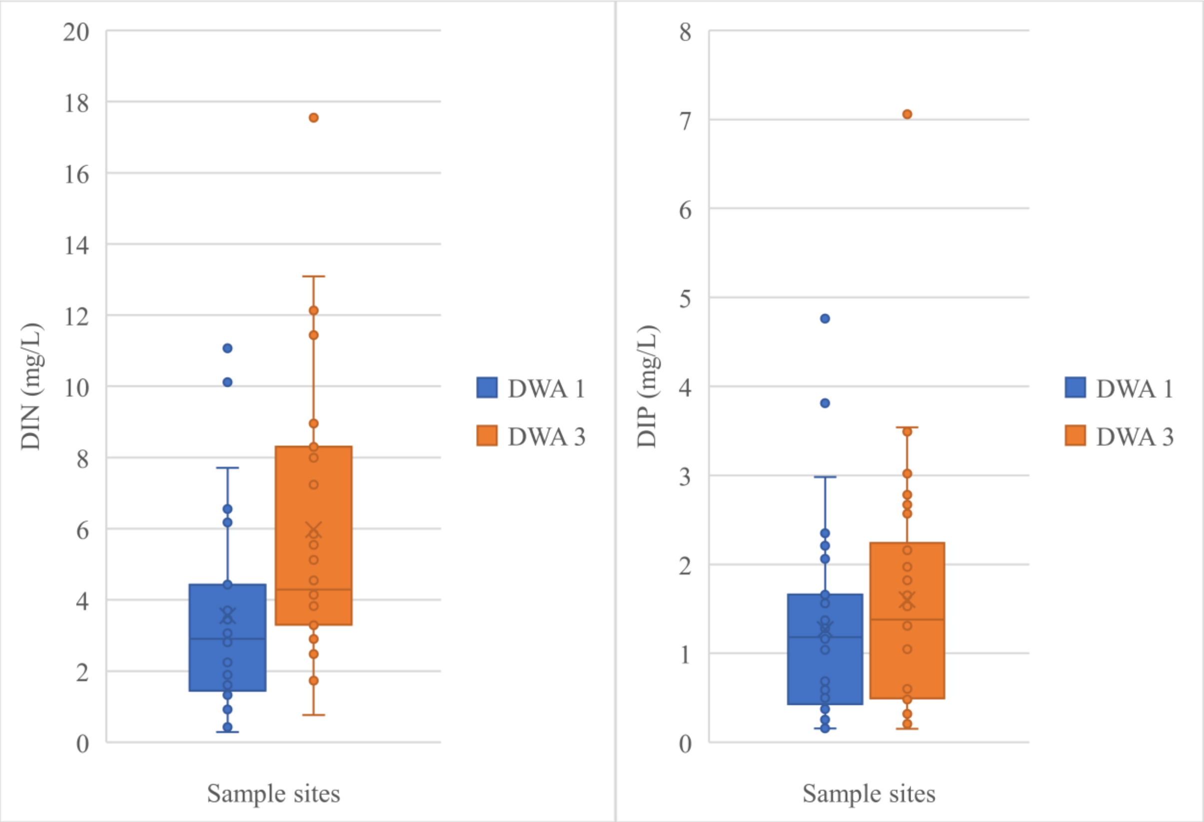


Figure 6-23: Concentration of nutrients at DWS sample sites

6.3.2 Microbiological analysis

The mean concentration of E. *coli* increased downstream from DWA 1 (7340 cfu/100 mL) to DWA 3 (16400 cfu/100 mL). As with the rest of the catchment, this suggests that raw sewage might be discharging into the river network due to the bucket system or overflowing manholes.

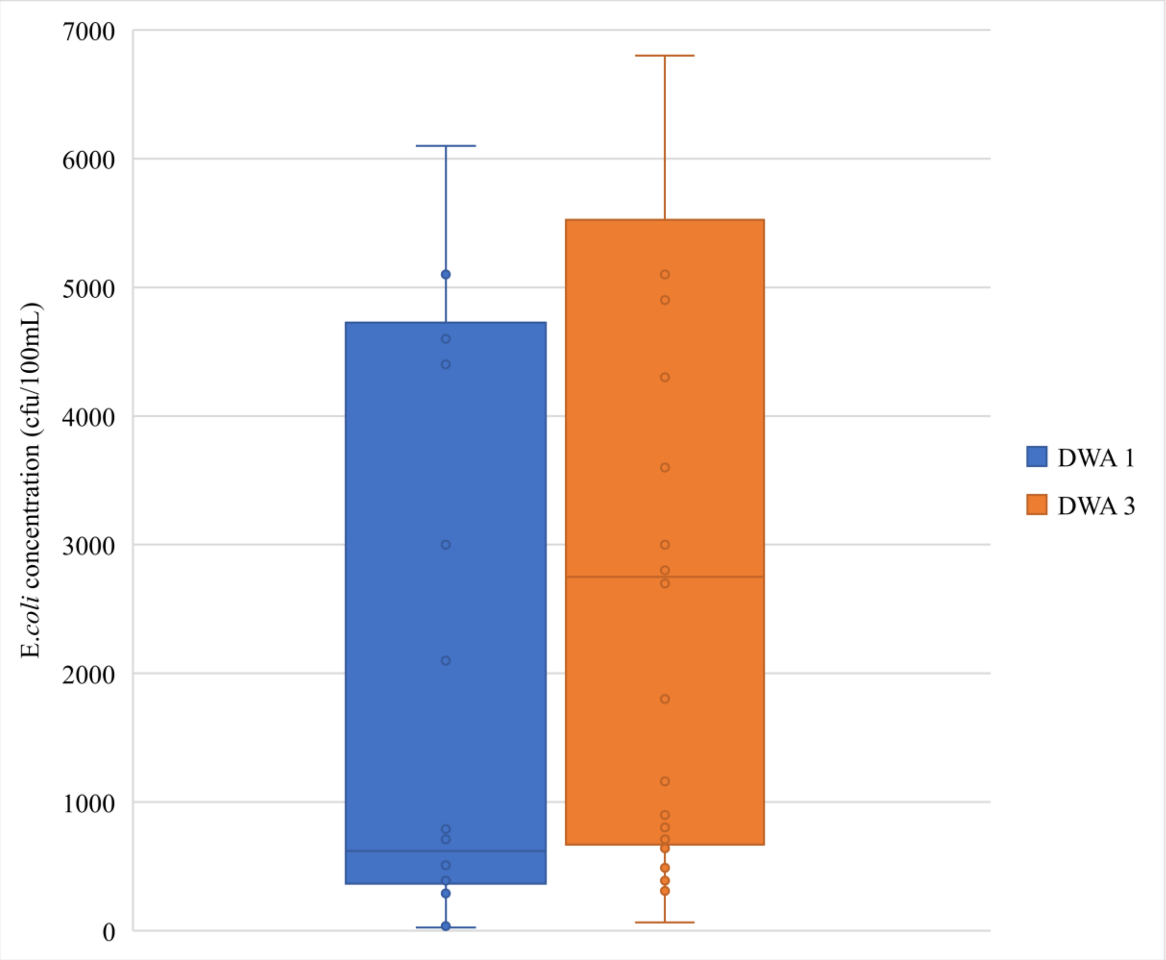


Figure 6-24: Concentration of E. *coli* at DWS sample sites

6.4 Event Mean Concentration estimation for the model

Stormwater runoff from urban areas, specifically impermeable surfaces, can contain significant concentrations of pollutants and be a crucial contributor to pollution levels in rivers and streams (Rossman & Huber, 2016b; Turpie *et al*., 2017). This project aimed to estimate the sediment and nutrient loads, subsequently assessing the impact of SuDS on water quality. Water quality modelling results were needed to compare the relative effects of change in the SuDS scenario models. A water quality component was, therefore, essential in the model. The simulation of runoff quality is an inexact science (Rossman & Huber, 2016a) and extensive data and effort is required to develop a predictable water quality model. PCSWMM provides various options for the modelling of water quality: the use of model equations, statistical methods, and finally, using constant concentrations.

Pollutant build-up and washoff parameters may be used for water quality modelling in SWMM. Pollutant build-up is estimated as a function of pollutant mass on land, area, and dry days. During dry days, pollutant build-up causes the catchment to attain some maximum pollutant mass that is then potentially removed during a storm. However, the long-term data required to calibrate the pollutant build-up parameters was unavailable therefore pollutant build-up was excluded from the model. Furthermore, in the study area, isolated events such as sewerage overflows were sporadic in nature. Build-up as a function of land use would not be useful unless isolated events took place in a specifically defined land use. Instead, this study used the constant concentration method, that is, using Event Mean Concentration (EMC) values. The EMC values represent the mean concentration of each pollutant in stormwater runoff and may be linked to distinct land use types within the catchment (Lin, 2004). Land use has a significant impact on the presence of pollutants in surface water with different land uses, for example, agriculture and mining contributing widely differing types and amounts of pollutants entering the drainage system.

Dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP) and Total suspended solids (TSS) were the pollutants tracked in the PCSWMM models. DIN and DIP were to evaluate the risk of eutrophication in the river. TSS is a good measure of pollution as it provides an estimate of the overall amount of solid particles in the water, which can act as potential carriers for pollutants such as heavy metals and other pollutants associated with suspended particles. DIP and TSS were also considered as their respective recommended range of treatment was outlined in the *Management of Urban Stormwater Impacts Policy by the City of Cape Town* (2009). The land uses used for the investigation were those listed in Table 6-8. The EMC estimation for each land use was undertaken using the following steps:

- The percentage contribution of each land use composition in the area contributing to each measuring point was extracted from PCSWMM.
- EMC values derived from literature (see Appendix A.3) were used in the Chatty River As-Is model. The model was run for the same period as the water quality monitoring – July 2021 to February 2022.
- The measured mean concentration at each site was calculated from the water quality grab samples collected during the study (Section 6.2).
- The measured mean concentration was compared to the modelled mean concentration at the corresponding measuring point to devise an adjustment factor to apply to the EMC values for each chosen location using Equation 6-1.

$$\boldsymbol{Adjustment\ factor}_{\,\boldsymbol{site\ X}} = \frac{\boldsymbol{Measured\ mean\ concentration}\ (\frac{\boldsymbol{mg}}{\boldsymbol{l}})}{\boldsymbol{Modeled\ mean\ concentration}\ (\frac{\boldsymbol{mg}}{\boldsymbol{l}})} \qquad (6\text{-}1)$$

- A measuring point was considered calibrated if the percentage variation of the modelled mean concentration to the measured mean concentration, shown by the adjustment factor, was within 10%.
- The EMC associated with a land use was finalized if either or both of the two conditions were met:
  - The land use was the most dominant in the contributing area of the measuring point. For example, 79% of the land use in the area contributing to Site 15 was Open space.
  - The measuring point had the highest percentage of the particular land use contributing to it compared to other measuring points. For example, if Site 15 had 79% open space land use and Site 2 had 62% land use, site 15 would be preferred for the estimation of the EMC associated with Open Space.
- An example of the estimation of the EMC is presented in Appendix A.3. The EMC values used in the model are presented in Table 6-8.

Table 6-8: EMC estimated values used in the models

Land Use	DIN (mgL^{-1})	DIP (mgL^{-1})	TSS (mgL^{-1})
Agriculture	2.3	0.37	11.28
Mine	2.1	0.22	16.43
Open Space	0.95	0.11	12.98
Roads	2.48	0.16	22.64
Formal	3.11	0.31	13.68
Informal	23.4	0.36	27.53
Natural Vegetation	0.42	0.08	12

The assumptions and limitations linked to the model water quality calibration include the following:

- The water quality monitoring program was undertaken biweekly for 7 months on 11 sample sites. The data, therefore, gives a glimpse of the water quality at a particular point at a specific time and is not necessarily representative of the fluctuating concentrations throughout the day.

- EMC values were estimated assuming diffuse pollution and ignoring pollution contributions made by point pollution sources, such as overflowing manholes, which occur randomly.

6.5 SuDS scenario development

This study explored the potential of gravity-based SuDS interventions to improve the water quality in the Chatty River through a scenario-based approach, using the Bethelsdorp River Catchment as a case study. This section outlines the site selection process, the application of the selected SuDS interventions on PCSWMM and the sizing of SuDS.

6.5.1 Site selection

The factors considered during the identification of SuDS opportunities were:

- The availability of open space.
- The proximity of potential sites to the known modelled drainage network.
- Topography.
- The size and characteristics of the contributing area – which would influence the pollutant load.
- Expected type of pollutant and removal mechanisms required.

The first step in the process was to identify open spaces contributing to the Bethelsdorp tributary. Open spaces were identified using the land use map (Section 5.1.5) that classified open space under high-density alien plants, recreational open space, and unused open space. In addition, the storage creator tool, which creates storage curves from the DEM layer on PCSWMM was used to identify open spaces with naturally ponding slopes. These were then narrowed down based on proximity to the Bethelsdorp River and adequate topography. Source, local and regional interventions were considered.

Upon completing the desktop study, a site visit with a DWA official and the NMU research team was undertaken to collect additional physical information observed at the potential sites such as undocumented land use and infrastructure (e.g., walkways) that might have been, unclear on satellite imagery. The Bethelsdorp catchment was found to be relatively steep, narrowing down the feasible sites. Furthermore, there was encroachment of various developments onto the river's 1:50 and 1:100-year floodplains (SRK Consulting, 2015), limiting the space available for the application of SuDS interventions. Only sites close to the river network were considered due to challenges in acquiring an existing stormwater network map. To maximize opportunities for water quality improvement, sites in the lower parts of the Bethelsdorp River Catchment were prioritized for scenario modelling.

6.5.2 SuDS simulation in PCSWMM

A ‘Low Impact Development (LID)’ Control Editor tool is available in PCSWMM to implement LIDs (referred to in this project as SuDS) in a scenario model. The tool has several SuDS to choose from including: rain gardens, green roofs, rain barrels (tanks), rooftop disconnections and permeable pavements, which are all source controls. In addition, the local controls available are bio-retention cells, infiltration trenches and vegetative swales. Although the options available are limited, other SuDS, such as detention ponds, retention ponds and wetlands, can be modelled through the manipulation of sub-catchments, conduits, junctions, storage units and outlet controls (weirs and orifices).

For this project, wetlands and ponds were modelled using storage units as was done by Gregory (2014) and recommended by James & Rossman (2010). Orifices were modelled to simulate the release of water quality volume (WQV), while weirs were modelled for overflow.

Infiltration practices can reduce stormwater pollutants through chemical and bacterial degradation, sorption, filtering and by virtue of reducing the runoff volume (Minnesota Pollution Control Agency, 2022) depending on the type of pollutant. While the source and local control options are available as LID control options in PCSWMM, their implementation at each site in the study area, with a relatively large size of 885 ha, would be highly intensive and introduce additional uncertainty. Source controls were modelled through re-routing overland flow. Runoff from impervious areas was routed to pervious areas where infiltration interventions, for example, rain gardens, bioretention areas, permeable pavements, infiltration trenches, etc., would be located. The concept of routing overland flow in this manner is shown in Figure 6-25. The Watershed Delineation Tool (WDT) Contributing area layer was developed using the DEM to analyse the contributing area to the targeted locations. The percentage of impervious area for each contributing sub-catchment was measured, and the percentage routed to the pervious area was determined. A variation of 10% between the upper and lower limit of the percentage of runoff from impervious areas routed to the pervious areas was applied to obtain an estimated range of pollutant removal.

Pollutant removal functions can be defined according to the concentration remaining (C) or the fraction removed (R). Pollutant removal functions were defined and assigned to storage units representing treatment facilities such as wetlands and ponds. The functions developed using storage nodes can depend on water depth, surface area, routing timestep and hydraulic residence time (HRT) (Rossman & Huber, 2016b).

Several treatment expressions are recognised in SWMM. This project adapted the k-C* model, a first-order model, for pollutant removal. The first-order model is a treatment expression commonly used in the treatment performance of wetlands (Rossman & Huber, 2016b). Many pollutants decline exponentially to a background concentration whilst passing through a wetland (Kadlec *et al.*, 2000). As no previous studies were identified that had monitored wetland performance in the neighbourhood of the catchment, decay functions were adapted from a study undertaken for Cape Town, South Africa (Thewlis, 2022) to model the possible impact of wetlands and ponds on water quality with respect to HRT. Maximum removal was bounded by the upper limit while minimum removal was bounded by the lower limit. The climate difference between Gqeberha and Cape Town was acknowledged by applying the upper and lower limits of treatment to the model and reporting on the range of potential treatment. The decay functions listed in Table 6-9 were derived from multiple studies which investigated the change of pollutant concentration with HRT. Upon completion of the long-term simulation, water quality removal was compared to the mandated removal percentages presented in the City of Cape Town (2009) *Management of Urban Stormwater Impacts Policy* in the absence of a Gqeberha-specific guideline.

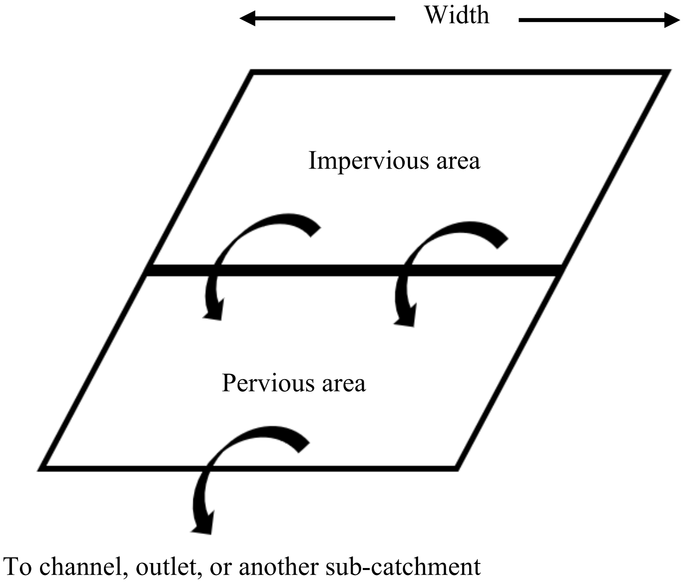


Figure 6-25: Re-routing of overland flow (Huber, 2001)

Table 6-9: Pollutant removal functions applied to modelled wetlands (Thewlis, 2022)

Pollutant	**Pollutant removal functions**	
	Lower Limit	**Upper Limit**
DIP	$R = 1 - e^{-0.0048}*HRT$	$R = 1 - e^{-0.017}*HRT$
DIN	$R = 1 - e^{-0.004}*HRT$	$R = 1 - e^{-0.012}*HRT$
TSS	$R = 1 - e^{-0.013}*HRT$	$R = 1 - e^{-0.03}*HRT$

6.5.3 Sizing of SuDS

The main objective of this project was to investigate the possible impact of SuDS interventions on water quality. The SuDS design, therefore, considered the water quality volume (WQV). Armitage *et al*. (2013) describe WQV as the runoff volume requiring water quality treatment to reduce a specified percentage of pollutants. It is considered a cost-effective method to minimize overall pollutant discharge, as most rainfall occurs in relatively small events (Smart, 2020). The storage pond calculator tool in PCSWMM was considered for the determination of the pond size required to reduce the peak outflow to the predevelopment flow rate, however, the sizes of the recommended ponds were larger than the spaces available for the interventions. The space available was therefore used to determine the pond size.

There are several ways to estimate the critical rainfall depth, *P*, to determine suitable WQVs. In this project, the half-year or 1 in 6-month 24-hour rainfall event was used (Armitage *et al*., 2013). PCSWMM was used to autogenerate events from the PORT rain gauge (see Section 5.1.2) and interpolate the return periods. This data was compared to Depth-Duration Frequency (DDF) curves generated on NetSTORM using the same rain gauge. Finally, these two data sets were compared to the return period rainfall depths generated by SRK Consulting (1999) and provided by the Nelson Mandela Bay Municipality (NMBM). The datasets are summarized in Table 6-10. Due to the closer relationship between the NMBM and PCSWMM 5-year and 10-year return periods, than the NMBM and NetSTORM data for the same return periods, the PCSWMM 1 in 6-month rainfall depth, *P*, of 34 mm was used in the form of a 24-hour Soil Conservation Service (SCS) Type I distribution (Weddepohl, 1988).

Table 6-10: 24-hour design rainfall depths

Source	Average Recurrence Interval rainfall depth (mm)													
	1-mo	3-mo	6-mo	1-y	2-y	5-y	10-y	20-y	25-y	50-y	100-y	200-y	500-y	1000-y
NetSTORM	8.0	20	30	34	40	56	68	-	87	100	120	150	180	210
PCSWMM	12	23	34	50.5	70	91	110	-	-	-	-	-	-	-
SRK Consulting, 2015	-	-	-	-	54	87	120	150	150	200	250	-	-	-

The Simple Equation (Debo & Reese, 2003) (Equations 6-2 and 6-3) served as a guideline for initial sizing at the sites selected to simulate retrofitted SuDS. This equation was also used as a check and was compared to the output produced by PCSWMM to verify that the model was functioning as expected.

$$WQV = \frac{P\,R_v\,A}{1000} \tag{6-2}$$

$$R_v = 0.05 + 0.009\;x\;I \tag{6-3}$$

where WQV= Water Quality Volume (m^3); P= total rainfall depth to be included (mm); R_v= volumetric runoff coefficient; A = total drainage area (m^2); I= percentage of impermeable cover (%).

Once the volume required was determined from PCSWMM, an initial estimation of the water storage capacity of the conceptualised ponds or wetland structures was calculated using Equation 6-4. Vertical height differences of 0.1 m were extrapolated from the developed DEM, and the areas corresponding to those heights were entered. The extrapolated values from the DEM were then used to develop a storage curve, tabulated in the form of area versus depth, for the modelling of the storage unit in PCSWMM.

$$V = \sum_{i=0}^{n} \frac{A_i + A_{i+1}}{2}\;x\;d_i \tag{6-4}$$

where V = storage volume (m^3); A_i = surface area at elevation i (m^2); A_{i+1}= surface area at elevation i+1 (m^2); d_i = vertical height difference (m).

Additional volume in the conceptual ponds and wetlands over the permanent depth caused by the 1 in 6-month storm is referred to in this study as the temporary storage depth. The temporary storage time was limited to 24 hours as recommended in the *'The South African Guidelines for Sustainable Drainage Systems'* by Armitage *et al.* (2013) to allow for the storage unit to be emptied and be ready for a potential next storm. The temporary storage time was assessed using the amount of time that the depth in the pond was above 0.015 m as undertaken in the *User's Guide To SWMM5* by James & Rossman (2010). Release of the water was simulated through an orifice. The temporary storage depth was maintained within the recommended depths, that is between 250 mm and 400 mm (Armitage et al., 2013). (Appendix E:).

The permanent storage depths for various ponds and wetlands differed from site to site based on the location and site characteristics. An emergency overflow depth was also considered for all the ponds. In this study, the emergency overflow depth was the additional water depth experienced in the pond or wetland due to flows caused by storms exceeding the 1 in 6-month, 24-hour design storm. This was simulated to drain out of the system using an overflow weir. A long-term simulation, using the rainfall time series from the PORT rain gauge, was undertaken to ensure that the maximum allowable emergency overflow depth was not exceeded.

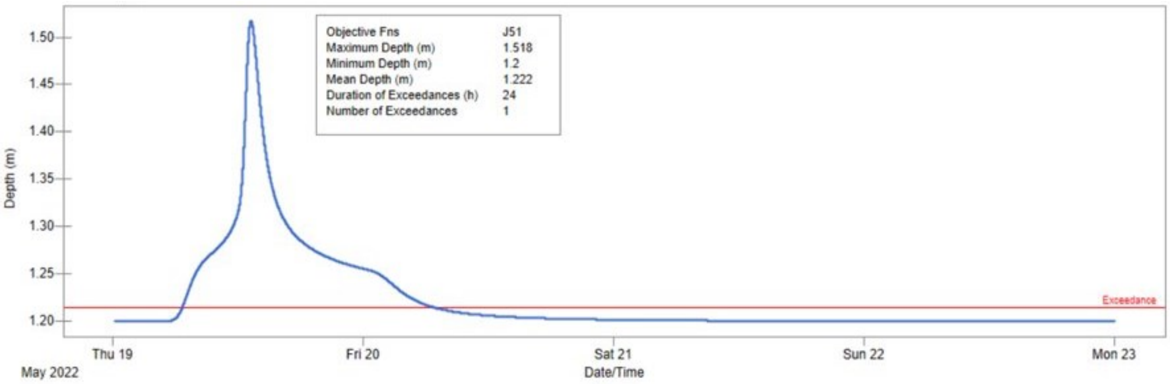


Figure 6-26: Hydrograph showing the temporary storage time in PCSWMM

7. Chatty River Catchment Model Scenarios and Results

This chapter presents the Chatty River Catchment (CRC) PCSWMM model scenarios and results with reference to flow and pollutant load. The representative Chatty River Catchment ‘As-is’ scenario was developed (Section 5.2) to highlight the catchment’s current hydrological state and serve as a baseline model for future projects. The drainage network consisted of engineered open and natural channels developed using the available topographical data and satellite imagery. Sub-catchment parameters were developed from the land cover and soil data available. The PORT rain gauge located in the lower reaches of the catchment was used for modelling. The construction of the likely predevelopment scenario aimed to represent the possible natural state as a benchmark before the influence of anthropogenic activities to indicate the extent of the likely deterioration.

7.1 Chatty River Catchment ‘As-is’ model

The Chatty River Catchment As-is components include a river network of 60 km, 61 sub-catchments and an area of 114 km^2. Although the model was uncalibrated, a sensitivity analysis was undertaken (Section 5.2.3.2).

The ‘As-is’ scenario was simulated for 9 years and 5 months – January 2013 to May 2022. The estimated flow and pollutant load results from the modelled outlet are presented in Table 7-1.

Table 7-1: Modelling results at the CRC ‘As-Is’ modelled outlet (2013 - 2022)

Parameter	Simulation results at the effective outlet
Total volumetric flow	55.5 x 10^6 m^3
Peak flow	135 m^3/s
Total OP load	11 tonnes
Total DIN load	84 tonnes
Total TSS load	755 tonnes

7.2 Chatty River Catchment Predevelopment scenario

A comparison of estimated flow runoff corresponding to the 1 in 6 month, 24-hour storm, with an SCS South Africa Type I distribution, which is used as a design basis for Sustainable Drainage Systems (SuDS), for the As-is and Predevelopment Scenarios is shown in Figure 7-1. As seen in the figure, the peak runoff is lower in the Predevelopment scenario than in the As-is scenario.

The increased infiltration in the Predevelopment scenario, due to the lower impervious area percentage and other sub-catchment attributes related to the natural state, significantly reduced the peak flow and, ultimately, the total runoff volume in the catchment. Furthermore, the time to peak is delayed by 30 minutes in the predevelopment model. This shows the influence of urbanisation on runoff, as mentioned in various studies (Du, Ottens & Sliuzas, 2010; Chow, Yusop & Shirazi, 2013; Enninful & Acquaye, 2014).

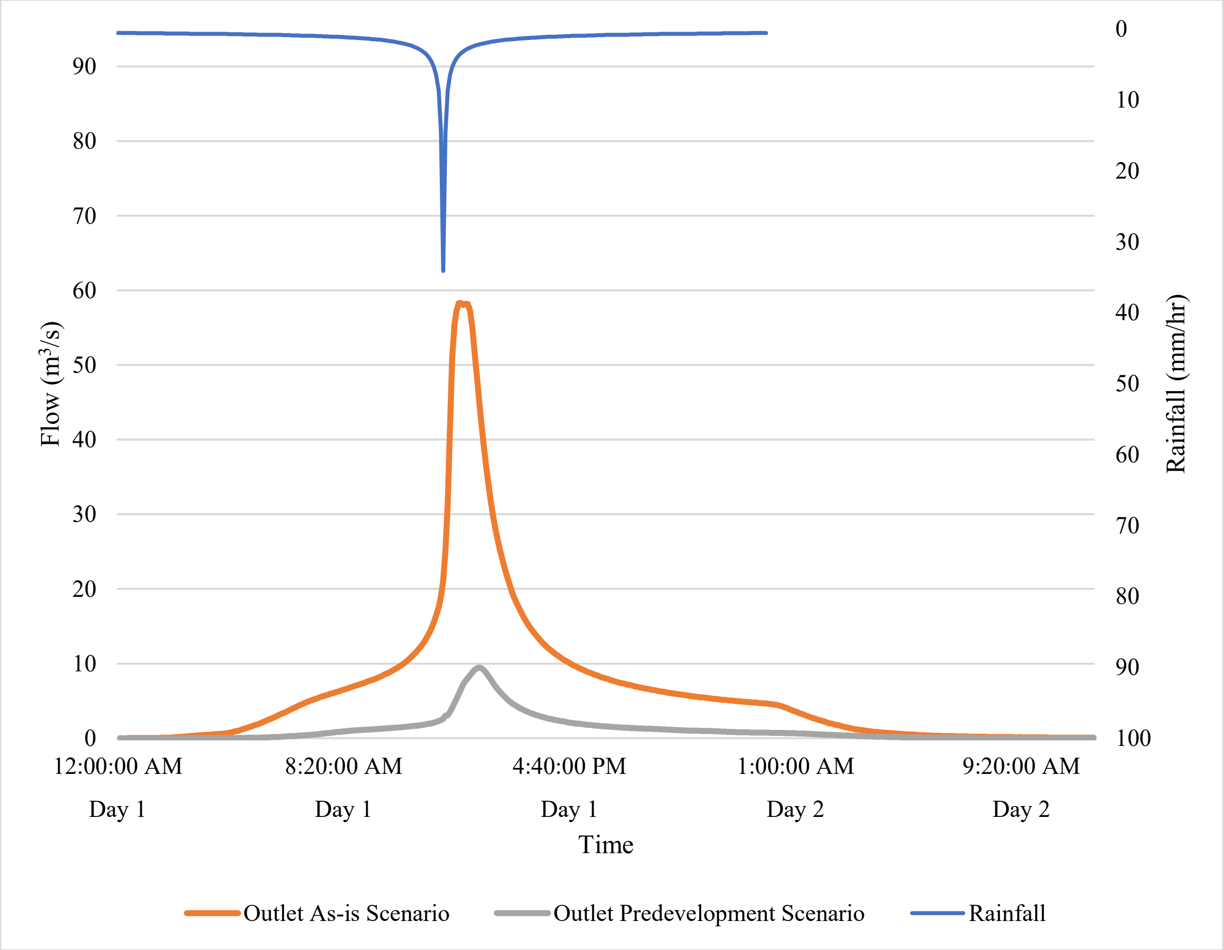


Figure 7-1: Comparison of 6-month recurrence interval outflow for As-is and Predevelopment CRC Scenarios

There was a modelled mean DIP, DIN and TSS reduction of 67%, 82% and 93% respectively in the predevelopment scenario highlighting the degradation of water quality in the catchment due to urbanisation as mentioned in the literature review (Section 2.1).

The comparison made between the 'As-Is' scenario and the predevelopment scenario and the water quality results in Sections 6.2 and 6.3 emphasizes the need to develop mitigation measures in the Chatty River Catchment to improve the water quality in the Chatty River and its tributaries.

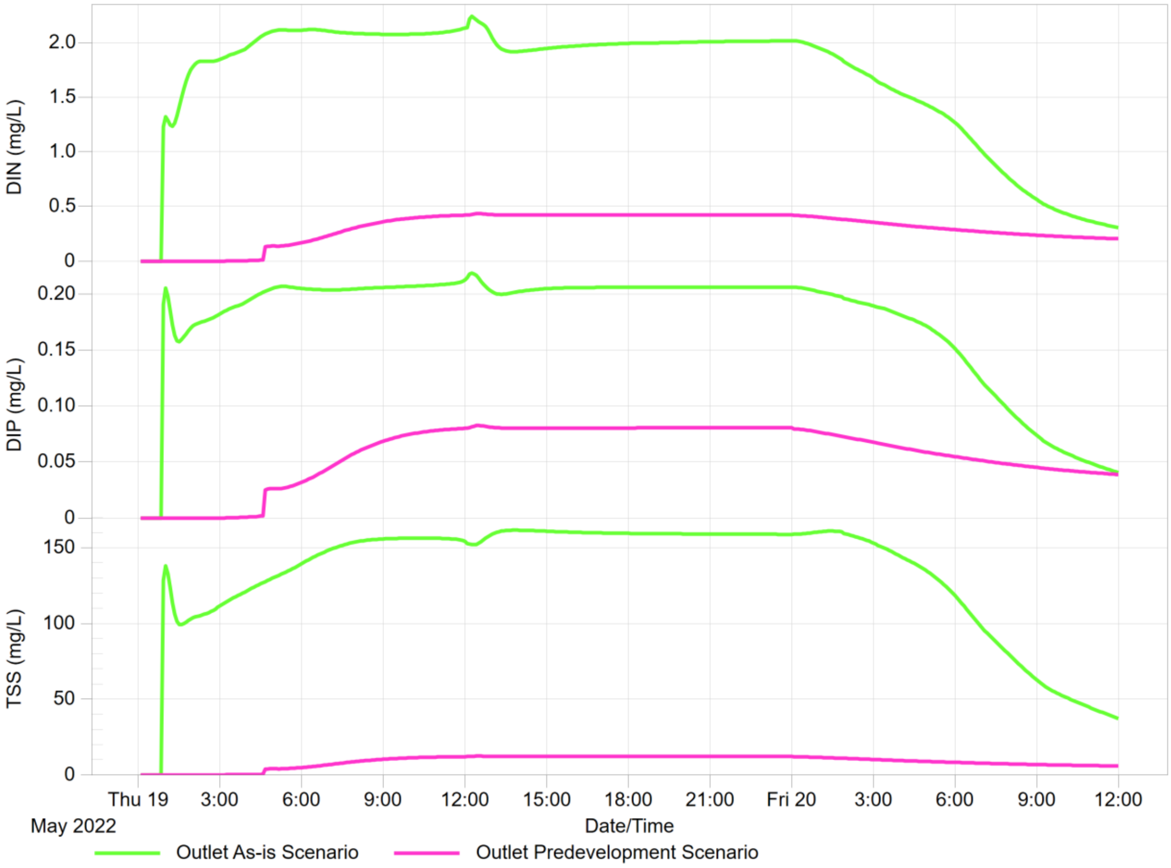


Figure 7-2: Comparison of pollutant concentration for As-is and Predevelopment CRC Scenarios during a 1 in 6-month storm

8. Bethelsdorp River Catchment Model Scenarios

8.1 Bethelsdorp River Catchment 'As-is' Model

A representative Bethelsdorp River Catchment (BRC) 'As-is' scenario was developed to represent the sub-catchment's current hydrological state and pollutant loading. The development of this sub-catchment of the Chatty River Catchment (CRC) was studied as attempting to model the much larger CRC would have unnecessarily increased the complexity. The potential impact of the inclusion of SuDS scenarios (Section 8.3) on pollutant load and runoff volume was then tested out on the smaller BRC. It was assumed that what lessons were learnt from the BRC model could be generalized in the larger Chatty River Catchment.

The Bethelsdorp River Catchment 'As-is' model included a drainage network of 13.1 km with 75 sub-catchments and a total area of 8.9 km^2. The drainage network consisted of concrete open channels, natural channels, and culverts under road crossings. As with the Chatty River As-is model, preliminary sub-catchment parameters were developed from the current land use and soil data identified during this project. Once the basic model was working, a sensitivity analysis and partial calibration of the model were undertaken, as described in Section 5.2.3.

8.2 Bethelsdorp River Catchment Predevelopment scenario

The Bethelsdorp River Catchment predevelopment scenario was developed to estimate the peak runoff and pollutant loads before urban development. The entire drainage network was converted to natural channels. Historic vegetation and soil data were used to define the sub-catchment parameters. The final model served as a baseline to compare with all other interventions.

8.3 SuDS Scenarios

The water quality results discussed in Chapter 6 show the extent of water quality degradation in the Chatty River. SuDS stormwater control measures were therefore modelled to assess their possible impact on water quality. This section describes the various SuDS scenarios tested to assess their likely effectiveness in pollutant removal.

8.3.1 Scenario 1 – Upstream constructed wetland

The site identified for the upstream constructed wetland was a natural ponding area. It was identified as a potential location for a constructed wetland through the inspection of open space and topography in the Bethelsdorp catchment using the storage creator tool on PCSWMM. As the river flowed through this naturally ponding area, the constructed wetland was modelled to be an instream system, that is, within the natural channel, as shown in Figure 8-1. The existing topography guided the development of a wetland with a permanent pool depth of 1.2 m and a maximum depth of 2 m as shown in Figure 8-1.

Figure 8-1: Scenario 1: Upstream constructed wetland

Figure 8-2: View of the proposed site for the upstream constructed wetland from Rensburg Street (Google Maps, 2022)

The contributing area immediately upstream and surrounding the site primarily consists of residential areas and schools; hence the total water depth in the model was restricted to 2 m to reduce safety risks (Woods-Ballard *et al.*, 2007). The wetland was modelled in PCSWMM as a storage unit. An orifice was sized on the outlet to restore the permanent water depth within 24 hours. An overflow weir was placed to enable flow caused by storms greater than the 1 in 6-month storm to bypass the wetland back into the stream while maintaining an emergency overflow depth between 0.25 m and 0.4 m. Design details used for the modelling are summarised in Table 8-1. For additional treatment, sediment forebays may be incorporated in open space upstream of the wetland. As seen in Figure 8-2, litter is an ongoing problem in the catchment. A litter trap should therefore be incorporated into the final design to avoid clogging the drainage system. Conceptual design considerations are highlighted in Appendix E.

Table 8-1: Upstream constructed wetland conceptual design details

SuDS	Surface Area (m^2)	Permanent depth (m)	Temporary Storage depth (m)	WQV depth (m)	Emergency overflow depth (m)	Total depth (m)
Constructed Upstream Wetland	16,200	1.20	0.38	1.58	0.4	1.98

The pond is situated just a few meters away from the road and it is therefore important to evaluate how it might affect the stability of the road embankment. To achieve this, a thorough site assessment led by a geotechnical engineer or geologist is essential. This assessment will help identify potential risks and propose suitable mitigation strategies for consideration in the detailed design phase.

8.3.2 Scenario 2 – Rehabilitation of wetlands

Wetlands are sensitive systems impacted by human activities and conventional stormwater management (Charbonneau & Bradford, 2016). The channelled valley-bottom wetland areas in the catchment were identified from the South African National Biodiversity Institute (SANBI) Archived National Wetland Types database (Figure 8-3). Only a small portion of the historic wetlands was observed during the site visit, as shown in Figure 8-5. Furthermore, satellite imagery taken as far back as 2004 did not record wetlands similar in shape and size to the ones in SANBI. In a study undertaken by Melly (2016), the size and shape of wetlands in the Nelson Mandela Bay Municipality have been impacted by urban development, artificial drainage and abstraction, pollution leading to nutrient enrichment and increased algal and reed growth, overgrazing, alternation of hydrology, invasive species, and irregular rainfall patterns.

During the site visit, several human pathways were observed on the site. The movement of people was therefore considered during the research. Alternative pathways would be required to ensure residents' safety and convenient movement. The site (Figure 8-6) was desirable as it neighboured the Kleinskool Community School, where the development of wetlands in this area could serve as an educational opportunity. Damaged infrastructure, such as a recently cleared overflowing manhole shown in Figure 8-5, require maintenance before the implementation of any water quality mitigation measures. Existing infrastructure, such as the sewerage system, would also need to be inspected during the project's planning stages.

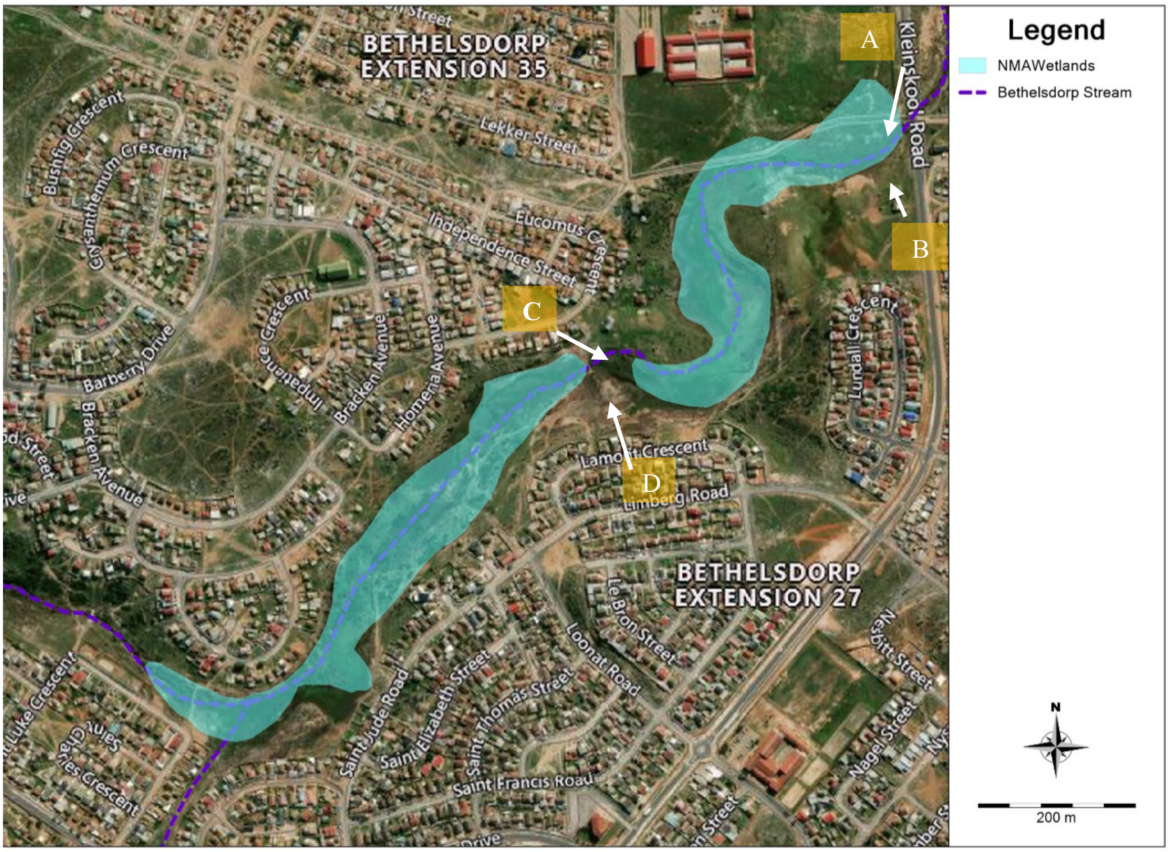


Figure 8-3: Valley-bottom wetlands documented in SANBI database

The rehabilitated wetlands were conceived as regional controls that aimed to improve the water quality of runoff from a relatively large catchment (Figure 8-6). There was limited space on either side of the river, resulting from the encroachment of urban development in the floodplain. As a result, the design of the wetlands was to be instream. Due to existing infrastructure, the historical outline and shape of the wetlands, recorded by SANBI, could not be replicated exactly in the conceptual scenario. Since the topography was relatively steep, the wetlands were modelled as having dam walls with a maximum height of 2 m. Table 8-2 presents the design parameters used for the wetlands model.

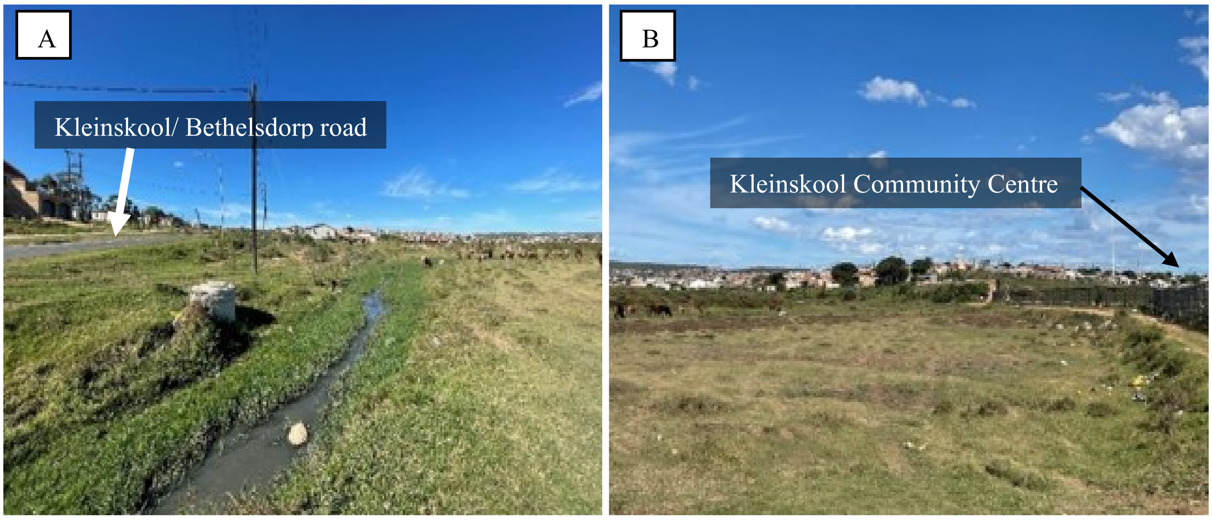


Figure 8-4: Views from locations A and B bordering the Kleinskool Community School

Figure 8-5: Views from locations C and D showing the existing wetland and damaged manhole respectively

Table 8-2: Rehabilitation of wetlands conceptual design details

SuDS	Surface Area (m^2)	Permanent depth (m)	Temporary Storage depth (m)	WQV depth (m)	Emergency overflow depth (m)	Total depth (m)
Upstream Wetland	17,400	1.00	0.75	1.75	0.25	2.00
Downstream Wetland	35,100	1.20	0.49	1.69	0.31	2.00

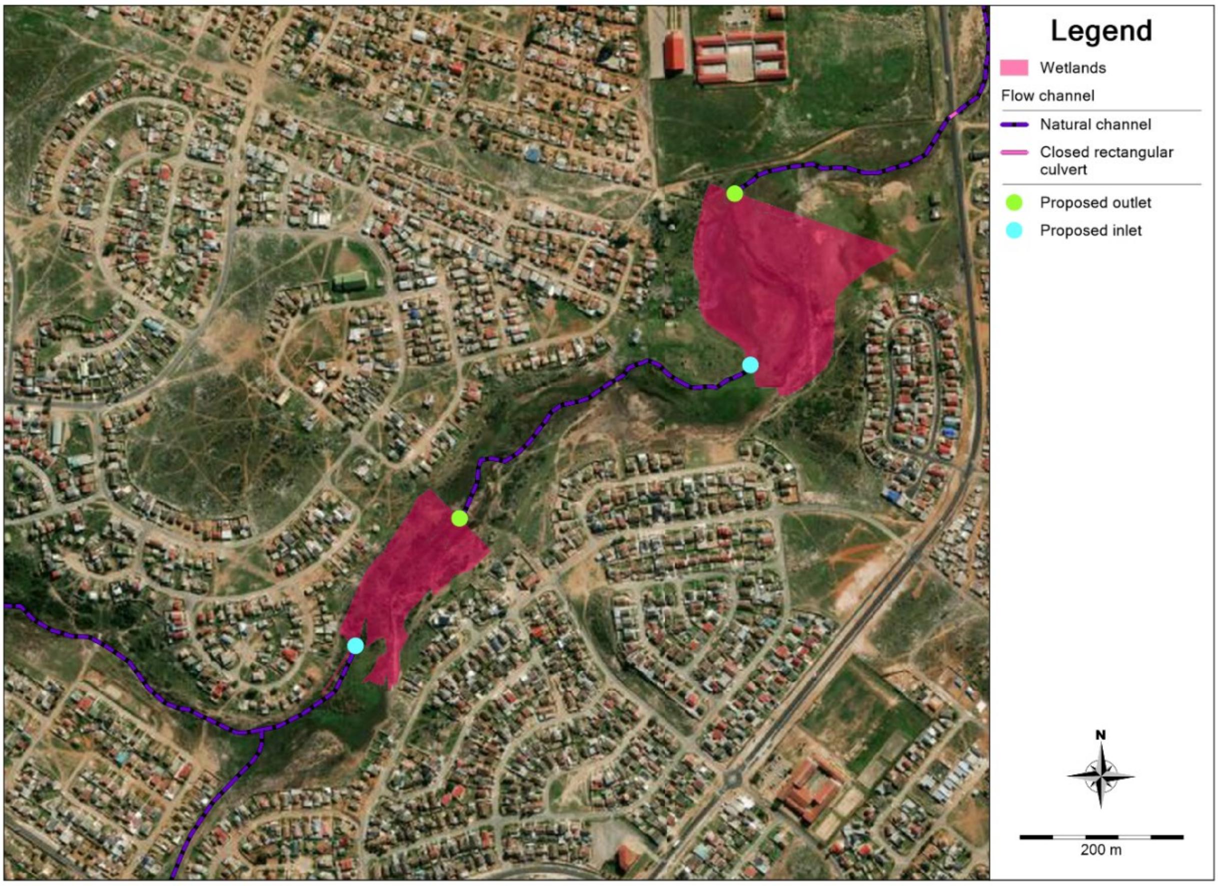


Figure 8-6: Scenario 2: Proposed rehabilitated wetlands

8.3.3 Scenario 3 – Downstream Retention Pond

The downstream pond was identified as the final opportunity to capture pollutants from the Bethelsdorp Catchment. Currently, a semi-circular concrete channel directs runoff out of the catchment and into the Chatty River, as shown in Figure 8-7. Although the channel side slopes are vegetated, constructing a concrete base was a missed opportunity for infiltration, treatment, and attenuation of flow out of the catchment and into the Chatty River. The surrounding area is low-income residential, and undocumented land use, such as grazing, was observed at the site.

Due to the sizeable contributing area of 885 ha and the site's location near the outlet, a retention pond was modelled (Figure 8-8). The area is relatively flat; hence excavation would be required to develop the ponded area. However, this alteration of the natural land layout, while enabling the operation of a nature-based system, represents a limitation of the intervention.

The concrete channel was modelled as a rehabilitated natural channel. Rehabilitation of the stream may be implemented with the assistance of riprap to stabilize the slopes. The pond on the right side of the natural stream was conceptualized to capture low flows making up the WQV. A flow divider may be used at the inlet to prevent the risk of flooding and ypass larger flows through the stream and into the Chatty River. The pond would require fencing as it could be a potential safety risk in the residential area. The permanent pool depth was limited to 1.2 m . Table 8-3 summarises the design parameters used during modelling.

Figure 8-7: Semi-circular concrete channel

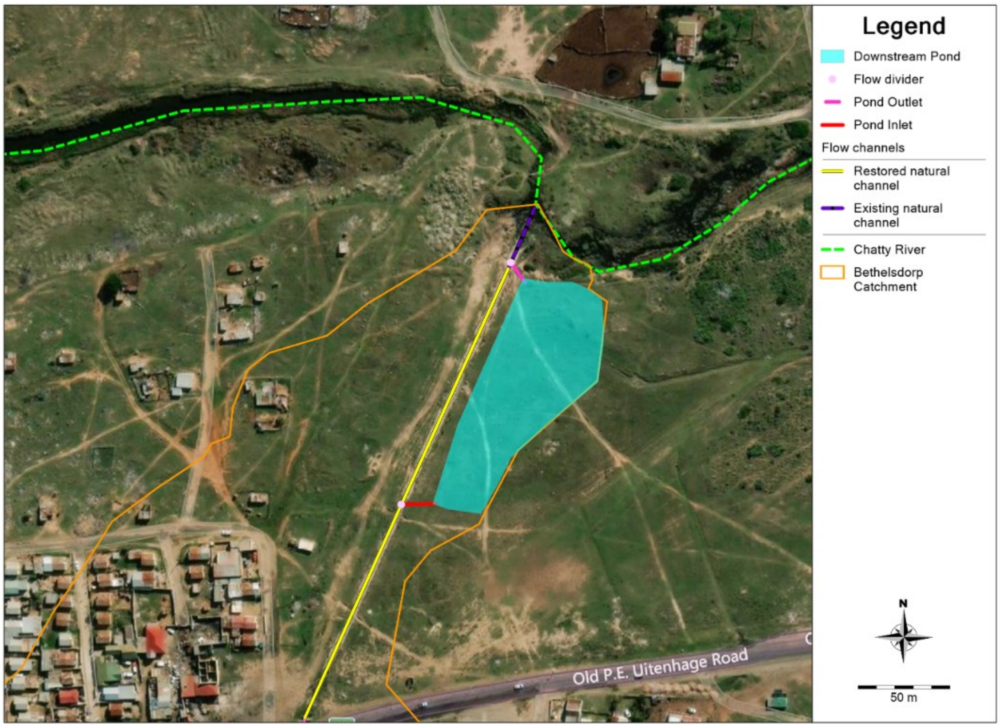


Figure 8-8: Scenario 3: Proposed downstream retention pond

Table 8-3: Downstream Pond conceptual design details

SuDS	Surface Area (m^2)	Permanent depth (m)	Temporary Storage depth (m)	WQV depth (m)	Emergency overflow depth (m)	Total depth (m)
Constructed Upstream Wetland	5,800	1.20	0.42	1.62	0.38	2.0

8.3.4 Scenario 4 – Infiltration practices

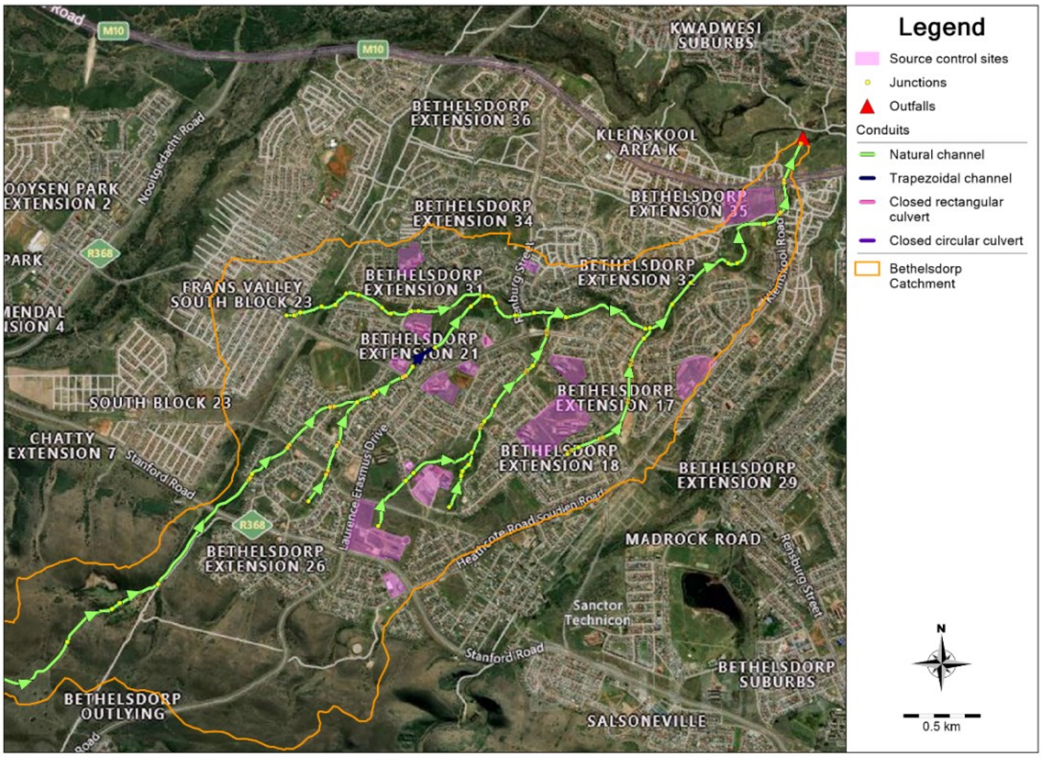


Figure 8-9: Scenario 4: Proposed source and local control sites

Scenario 4 simulated the use of source and local controls by routing flows from the impervious areas to designated pervious areas. 15 sites were chosen and sub-catchments containing unused areas, lawns, or parking spaces were targeted, as shown in Figure 8-9. The total area which could potentially be occupied by the infiltration interventions in the sites within the catchment was estimated to be 30 ha draining an impervious area of 40 ha. In the model, the source and local controls implemented in these areas reduce pollutant loads by virtue of reducing water quantity, as discussed in Section 6.5.2. The controls that operate primarily through infiltration are soakaways, bioretention areas, filter strips, permeable pavements, and infiltration trenches.

Ultimately, source and local control sites in the model were limited to enclosed institutions such as schools, shopping centres and churches. Choosing enclosed sites would facilitate infrastructure protection from damage due to illegal dumping and waste disposal in the catchment. Furthermore, the various institutions would be possible collaborators when it comes to maintaining the interventions and educating the public on the function of SuDS.

8.3.5 Scenario 5 – Regional controls

A treatment train is modelled in a catchment to rehabilitate waterways, enhance water resource management, and promote biodiversity and amenity (Vice, 2011). This scenario assessed the combination of the previously described regional controls to form a treatment train through the catchment. They included: the constructed wetland upstream, the rehabilitated wetlands and the downstream retention pond, as shown in Figure 8-10. Regional controls have the potential to effectively manage stormwater runoff and careful planning, design, and maintenance of SuDS systems are crucial to ensure their long-term effectiveness and to avoid adverse impacts on developments and existing flood management infrastructure.

Community members may use open ponds for recreation and interventions, such as fencing and educational signage, will be required to prevent access to the sites. Furthermore, waste management strategies will be required to compliment the application of regional controls and ensure that pollution levels in the water body are maintained below those required for recreation.

Figure 8-10: Scenario 5: Combination of regional controls

8.3.6 Scenario 6 – Combination of all the interventions

This scenario was used to analyse the additional influence of source and local controls if implemented in the catchment to form a treatment train with a wider variety of interventions. A system with source, local and regional controls reduces the shock load in the system, as discussed in Section 2.2.2. Improving water quality at the source would alleviate the burden on regional controls and promote better functioning of the interventions by capturing the WQV upstream. Figure 8-11 gives an overview of the SuDS locations.

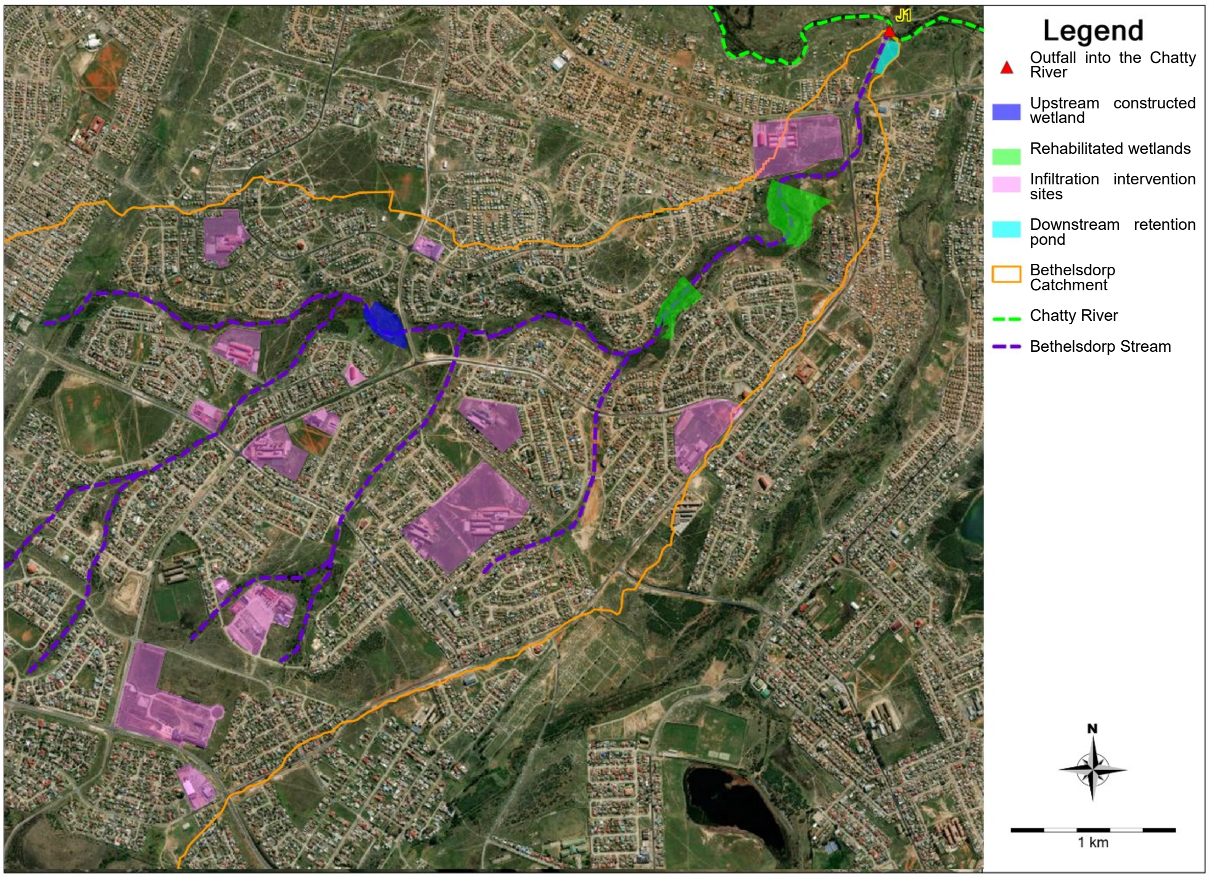


Figure 8-11: Proposed SuDS treatment train

9. Bethelsdorp River Catchment Scenario Results

This chapter discusses the results of the scenarios developed on PCSWMM using the methods detailed in Sections 5.2 and 6.5. The results discussed in this chapter correspond to the 1 in 6 month, 24-hour SCS design storm and the continuous simulation. The 1 in 6 month, 24-hour SCS design storm was chosen to estimate the Water Quality Volume (WQV) required to meet the City of Cape Town pollutant removal requirements as stipulated in the *Management of Urban Stormwater Impacts Policy* by the City of Cape Town (2009). The continuous simulation, on the other hand, was used to assess the possible long-term impact of the modelled interventions and the results are also discussed in this chapter. The analysis of results from the PCSWMM model simulations was constrained by the computer's speed to produce long-duration hydrographs and flow duration curves hence the alternative was to show the 6-month RI (WQV) and annual changes.

9.1 Bethelsdorp River Catchment 'As-Is' model

A partially calibrated model of the current state of the Bethelsdorp River Catchment (BRC), a sub-catchment of the Chatty River Catchment, was developed as a base model for the modelling of retrofitted SuDS interventions. The 9 years and 5 months simulation period produced the results shown in Table 9-1 at the BRC outlet, where the Bethelsdorp tributary flows into the main Chatty River channel.

Table 9-1: Modelling results at the BRC outlet (2013 - 2022)

Parameter	Simulation results at the effective outlet
Total volumetric flow	10.4 x 10^6 m^3
Peak flow	9.11 m^3/s
Total OP load	2.19 tonnes
Total DIN load	13.8 tonnes
Total TSS load	126 tonnes

9.2 Bethelsdorp River Catchment predevelopment model

The BRC predevelopment model was developed to estimate the flow and pollutant load characteristics of the catchment prior to urban development. Due to the lack of flow data of the Bethelsdorp tributary before development, the predevelopment model developed was uncalibrated. An SCS Type 1 distribution, 1 in 6-month 24-hour storm was used to compare the As-is and predevelopment models. Figure 9-1 compares the runoff between the As-is and predevelopment scenarios, highlighting the influence of urban development on runoff and, subsequently, river flow. The predevelopment flow curve indicates a reduced peak flow compared to the As-is flow curve. Furthermore, results indicated a delayed peak time of 1 hour in the predevelopment model. This is longer than the Chatty River Catchment (CRC), which showed a 30 min change in time to peak. Various characteristics in the other sub-catchments such as channel characteristics, slope, land use changes and hydrological influence the entire CRC leading to a smaller difference in peak times than the BRC.

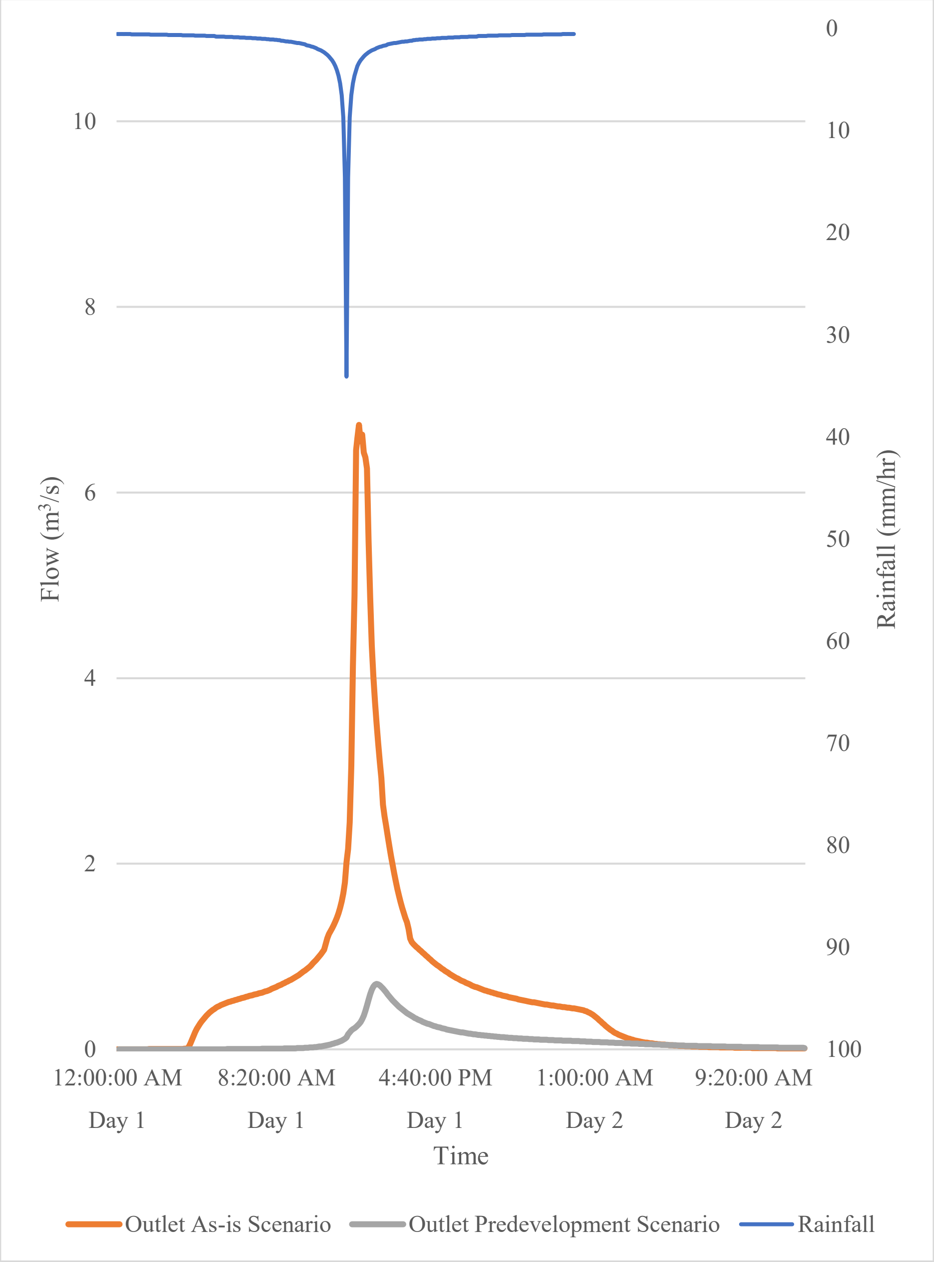


Figure 9-1: Comparison of 6-month recurrence interval outflow for As-is and Predevelopment CRC Scenarios

9.3 SuDS Scenarios

Retrofitted SuDS interventions were added to the BRC As-is model to assess their possible impact on water quality in the Bethelsdorp tributary feeding into the Chatty River. The upper and lower limit pollutant removal ranges for each SuDS intervention were modelled as detailed in Section 6.5.2.

Six scenarios were assessed and compared to the 'As-is' and predevelopment scenario conditions. These scenarios consisted of both individual interventions and various combinations. The SuDS scenarios (Section 8.3) are listed in Table 9-2. This section discusses the potential impact of the conceptualized SuDS interventions on water quality in the river network. Furthermore, it highlights the possible impact on river flow.

Table 9-2: Summary of SuDS Scenarios

Scenario	SuDS intervention(s)
Scenario 1	Constructed wetland
Scenario 2	Rehabilitated wetlands
Scenario 3	Retention Pond
Scenario 4	Infiltration practices
Scenario 5	Regional controls – Constructed wetland, rehabilitated wetlands and retention pond
Scenario 6	All interventions – Regional controls and infiltration practices to form a complete treatment train

9.3.1 Potential impact on water quality

The primary goal for investigating the implementation of retrofitted SuDS was to evaluate mitigation measures to cater for the current high volumes of pollution in the Chatty River.

9.3.1.1 Long-term continuous simulation results

The models were run for an equivalent period of 9 years and 5 months (January 2013 – May 2022). Figure 9-2, Figure 9-3 and Figure 9-4 show the pollutant load results from the simulations while Figure 9-5 presents the percentage of pollutant reduction.

Scenario 4 (Infiltration practices) had the smallest impact with regard to pollutant reduction. Pollution reduction was simulated through infiltration in pervious areas identified in enclosed public institutions in the study area. Source and local controls such as soakaways, bioretention areas, filter strips, permeable pavements, and infiltration trenches were represented under infiltration practices. The limited area for the application of source and local controls, which was approximately 5%, and respective drainage area may have attributed to the low pollution reduction. Furthermore, source and local controls treat a relatively small amount of runoff, approximately 10%, compared to the regional controls modelled in the other scenarios, with the smallest contributing area being 50%.

Rehabilitating the wetlands in Scenario 2 resulted in the highest pollutant load reduction compared with the individual regional controls tested. The higher impact may be due to the large WQV captured compared to the other two regional controls in Scenario 1 and 3, and their location in the middle to lower reaches of the catchment.

The combined regional controls in Scenario 5 resulted in increased pollutant removal over Scenarios 1, 2, 3 and 4; however, a complete treatment train, with source, local and regional controls, as modelled in Scenario 6, managed to achieve the annual pollutant removal targets stated in the *Management of Urban Stormwater Impacts Policy* (City of Cape Town, 2009).

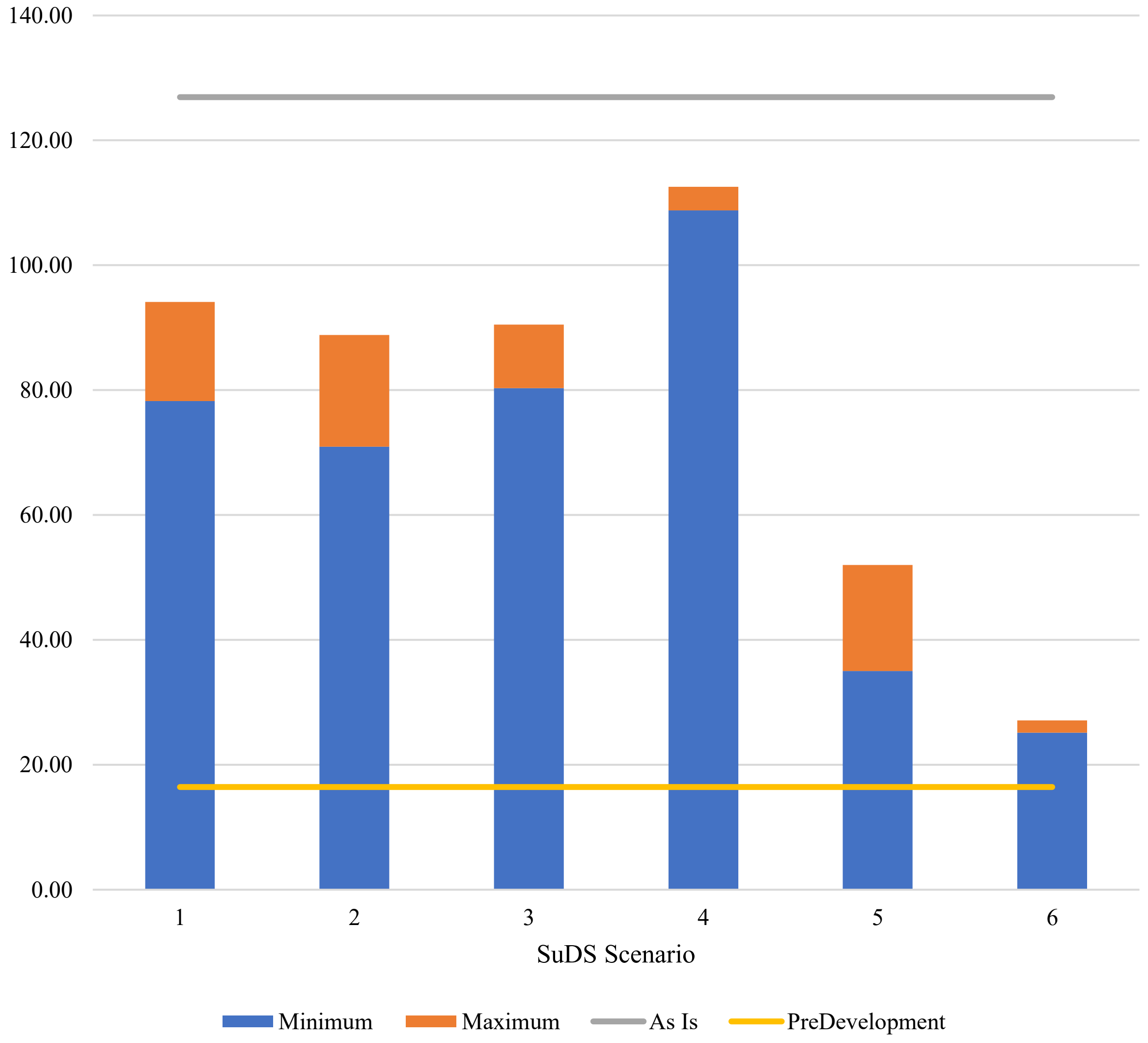


Figure 9-2: Modelled pollutant TSS loads (tonnes) in the BRC (2013 – 2022)

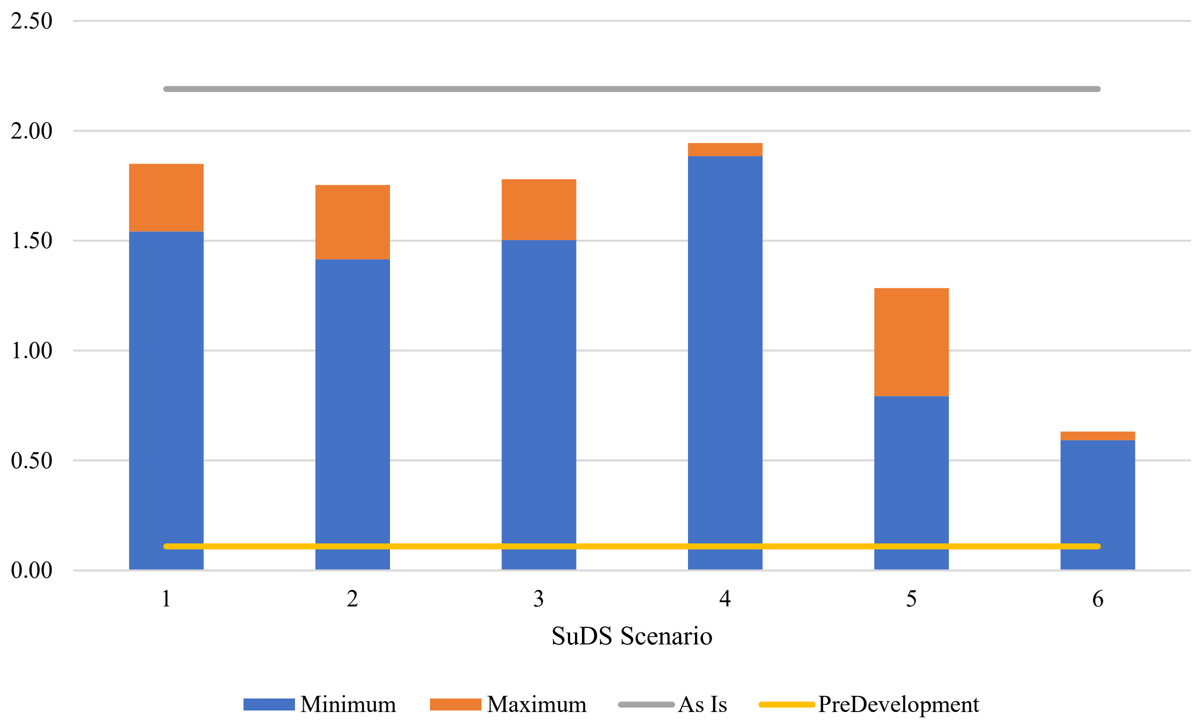


Figure 9-3: Modelled pollutant DIP loads (tonnes) in the BRC (2013 – 2022)

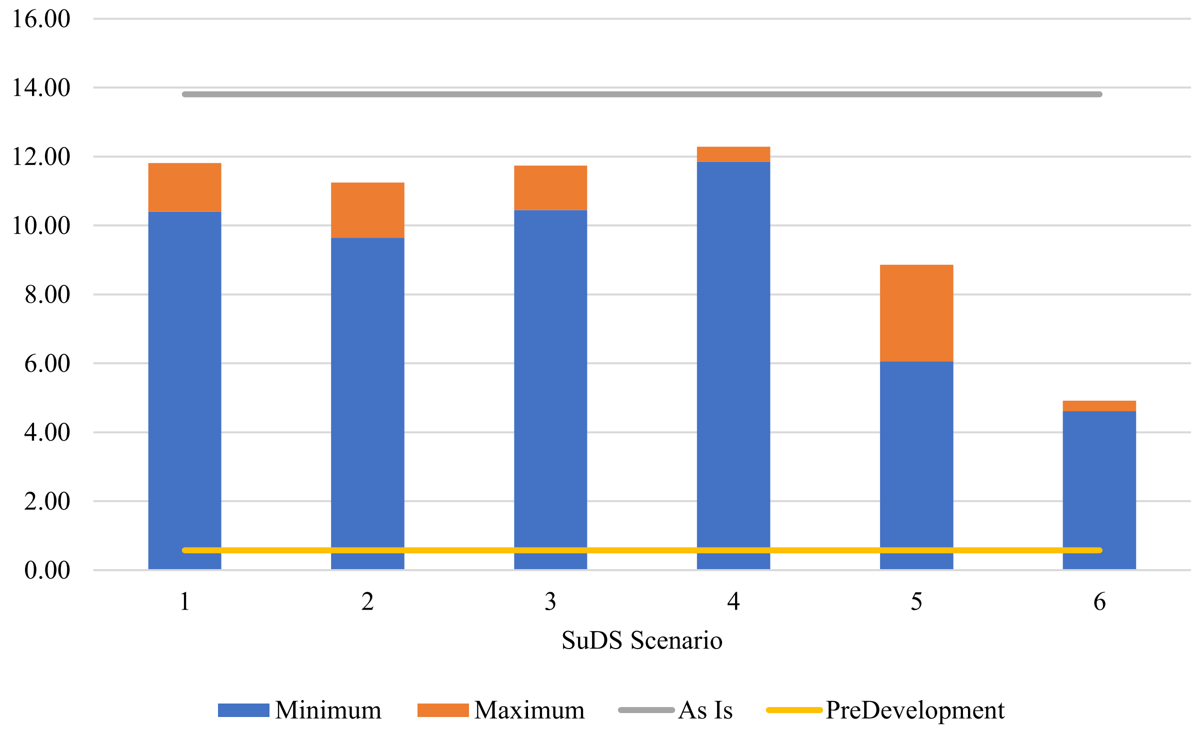


Figure 9-4: Modelled pollutant DIN loads (tonnes) in the BRC (2013 – 2022)

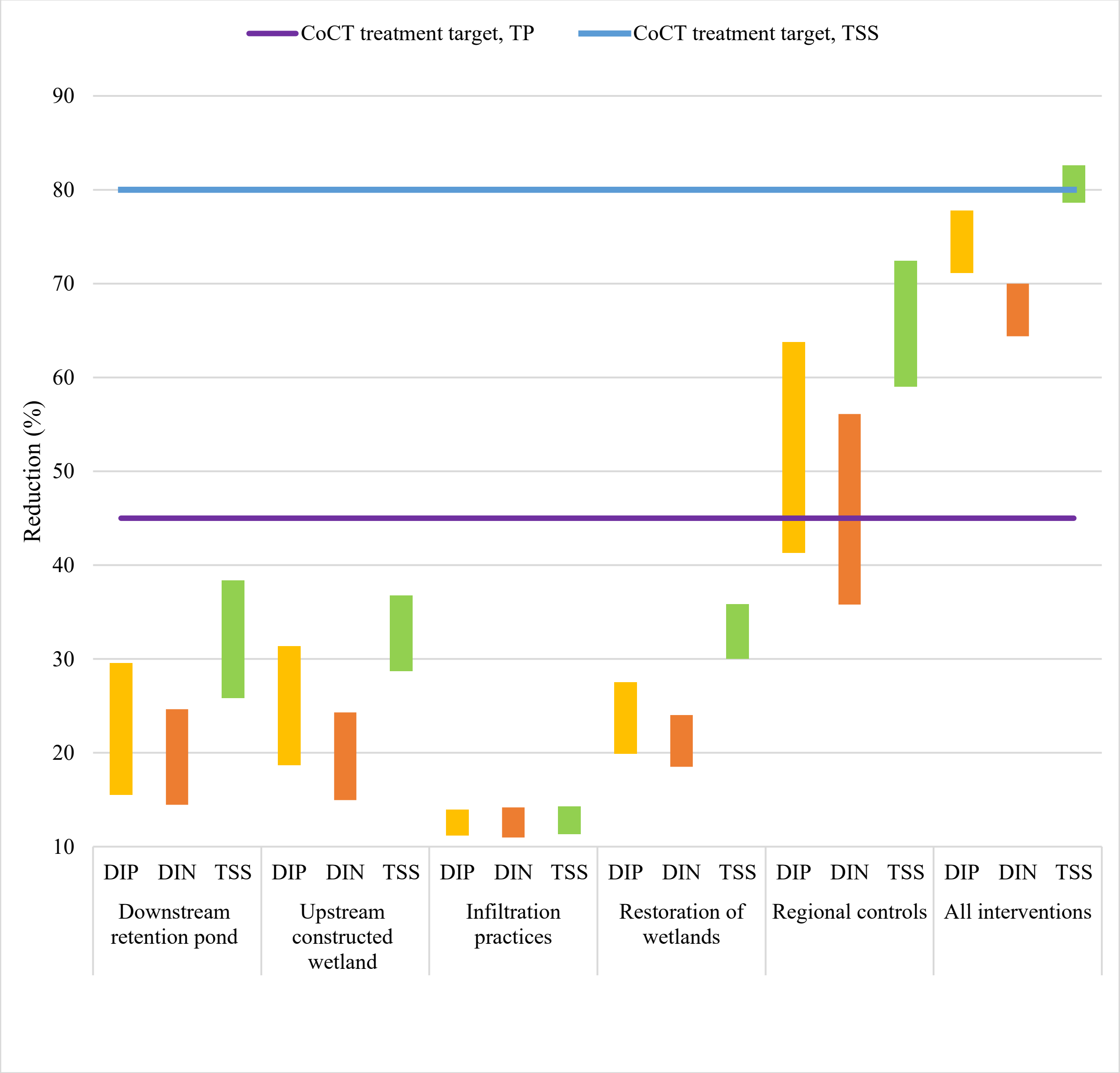
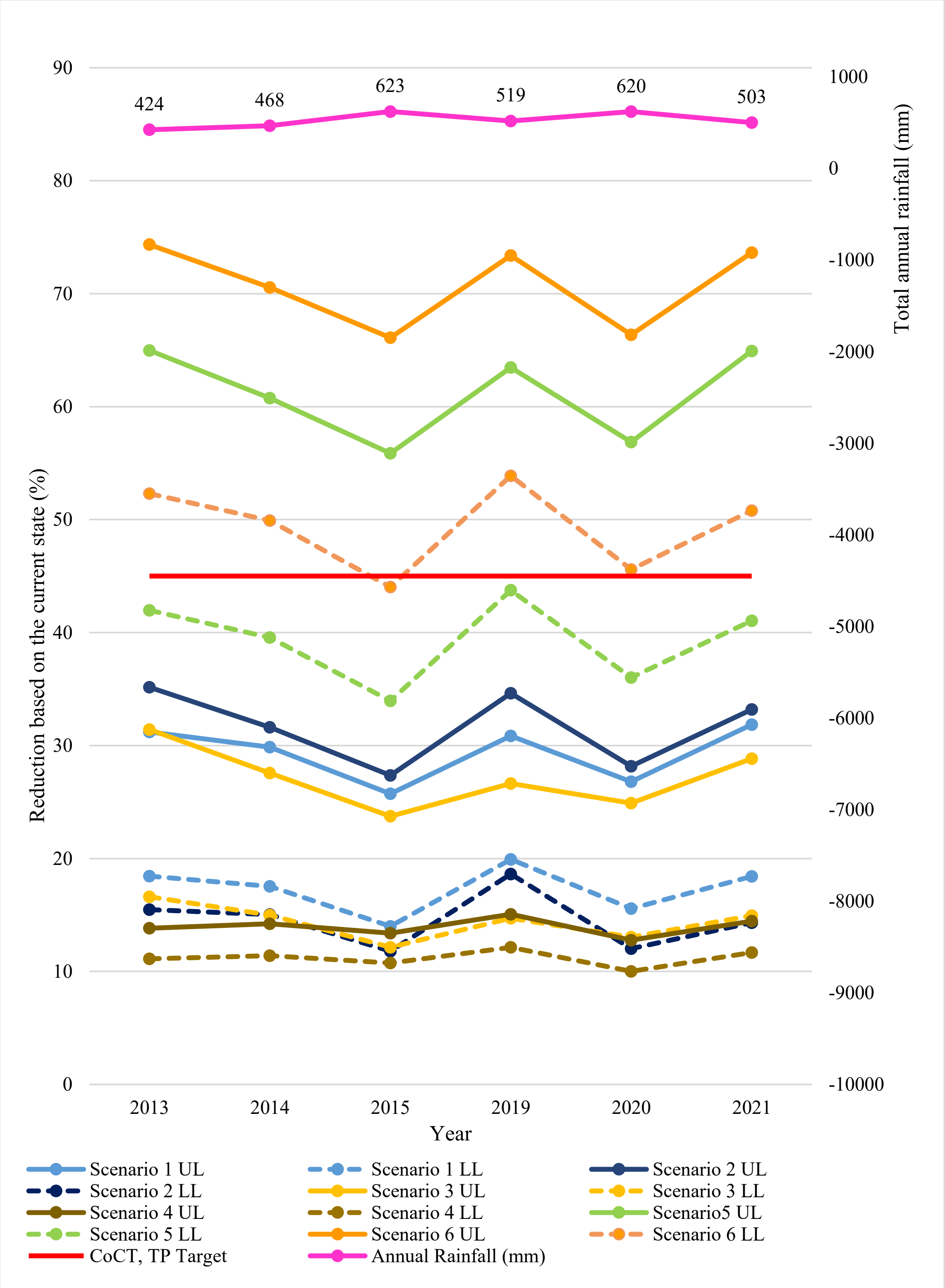


Figure 9-5: Percentage reduction in pollutant load over the 9 years and 5 months simulation period

9.3.1.2 Annual simulation results

The annual pollutant reduction of DIP, DIN and TSS was assessed to identify a relationship between the total annual rainfall patterns and the percentage of pollutant reduction in the various scenarios. The annual rainfall was seen to have a clear relationship with the percentage of pollutant reduction, with an increase in annual rainfall leading to a reduction in pollutant removal. The modelled SuDS interventions that operate through infiltration showed a higher pollutant removal percentage in years with lower total rainfall. This pattern is likely due to higher infiltration rates into less saturated soils.

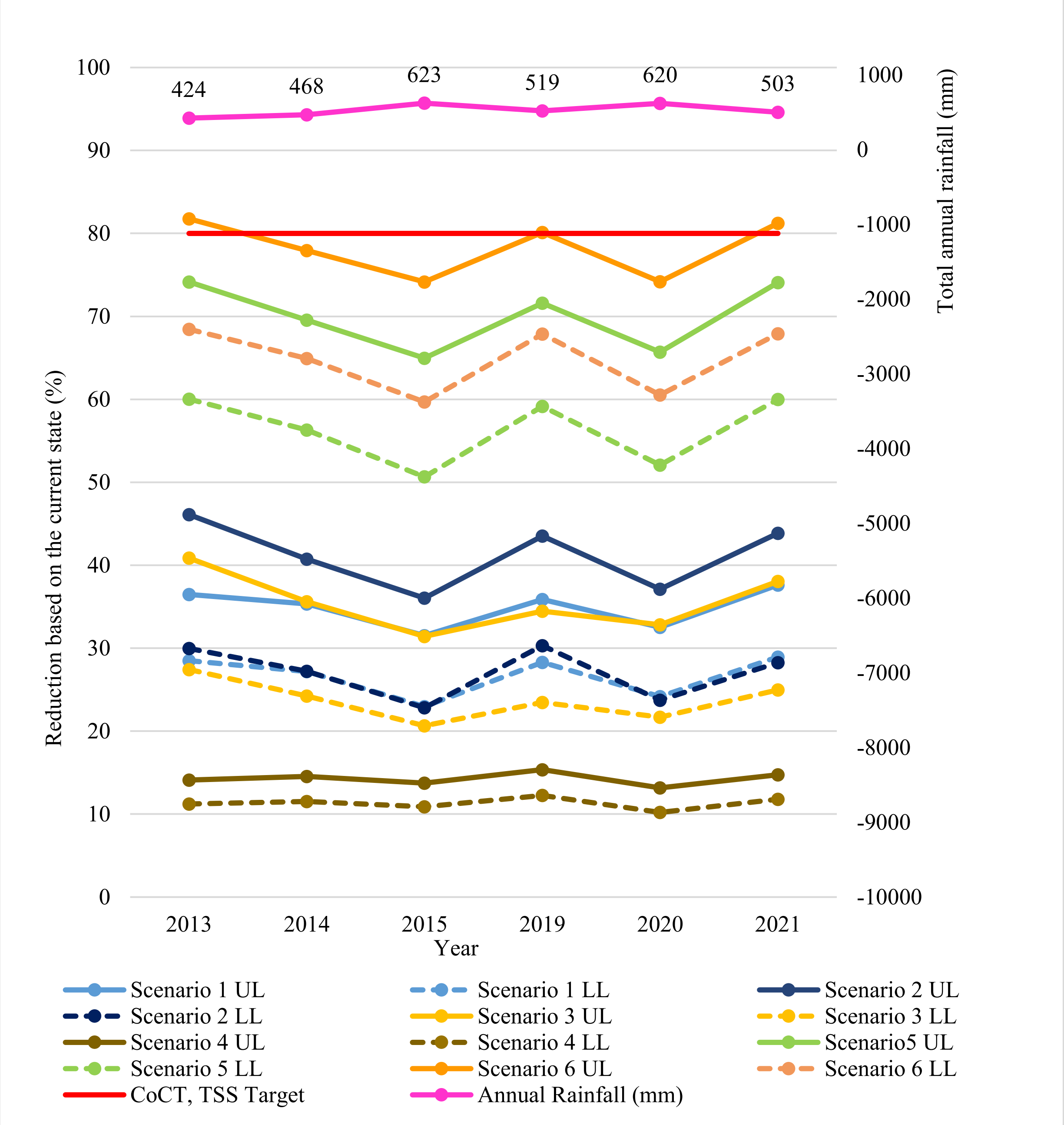


*UL – Upper Limit

*LL – Lower Limit

Figure 9-6: Annual percentage reduction in pollutant load for DIP

As shown in Figure 9-6, the DIP percentage removal is likely to meet the target set by the City of Cape Town (2009) in Scenarios 5 and 6 (Regional controls and all interventions, respectfully) for the various rainfall conditions when functioning efficiently. Only the upper treatment limit defined in Scenario 6 met the annual TSS removal target in 2013, 2019 and 2021, where the lower annual rainfall was recorded in Figure 9-7.



*UL – Upper Limit

*LL – Lower Limit

Figure 9-7: Annual percentage reduction in pollutant load for TSS

9.3.2 Potential impact on water quantity

Another significant impact of the inclusion of SuDS interventions was to peak flow and volume in the river system. As discussed in Section 2.1, urban development has increased runoff rates, early peak times, and high runoff volumes. SuDS interventions can assist with reducing runoff rates and volume. This section discusses the likely impact on water quantity at the Bethelsdorp tributary outlet.

Scenario 6, a combination of all the interventions, was the closest to achieving predevelopment peak flow rates at the BRC outlet for the 1 in 6-month 24-hour storm, as shown in Figure 9-8. Among the regional controls developed in Scenarios 1, 2 and 3, a delay in peak time was most significant in Scenario 2, the rehabilitated wetlands. Scenario 5 (Regional controls) and Scenario 6 also had significant peak-time delays. The delay in peak flow indicates attenuation of the flow. Larger temporary storage volumes would be required to achieve the target predevelopment peak discharge, however, the space available was prioritized in the determination of pond size.

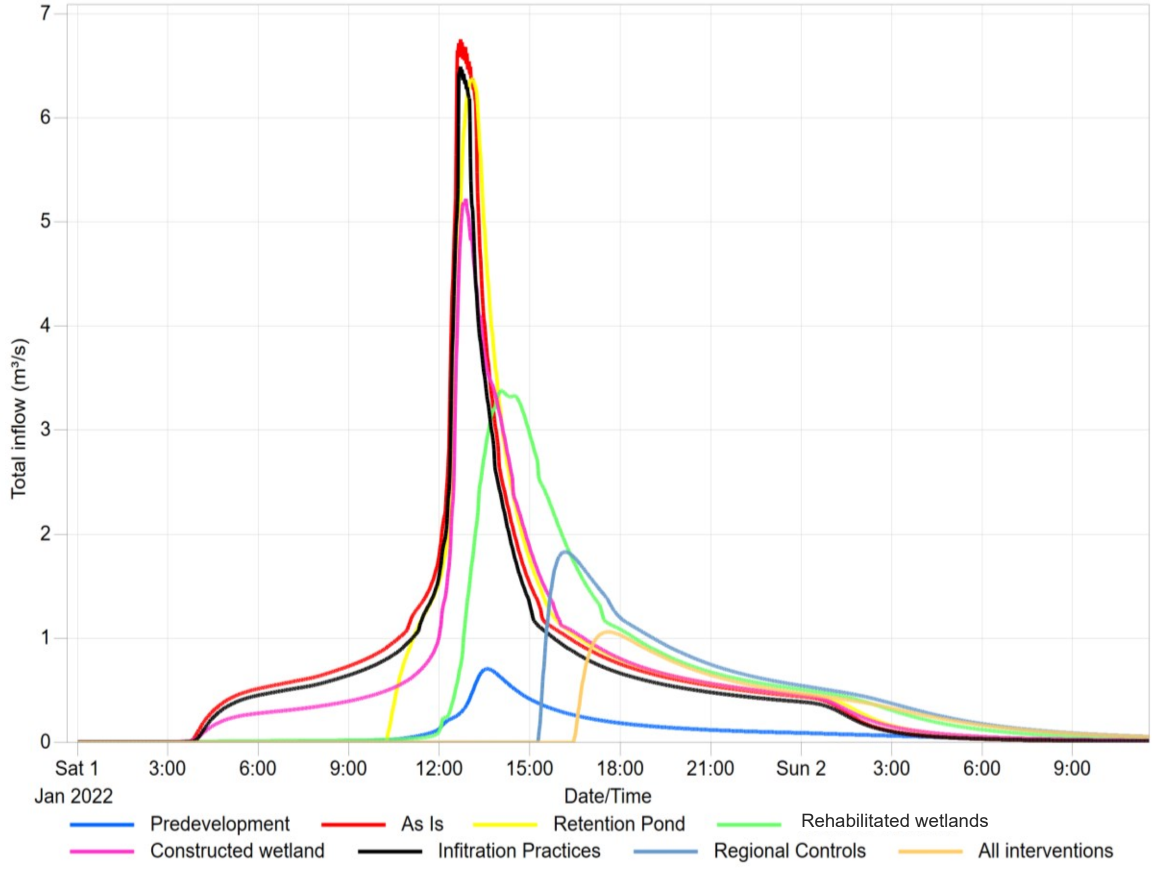


Figure 9-8: BRC Outlet flow rates during a 1 in 6-month, 24-hour SCS design storm

A noticeable reduction in runoff volume during the 24-hour storm was seen in Scenarios 4 and 6 from the As-is runoff volume. The reduction in runoff volume may be attributed to the increased infiltration in the scenarios due to the routing of runoff to pervious areas for infiltration. Scenarios 1, 2, 3 and 5 are exclusively made up of regional controls and had relatively small percentage reductions in runoff volume ranging from 0.1% and 0.2%.

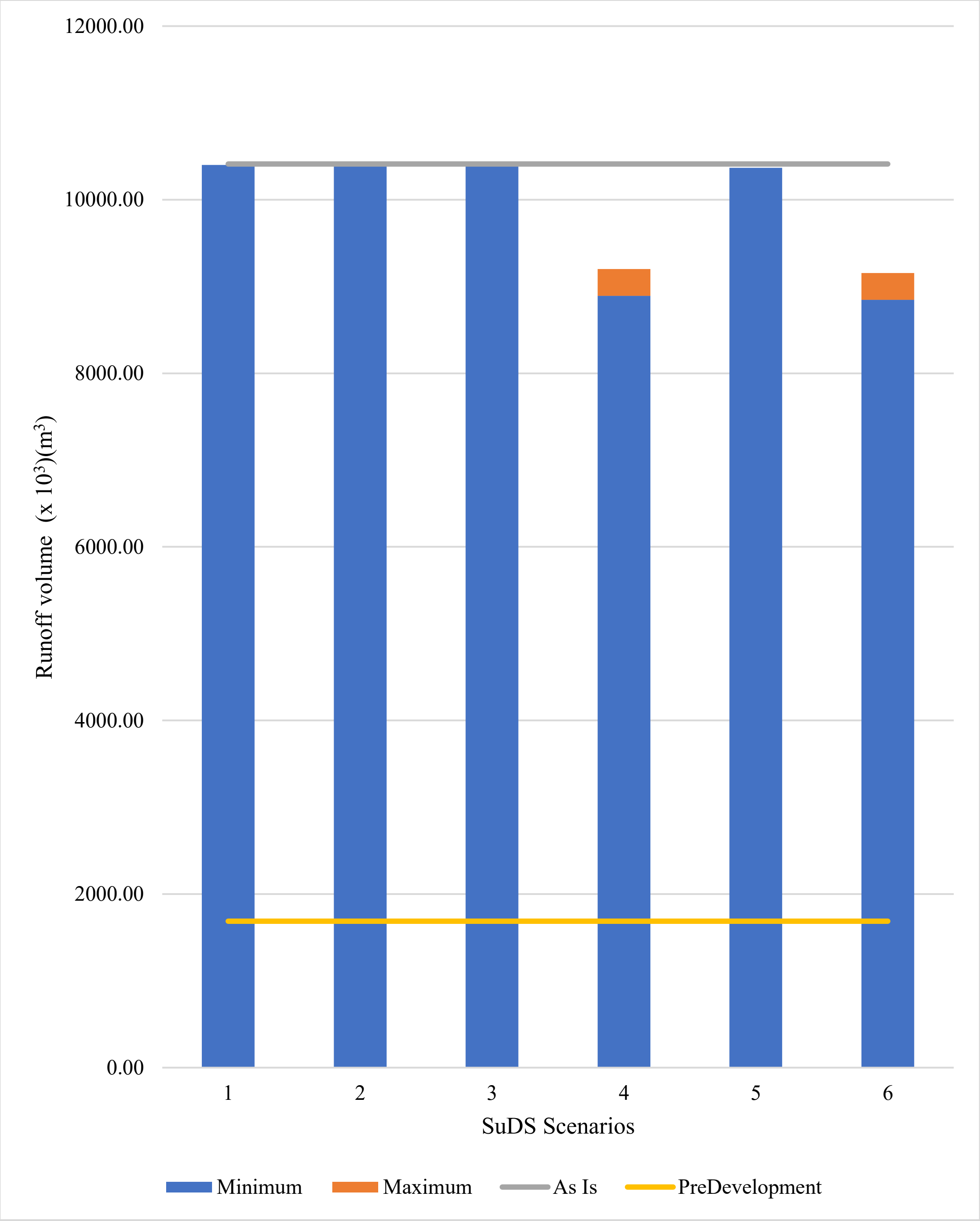


Figure 9-9: SuDS Scenarios runoff volume at the outlet (2013 – 2021)

10. Conclusions and recommendations

This study aimed to assess the current extent of pollution in the Chatty River Catchment and identify mitigation opportunities in a representative sub-catchment. The Bethelsdorp River Catchment was the representative catchment chosen to assess the impact of various mitigation strategies. Sustainable Drainage Systems (SuDS) were modelled as the potential mitigation measures as they not only have the potential to improve water quality, which was the primary focus in this study, but also to minimise the impact of development by maximizing amenity and biodiversity as described in the literature review. By reducing pollution levels in the Bethelsdorp River, and subsequently the Chatty River, the ecological state of the Swartkops Estuary would improve.

Water quality results from sample collection and historical data highlighted the extent of pollution in the Chatty River Catchment. Nutrient characteristics, that is, of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP), indicated eutrophic and hypertrophic conditions at the majority of the sample sites. During the site visits, residents were seen collecting water or playing in the Chatty River and its tributaries, however, *Escherichia coli* (E. *coli*) results highlighted the possible high gastrointestinal health risks to residents in the catchment who utilise the water for domestic and recreational use. The cost-effective application of SuDS to reduce pollution in the river would therefore need to be complimented by improved sanitary practices and an improved wastewater management system.

The potential of retrofitted SuDS to improve water quality was tested in PCSWMM against the current scenario ('As-Is) and the scenario prior to urban development (Predevelopment). DIN, DIP and total suspended solids (TSS) were the pollutants indicators tracked in the model. The likely maximum and minimum pollutant treatment limits were identified in the various scenarios. The SuDS interventions included: a constructed wetland, a retention pond, and various infiltration practices. Six scenarios were explored including various individual interventions, some regional controls and finally, the combination of all the interventions.

The scenario with the most significant impact was Scenario 6, a combination of all the interventions with the highest pollutant removal when functioning efficiently of 72% and 80% for DIP and TSS, respectively. The TSS removal range in Scenario 6 partially met the annual targets outlined in the *Management of Urban Stormwater Impacts Policy* by the City of Cape Town (2009) in 2016, 2019 and 2021. Complementary structures such as sedimentation ponds should be strongly considered for additional treatment and regular maintenance should be undertaken to meet the pollutant removal targets adequately. The fate of pollutants captured will also need to be considered and will depend on the specific detailed design and maintenance practices employed to avoid adverse effects due to their accumulation in the system. Furthermore, although proposals can be made, it would require stakeholder engagement to assess the needs and capacity of the relevant stakeholders.

Locating adequate space to treat the runoff flowing from the large catchment was a challenge because of, for example, the encroachment of developments in the floodplain, overall limited space due to dense urban development, and relatively steep slopes. Installing a treatment train with a variation of SuDS interventions was therefore identified as the most effective strategy to adequately improve water quality in the catchment. Challenges with locating space highlighted the importance of regional land use planning and the incorporation of strategies that include sustainable stormwater management. By considering stormwater management during the land use planning process, it becomes possible to strategically allocate space for effective runoff management and integrate it into the overall design of a region. Including stormwater engineers as part of the planning team allows for the integration of stormwater management considerations early in the planning process, enabling better coordination between land use planning and stormwater infrastructure design.

Data acquisition during the project also faced some challenges. The following tasks are recommended to avail a sufficient local database for future development and research:

- The establishment of secure flow measurement stations in the lower reaches of the catchment and various tributaries to facilitate the collection of calibration data required during hydrological modelling.
- Continuous water quality data collection to better understand spatial and temporal variations and the correlation of water quality to land use. Further research on this topic will enable the development of build-up and wash-off factors required for constructing water quality models. The impact of isolated events like sewage overflows and the cumulative effects of various land use practices, which play a crucial role in water pollution, should be evaluated further.
- Only one local rain gauge was identified as operational during the project—this limited the data on the variation of rainfall patterns in the catchment. Furthermore, there was no available and up-to-date temperature and evaporation data. The establishment and maintenance of additional weather stations across the catchment would be a great asset. Weather stations can be set up in various public institutions, such as schools, where they may provide additional benefits for the residents.

Although the implementation of SuDS seems to be a viable way to improve water quality in the Chatty River, it will require cooperation from the residents, municipality and various entities operating within the catchment to ensure its success. The following are some recommendations on how the community and governance structures may aid in efficiently implementing SuDS.

- Develop strategies and policies to reduce illegal litter and debris pollution in the catchment's open spaces and riverbanks. Litter and debris may lead to the clogging of SuDS structures.

- Undertake regular maintenance of existing infrastructure to avoid point pollution sources such as overflowing manholes which may convert SuDS interventions required to treat runoff to sewer treatment sites and thus reduce their operational capacity.
- Develop, implement or revise sanitation strategies for the residents of the catchment to hasten the eradication of the bucket system currently operating in the catchment and reduce pollution levels due to raw sewage.
- Collaborate with various non-profit organizations to undertake a variety of educational workshops in the various primary and high schools in the catchment to educate the residents on the importance of preserving the natural waterways and the greater environment.
- Finally, undertake future studies, utilising community engagement, to identify multifunctional opportunities of the recommended SuDS interventions.

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Appendices

Appendix A: Water quality

A.1 Preliminary testing

Table A-1: Results from the probe tests

Sample Site	Temperature (°C)	Salinity (ppt)	pH	Electrical Conductivity (µs/cm)	TDS (mg L^{-1})
1	15	4.3	8.36	Above 1999	Above 1000
2	15	1.4	7.95	Above 1999	Above 1000
3	13.6	2.8	8.07	Above 1999	Above 1000
4	13.7	1.4	8.11	Above 1999	Above 1000
5	14.7	0.7	7.6	1263	Above 1000
6	14.3	0.7	7.81	1170	Above 1000
7	13.9	1.2	7.75	1918	Above 1000
8	15.3	0.6	8.03	1075	Above 1000
9	14.3	1.2	7.80	Above 1999	Above 1000
10	17.6	0.7	7.30	1346	Above 1000
11	16.7	0	7.67	836	Above 1000

A.2 NMU sample results

Table A-2: Total Suspended solids (TSS) measurements (mg L^{-1})

Date	Chatty outflow 1	Chatty river 2	Kwadwesi stream 3	Bethelsdorp stream 4	Kemps Kloof 5	Chatty river 6	Booysen Park 7	Chatty river 10	Kemps Kloof 11	Kemps Kloof 12	Kemps Kloof 15	Bethelsdorp 14
25/08/2021	40.75	7.25	5.00	13.25	1.75	9.25	73.00	60.25	2.75	-	-	-
08/09/2021	58.25	9.75	28.50	21.75	1.75	6.75	46.75	16.75	11.25	-	-	-
15/09/2021	54.50	42.00	41.50	94.25	15.75	36.00	64.00	97.75	21.50	20.25	28.50	13.25
22/09/2021	41.50	19.75	35.25	137.75	23.00	13.50	64.50	41.50	11.00	18.00	17.25	27.50
06/10/2021	94.50	24.00	27.25	70.50	11.75	12.25	45.00	37.38	8.75	7.25	7.00	11.00
20/10/2021	253.00	35.25	41.50	47.25	10.00	19.00	102.00	21.00	15.50	13.75	19.25	10.25
03/11/2021	84.00	9.25	68.75	31.25	16.50	14.75	115.00	17.00	13.50	37.00	23.25	9.25
17/11/2021	137.00	19.25	19.25	53.75	22.25	30.25	43.25	22.75	17.75	11.25	17.00	25.75
01/12/2021	94.50	27.50	30.50	78.75	10.75	12.00	47.00	9.00	5.00	18.75	3.75	18.25
15/12/2021	40.00	13.25	20.50	85.25	6.25	10.50	43.75	4.00	8.00	17.25	6.50	5.50
12/01/2022	24.25	18.50	32.75	76.75	53.50	11.50	39.25	9.00	11.75	13.25	19.50	17.00
26/01/2022	21.75	18.50	9.75	357.00	23.75	5.00	16.75	7.00	11.75	16.75	16.50	9.00
09/02/2022	35.50	18.25	18.00	145.50	35.75	10.25	35.00	4.50	29.75	6.75	8.00	17.00
23/02/2022	50.00	5.75	32.50	14.25	3.25	8.25	38.50	5.00	10.25	28.00	22.75	8.50

Table A-3: ***Escherichia coli*** **(E.** ***coli*****) (colonies/100ml)**

Date	Chatty outflow 1	Chatty river 2	Kwadwesi stream 3	Bethelsdorp stream 4	Kemps Kloof 5	Chatty river 6	Booysen Park 7	Chatty river 10	Kemps Kloof 11	Kemps Kloof 12	Kemps Kloof 15	Bethelsdorp 14
28/07/2021	7100	190000	52000	60000000	2700	60	1400	3000	530000	-	-	-
11/08/2021	14000	1500	3700	8900	210000	68	3900	780	610000	-	-	-
25/08/2021	2000	2000	2000	2000	>2000	310	540	58	2000	-	-	-
08/09/2021	2000	2000	2000	2000	>2000	108	430	74	2000	-	-	-
15/09/2021	1200	2000	2000	2000	>2000	1400	2000	36	2000	260	500	860
22/09/2021	3700	69000	720000	700000	40000	680	30000	700	750000	90	800	1800
06/10/2021	550	290000	39000000	61000000	29000	1800	6500	2400	730000	6400	170	4000
20/10/2021	158	220000	1600000	47000	8200	280	4800	48	1500000	400	400	6500
03/11/2021	102	6800000	41000000	470000	470000	74	2500000	38	49000000	590	58	2300
17/11/2021	450	49000	2900000	3200000	32000	300	22000	148	79000	610	10	5200
01/12/2021	36	45000	690000	47000	15000	790	5200	1600	26000000	490	170	3000
15/12/2021	890	49000	590000	420000	18000	790	4600	940	1700000	400	28	4700
12/01/2022	90	155000	1840000	14000000	24500	290	1600	340	1150000	110	30	330
26/01/2022	93	53700	833000	22240000	281	480	2880	318	794000	39	14	272
09/02/2022	1120	53000	3076000	14210000	9804	132	1320	1046	1211000	82	687	8
23/02/2022	1203	7270	6488000	17300	663	135	720	565	474000	548	0	435

Table A-4: Dissolved Inorganic Nitrogen (mg L^{-1})

Date	Chatty outflow 1	Chatty river 2	Kwadwesi stream 3	Bethelsdorp stream 4	Kemps Kloof 5	Chatty river 6	Booysen Park 7	Chatty river 10	Kemps Kloof 11	Kemps Kloof 12	Kemps Kloof 15	Bethelsdorp 14
28/07/2021	2.43	2.69	3.28	3.81	3.61	3.42	4.07	2.41	2.95	-	-	-
11/08/2021	1.77	2.81	2.87	2.32	3.04	2.97	3.11	1.91	2.44	-	-	-
25/08/2021	0.76	2.51	2.83	2.21	3.22	2.74	2.94	2.03	2.35	-	-	-
08/09/2021	1.01	2.04	2.38	2.12	2.65	2.21	1.79	2.22	1.97	-	-	-
15/09/2021	1.58	1.63	1.37	1.13	1.40	3.42	2.61	1.70	1.16	3.13	1.77	3.23
22/09/2021	2.42	0.76	1.37	1.10	2.05	0.34	1.97	1.80	1.41	3.76	2.47	1.30
06/10/2021	2.67	2.65	1.93	1.67	1.75	2.62	3.26	2.03	1.68	2.33	3.98	1.90
20/10/2021	6.16	1.48	1.64	3.04	1.60	3.75	5.08	1.99	1.47	1.35	2.24	1.41
03/11/2021	4.35	2.10	1.84	2.30	2.04	2.37	2.72	2.15	2.09	2.11	1.49	1.42
17/11/2021	0.87	1.90	1.80	1.86	1.88	1.78	2.10	1.47	1.58	1.71	0.99	1.80
01/12/2021	2.87	2.04	2.08	1.73	1.65	2.13	4.18	2.37	1.87	1.36	1.77	4.52
15/12/2021	4.42	2.51	2.48	2.53	2.67	3.81	4.56	2.72	2.31	1.95	3.01	2.14
12/01/2022	3.20	3.14	3.26	3.50	2.95	2.96	5.83	2.55	2.80	2.02	1.67	2.02
26/01/2022	3.74	2.86	2.55	2.62	2.64	2.53	14.89	2.68	2.28	1.95	1.33	2.33
09/02/2022	3.25	2.78	2.55	2.27	2.70	7.01	20.53	2.84	2.39	2.08	1.14	1.85
23/02/2022	2.23	2.98	3.08	2.27	3.39	2.24	9.44	2.82	2.96	2.47	2.32	2.14

Table A-5: Dissolved Inorganic Phosphorus (mg L^{-1})

Date	Chatty outflow 1	Chatty river 2	Kwadwesi stream 3	Bethelsdorp stream 4	Kemps Kloof 5	Chatty river 6	Booysen Park 7	Chatty river 10	Kemps Kloof 11	Kemps Kloof 12	Kemps Kloof 15	Bethelsdorp 14
28/07/2021	0.35	0.67	0.64	1.11	0.81	0.41	0.25	0.02	0.39	-	-	-
11/08/2021	0.30	0.53	0.70	0.27	1.03	0.23	0.53	0.00	0.41	-	-	-
25/08/2021	0.32	0.69	0.63	0.50	0.86	0.76	0.55	0.01	0.35	-	-	-
08/09/2021	0.39	0.55	0.64	0.32	0.94	0.78	0.12	0.01	0.42	-	-	-
15/09/2021	0.52	0.50	0.62	0.60	0.73	0.46	0.07	0.02	0.34	0.27	0.02	0.50
22/09/2021	0.28	0.33	0.56	0.75	0.56	0.06	0.33	0.03	0.44	0.40	0.17	0.02
06/10/2021	0.65	0.47	0.57	0.97	0.64	0.47	0.39	0.02	0.40	0.23	0.40	0.02
20/10/2021	0.43	0.47	0.37	0.29	0.27	0.28	0.22	0.03	0.17	0.09	0.20	0.04
03/11/2021	0.71	0.89	0.79	0.72	0.82	0.55	0.42	0.01	0.46	0.04	0.23	0.02
17/11/2021	0.35	0.84	0.77	0.93	0.81	0.58	0.54	0.03	0.47	0.05	0.31	0.04
01/12/2021	0.49	0.47	0.43	0.40	0.34	0.41	0.21	-	0.19	0.11	0.00	0.01
15/12/2021	0.83	0.70	0.63	1.02	0.70	0.60	0.43	0.03	0.48	0.16	0.42	0.05
12/01/2022	0.50	0.86	0.64	1.02	0.59	0.62	0.30	0.03	0.57	0.28	0.39	0.07
26/01/2022	0.22	0.36	0.32	0.33	0.35	0.19	0.15	-	0.23	0.01	0.09	0.02
09/02/2022	0.25	0.25	0.33	0.36	0.33	0.33	0.17	-	0.29	0.01	0.01	0.10
23/02/2022	0.44	0.41	0.48	0.17	0.49	0.43	0.24	0.00	0.46	0.01	0.12	0.05

Table A-6: Salinity (ppt)

Date	Chatty outflow 1	Chatty river 2	Kwadwesi stream 3	Bethelsdorp stream 4	Kemps Kloof 5	Chatty river 6	Booysen Park 7	Chatty river 10	Kemps Kloof 11	Kemps Kloof 12	Kemps Kloof 15	Bethelsdorp 14
28/07/2021	3.31	1.77	1.09	1.41	0.89	1.82	3.42	0.96	0.63	-	-	-
11/08/2021	3.32	1.31	0.96	1.95	0.89	0.73	2.39	0.89	0.61	-	-	-
25/08/2021	3.73	1.62	0.92	1.77	0.91	2.23	2.00	0.84	0.67	-	-	-
08/09/2021	3.01	1.26	0.82	1.97	0.82	1.69	0.92	0.91	0.59	-	-	-
15/09/2021	7.48	1.71	0.82	1.34	0.82	2.22	1.61	0.96	0.6	0.58	0.62	0.5
22/09/2021	4.61	0.73	0.82	1.29	0.83	0.31	2.18	1.04	0.59	0.57	0.71	0.52
06/10/2021	11.85	1.39	0.82	1.29	0.83	2.13	2.01	1.08	0.66	0.6	0.68	0.61
20/10/2021	13.24	1.53	0.82	1.5	0.84	1.88	2.37	0.99	0.65	0.55	0.64	0.59
03/11/2021	6.71	1.62	0.91	1.58	0.94	1.95	2.11	1.06	0.69	0.53	0.72	0.7
17/11/2021	5.81	1.75	1.00	1.72	1.03	2.02	2.33	1.11	0.7	0.55	0.71	0.77
01/12/2021	5.45	1.67	1.01	1.72	0.94	1.68	2.33	1.23	0.72	0.55	0.72	0.71
15/12/2021	4.42	1.95	1.05	1.58	1.07	2.18	2.98	1.2	0.77	0.63	0.69	0.84
12/01/2022	4.22	1.64	0.87	1.23	0.92	1.79	2.58	1.31	0.68	0.55	0.74	0.72
26/01/2022	17.75	1.52	0.84	1.38	0.79	1.24	2.14	1.16	0.68	0.54	0.79	0.82
09/02/2022	5.48	1.7	0.88	1.89	0.91	1.79	2.37	1.24	0.69	0.54	0.82	0.61
23/02/2022	6.18	1.65	0.8	2.45	0.8	1.29	1.88	1.01	0.67	0.53	0.83	0.54

Table A-7: Dissolved Oxygen (%)

Date	1 Chatty Outflow	2 Chatty	3 Kwadwesi	4 Bethelsdorp	5 Kemps Kloof	6 Chatty	7 Booysen Park	10 Chatty	11 Kemps Kloof	12 Kemps Kloof	15 Kemps Kloof	14 Bethelsdorp
28/07/2021	102.6	12.2	52.8	10.7	27.1	54.9	66.1	61.1	19.3	-	-	-
11/08/2021	66.5	24.3	29.9	82.9	27.9	61.8	62.5	52	24.7	-	-	-
25/08/2021	75.1	12	21.5	55.5	9.1	36.3	46.3	46.1	16.9	-	-	-
08/09/2021	96.6	38.5	28	151.9	22.6	47.2	80.7	58.5	17.4	-	-	-
15/09/2021	114.5	23.5	19.6	7.7	30.3	43.7	49.8	88	17.2	73.2	68.4	118.7
22/09/2021	141.3	9	28.5	10.4	18.5	95.8	38.5	41.4	15.3	77.8	48.4	120.8
06/10/2021	67.7	7	17.5	2.8	14.5	47.8	48.2	49.4	13	74.3	39.4	111.7
20/10/2021	202.9	7.6	9.8	53.2	12.2	32.7	43	37.4	9.8	73.7	167.7	139.4
03/11/2021	65.1	16.6	26.4	47.6	20.5	46.1	47.7	47.3	17.2	81.7	76.1	131.1
17/11/2021	61.9	21.2	33.6	23.6	19.8	43.7	39.3	36.1	20.6	84.5	69.8	117.8
01/12/2021	27	25.7	51.7	53.7	20	52.8	56.7	56.4	13.7	83.7	56.2	113.3
15/12/2021	75.7	23.6	57.2	10.6	17.6	38.9	53.9	50	16.7	86.7	55	132.2
12/01/2022	43.4	19.1	38.4	8.9	15.6	42.4	47.9	57.7	136.3	82.5	62.4	15.1
26/01/2022	17.4	18.6	31.2	12.2	14.9	37.7	41.4	44.5	11.5	83.3	53.6	83.5
09/02/2022	131.9	23.9	29.7	11.8	17.2	35.8	43.1	40.9	18.7	88.4	100.1	186.6
23/02/2022	22	22.3	21.7	83.8	31.3	48.9	53.8	43.2	15.7	86.4	73.1	162.5

Table A-8: Turbidity (FNU)

Date	Chatty outflow 1	Chatty river 2	Kwadwesi stream 3	Bethelsdorp stream 4	Kemps Kloof 5	Chatty river 6	Booysen Park 7	Chatty river 10	Kemps Kloof 11	Kemps Kloof 12	Kemps Kloof 15	Bethelsdorp 14
28/07/2021	27.7	26.52	6.97	162.54	16.67	33.9	34.41	2.64	27.56	-	-	-
11/08/2021	30.71	2.45	24.1	4.82	14.35	5.09	16.72	5.03	43.36	-	-	-
25/08/2021	21.25	5.3	21.2	12.14	3.7	9.43	39.99	2.85	26.16	-	-	-
08/09/2021	26.95	2.91	75.03	9.99	38.32	10.47	24.05	1.91	52.59	-	-	-
15/09/2021	7.12	9.21	20.93	76.64	16.74	13.06	33.39	598	33.1	5.82	2.78	3.67
22/09/2021	6.3	15.1	19.28	200.52	61.55	5.52	37.31	2.08	49.7	4.47	3.43	5.16
06/10/2021	21.9	9.66	10.42	268.96	1.97	6.88	22.68	2.29	68.74	2.61	10.01	6.29
20/10/2021	30.46	51.76	23.46	19.79	10.75	5.64	56.33	24.52	80.53	8.14	12.97	10.65
03/11/2021	30.64	42.06	34.15	18.57	56.83	8.08	65.76	3.15	34.21	14.71	15.28	28.42
17/11/2021	50.32	35.37	25.07	21.57	58.68	7.01	21.14	1.7	48.08	5.07	8.48	9.03
01/12/2021	40.64	23.09	26.53	41.97	3.61	6.78	31.81	5.96	42.64	5.41	6.12	13.58
15/12/2021	20.98	32.56	11.24	111.67	11.53	22.06	25.53	5.85	108.94	8.21	9	4.93
12/01/2022	7.59	25	16.66	183.55	21.15	4.11	19.73	1.71	24.24	5.61	8.85	99.3
26/01/2022	8.84	47.93	14.42	4	39	4.6	19.31	34.41	0.96	5.79	8.22	12.21
09/02/2022	8.41	13.37	36.86	121.67	14.26	3.42	17.81	61.13	75.98	5.6	8.44	6.99
23/02/2022	202.97	2.57	35.44	24.12	7.45	4.84	22.73	10.83	150.58	7.83	8.89	5.9

Table A-9: Electrical Conductivity (ms/cm)

Date	Chatty outflow 1	Chatty river 2	Kwadwesi stream 3	Bethelsdorp stream 4	Kemps Kloof 5	Chatty river 6	Booysen Park 7	Chatty river 10	Kemps Kloof 11	Kemps Kloof 12	Kemps Kloof 15	Bethelsdorp 14
28/07/2021	4.715	2.604	1.778	2.302	1.371	2.619	5.098	1.61	0.995	-	-	-
11/08/2021	4.273	1.859	1.379	2.589	1.274	1.082	3.13	1.467	0.994	-	-	-
25/08/2021	5.136	2.391	1.403	2.558	1.351	3.159	2.859	1.398	1.052	-	-	-
08/09/2021	4.381	1.914	1.357	3.088	1.287	2.52	1.496	1.548	0.947	-	-	-
15/09/2021	10.837	2.672	1.404	2.326	1.377	3.492	2.715	1.641	0.992	0.979	1.043	0.86
22/09/2021	6.579	1.142	1.306	2.127	1.287	0.542	3.258	1.696	0.954	0.948	1.136	0.934
06/10/2021	16.322	2.186	1.342	2.181	1.327	3.222	3.102	1.795	1.08	1.004	1.113	1.109
20/10/2021	19.058	2.49	1.445	2.657	1.362	2.977	3.913	1.681	1.085	0.969	1.078	1.138

Table A-10: pH

Date	Chatty outflow 1	Chatty river 2	Kwadwesi stream 3	Bethelsdorp stream 4	Kemps Kloof 5	Chatty river 6	Booysen Park 7	Chatty river 10	Kemps Kloof 11	Kemps Kloof 12	Kemps Kloof 15	Bethelsdorp 14
28/07/2021	6.27	8.35	7.5	7.56	7.64	7.24	6.81	6.41	7.05	-	-	-
11/08/2021	8.94	7.25	7.5	7.76	7.17	7.53	7.5	6.76	7.6	-	-	-
25/08/2021	6.99	7.52	7.45	7.49	7.52	7.35	7.47	7.34	7.26	-	-	-
08/09/2021	10.15	8.76	7.88	8.4	9.09	8.04	8.8	7.74	10.07	-	-	-
15/09/2021	6.34	7.32	5.8	6.7	8.17	6.97	5.65	8.26	6.6	6.39	5.56	6.38
22/09/2021	8.15	6.4	5.39	5.13	6.11	6.09	5.97	4.72	8.21	5.86	7.04	5.81
06/10/2021	6.61	6.7	7.1	6.12	7.7	6.25	6.47	6.01	8.34	7.25	8.26	7.62
20/10/2021	9.36	9.13	7.74	7.46	11.62	8.32	7.64	8.57	9.88	8.09	8.82	8.46
03/11/2021	8.37	7.84	7.95	7.97	7.7	7.75	7.88	7.23	7.37	7.77	8.17	8.94
17/11/2021	8.91	8.02	8.04	8.03	7.55	7.79	7.92	7.39	7.48	7.9	7.81	8.67
01/12/2021	8.04	7.9	7.9	8.04	7.65	7.71	7.77	7.37	7.43	7.79	7.66	8.71
15/12/2021	8.13	7.73	7.8	7.83	7.63	7.59	7.72	7.3	6.96	7.76	7.55	8.54
12/01/2022	8.34	7.91	7.79	7.6	7.56	7.66	7.77	7.62	9.1	7.86	7.8	7.48
26/01/2022	7.44	8.01	7.85	7.78	7.66	7.75	7.79	7.74	7.32	7.91	7.85	8.19

A.3 Event Mean Value estimation

Table A-11: Published EMC Values (in mg L^{-1})

Pollutant	Land Use	Cerfonteyn & Day (2010)	Chow, Yusop & Shirazi (2013)	Song *et al.* (2019)	Line *et al.* (2002)	Wicke *et al.* (2021)	DEFRA (2013)	Mean
DIN	Urban formal	3.41			1.34		0.98	1.91
	Urban Informal	22						22.0
	Mining	2.1		120	0.71		1.16	31.0
	Agricultural	1.56			1.61			1.59
	Open space	1.56					0.94	1.25
	Freeways	2.1					0.81	1.70
	Natural vegetation	1.51						1.51
DIP	Urban formal		0.07	20			0.19	6.75
	Urban Informal		3.00					3.00
	Mining						0.16	0.16
	Agricultural					0.4		0.4
	Open space		140				0.06	70.03
	Freeways			20			0.18	6.76
TSS	Urban formal	100		31.9	73			68.3
	Urban Informal	497						497
	Mining	166		35.57	231		50	121
	Agricultural	201			151			176
	Open space	201	147				126	158
	Freeways	166		143			132	147
	Natural vegetation	70						70

A.1.1 Event Mean Concentration example

This example details the procedure used to estimate the DIN Event Mean Concentration (EMC) factors for water quality modelling. The first step was to determine the percentage variation of land use in the areas contributing to each site (Table A-12).

Table A-12: The percentage weight of each land use in the areas contributing to a measuring point

	Agriculture (%)	Mine (%)	Open Space (%)	Roads (%)	Formal (%)	Informal (%)	Total (%)
Site 14 (Bethelsdorp)	0	2	62	0	36	0	100
Site 4 (Bethelsdorp)	0	1	52	0	46	1	100
Site 15 (Kemps Kloof)	1	7	79	1	8	5	100
Site 12 (Kemps Kloof)	1	7	77	1	10	4	100
Site 11 (Kemps Kloof)	1	7	76	1	11	4	100
Site 5 (Kemps Kloof)	1	5	69	1	20	5	100
Site 10 (Chatty)	23	2	68	2	2	3	100
Site 6 (Chatty)	18	8	61	1	10	2	100
Site 2 (Chatty)	24	2	62	2	9	2	100

*Green indicated the site with the highest percentage of a particular land use

The PCSWMM Chatty River Catchment model was simulated with the published EMC values (Table A-11) for the testing period, July 2021 to February 2022. The output from the model was used to calculate the modelled mean concentrations at each site using Equation A-1 (Table A-14). The modelled mean concentration was compared to the measured mean concentration for the water sample testing period (July 2021 to February 2022). A site was considered calibrated if the modelled mean concentration was within 10% of the measured mean concentration, indicated by the adjustment factor (Equation 6-1).

$$\boldsymbol{Modelled\ mean\ concentration} = \frac{\boldsymbol{Total\ pollutant\ load\ x\ 10^6}}{\boldsymbol{Total\ inflow\ at\ measuring\ point}} \qquad \text{(A-1)}$$

where Modelled mean concentration (mg L^{-1}); Total pollutant load (kg); and Total volume at measuring point (L)

Sites 15, 12 and 11 were within 10% of the measured mean concentration. Furthermore, the 'open space' land use was most dominant at the three sites and occupied a majority of their contributing areas. The EMC for open space was therefore estimated as 0.95.

Table A-13: Modelled mean concentration at each site using the published EMC factors

	Mean measured concentrations (mg L^{-1})	Modelled mean concentration (mg L^{-1})	Adjustment factor
Site 14 (Bethelsdorp)	2.17	1.25	1.74
Site 4 (Bethelsdorp)	2.28	1.67	1.36
Site 15 (Kemps Kloof)*	2.02	2.18	0.93
Site 12 (Kemps Kloof)*	2.18	2.11	1.03
Site 11 (Kemps Kloof)*	2.11	2.01	1.05
Site 5 (Kemps Kloof)	2.45	2.08	1.18
Site 3 (Kwadwesi)	2.33	3.12	0.75
Site 10 (Chatty)	2.23	1.42	1.57
Site 6 (Chatty)	2.89	2.02	1.43
Site 2 (Chatty)	2.31	1.42	1.63

*Yellow indicates the sites whose modelled mean concentration is within 10% of the measured mean concentration

Table A-14: Phase 1 adjusted EMC factors

	Agriculture	Mine	Roads	Formal	Informal
Site 14 (Bethelsdorp)	-	1.8	1.2	3.0	-
Site 4 (Bethelsdorp)	-	1.4	0.9	2.4	30.0
Site 5 (Kemps Kloof)	1.4	1.2	0.8	2.1	26.0
Site 10 (Chatty)	1.8	1.7	1.1	2.7	34.5
Site 6 (Chatty)	1.9	1.7	1.1	2.8	35.8
Site 2 (Chatty)	1.7	1.5	1.0	2.5	31.5
Mean value	1.8	1.6	1.87	2.58	31.5

The adjustment factor was applied to the published EMC values for the various land use EMC factors that required calibration (Table A-14). The mean EMC factors from the various land uses were calculated and applied in the model. The output of the simulation is documented in Table A-15.

Table A-15: Modelled mean concentrations at each site using the first phase EMC factors

	Mean measured concentrations (mg L^{-1})	Modelled mean concentration (mg L^{-1})	Adjustment factor
Site 14 (Bethelsdorp)	2.17	1.52	1.42
Site 4 (Bethelsdorp)*	2.28	2.13	1.06
Site 5 (Kemps Kloof)*	2.45	2.58	0.95
Site 10 (Chatty)	2.23	1.721	1.30
Site 6 (Chatty)	2.31	1.74	1.37
Site 2 (Chatty)	2.89	2.52	1.15

*Yellow indicates the sites whose modelled mean concentration is within 10% of the measured mean concentration

The area contributing to Site 4 had the highest percentage of formal land use. Furthermore, formal land use was the second most dominant land use in the contributing area following open space which had been calibrated. An EMC factor associated with formal land use was estimated at this stage as 2.58. Although Site 5 was within 10%, open space land use was dominant in the contributing area followed by formal land use which had already been estimated. The adjustment factors were therefore applied and the new EMC values were input into the model (Table A-16).

Table A-16: Phase 2 adjusted EMC factors

	Agriculture	Mine	Roads	Informal
Site 14 (Bethelsdorp)	-	2.1	1.4	-
Site 5 (Kemps Kloof)	1.7	1.4	0.9	27.6
Site 10 (Chatty)	2.3	1.9	1.2	37.6
Site 6 (Chatty)	2.4	1.9	1.3	38.5
Site 2 (Chatty)	2.1	1.7	1.1	33.3
Mean value	2.3	1.9	2.25	36.5

Site 2 (Table A-17) was within 10% of the measured mean concentration and had the highest percentage of agricultural land use. Furthermore, other than open space, agriculture was the second highest land use in the area contributing to Site 2. The EMC factor associated with agriculture was therefore estimated in this phase as 2.3.

Table A-17: Modelled mean concentrations at each site using the second phase EMC factors

	Mean measured concentrations (mg L^{-1})	Modelled mean concentration (mg L^{-1})	Adjustment factor
Site 14 (Bethelsdorp)	2.17	1.63	1.33
Site 5 (Kemps Kloof)	2.45	2.73	0.90
Site 10 (Chatty)	2.23	1.87	1.19
Site 6 (Chatty)	2.31	1.89	1.22
Site 2 (Chatty)*	2.89	2.75	1.05

*Yellow indicates the sites whose modelled mean concentration is within 10% of the measured mean concentration

Table A-18: Phase 3 adjusted EMC factors

	Mine	Roads	Informal
Bethelsdorp stream 14	2.5	3.0	-
Kemps Kloof 5	1.9	2.2	32.7
Chatty 10	1.7	2.0	43.5
Chatty 6	2.2	2.7	44.6
Mean value	2.1	2.48	40.3

Table A-19: Modelled mean concentrations at each site using the third phase EMC factors

	Mean measured concentrations (mg L^{-1})	Modelled mean concentration (mg L^{-1})	Adjustment factor
Site 14 (Bethelsdorp)	2.17	1.811687764	1.19
Site 5 (Kemps Kloof)	2.45	3.294406897	0.74
Site 10 (Chatty)*	2.23	2.097679012	1.06
Site 6 (Chatty)*	2.31	2.13232	1.08

*Yellow indicates the sites whose modelled mean concentration is within 10% of the measured mean concentration

The EMC factors associated with mining, road infrastructure and informal land use were adjusted using the adjustment factors in Table A-17 for the remaining sites and their associated EMC factors were inputted into the model (Table A-19).

Amongst the sites remaining for calibration, the contributing areas of Sites 10 and 6, within 10% of the measured mean concentration, had the highest percentage of roads and mining land use respectively. The associated EMC values were therefore estimated in this phase as 2.1 for mining and 2.48 for roads (Table A-19).

The final EMC factor to be estimated (Table A-20) was associated with informal land use. The adjustment factor of 0.74 was applied to the EMC factor from the third phase, 40.3 to obtain a new EMC factor, 30 in the 4th phase. This EMC was inputted for informal land use and after the simulation, the modelled mean concentration at Site 5 (Kemps Kloof) was 3.13, which was outside the 10% range. The EMC factor was recalculated in the 5th phase to 23.4 using the adjustment factor. The modelled concentration at Site 5 was 2.56, within 10% of the measured mean concentration. The EMC factor associated with informal land use was therefore estimated to be 23.4.

Table A-20: Summary of data used in phase 4 and phase 5 EMC estimation

	Mean measured concentrations (mg L^{-1})	Modelled mean concentration (mg L^{-1})	Informal land use
Site 5 (Kemps Kloof) phase 4	2.45	3.14	30
Site 5 (Kemps Kloof)* Phase 5	2.45	2.56	23.4

*Yellow indicates the sites whose modelled mean concentration is within 10% of the measured mean concentration

Table A-21: Percentage of variation of modelled mean concentration to measured mean concentration using final EMC factors

	Mean measured concentrations (mg L^{-1})	Modelled mean concentration (mg L^{-1})	Percentage variation from the measured mean
Site 14 (Bethelsdorp)	2.17	1.97	1.09
Site 4 (Bethelsdorp)	2.28	2.15	1.06
Site 15 (Kemps Kloof)*	2.02	2.44	0.83
Site 12 (Kemps Kloof)*	2.18	2.38	0.92
Site 11 (Kemps Kloof)*	2.11	2.29	0.92
Site 5 (Kemps Kloof)	2.45	2.42	1.01
Site 10 (Chatty)	2.23	1.77	1.26
Site 6 (Chatty)	2.31	1.81	1.27
Site 2 (Chatty)	2.89	2.48	1.17

*Yellow indicates the sites whose modelled mean concentration is within 10% of the measured mean concentration

The final step was to run the model with the estimated EMC values to assess the percentage variation of the modelled mean concentrations during the testing period to the measured mean concentrations. The modelled mean concentration of the majority of sites in the Bethelsdorp tributary and Kemps Kloof tributary were within 10% variation of the measured mean concentration.

A.4 Water quality standards

Table A-22: Nitrogen (Inorganic) and Phosphorus (Inorganic) Trophic ranges for aquatic ecosystems (DWS, 1996)

Mean Summer Concentration (mgL^{-1})		Trophic state
Inorganic Nitrogen	Inorganic Phosphorus	
<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

Appendix B: Climate data

B.1 Evapotranspiration data

Table B-1: Average monthly evapotranspiration

Month	Monthly average temperature (ºC)	Mean daily maximum temperature (ºC)	Mean daily minimum temperature (ºC)	Extra-terrestrial radiation, Ra $(MJm^{-2}d^{-1})$	Monthly average evaporation (mm/day)
January	22.8	27.0	18.6	56.9	15.9
February	22.3	26.7	17.9	31.8	13.8
March	21.4	26.4	16.4	33.0	10.8
April	19.2	24.8	13.6	23.5	8.0
May	17.5	23.9	11.1	21.5	5.9
June	14.8	22.2	7.5	17.2	4.8
July	14.5	21.1	7.9	18.2	5.0
August	15.9	22.4	9.3	22.1	6.8
September	16.2	21.9	10.4	35.0	9.0
October	18.1	22.9	13.2	38.3	11.9
November	19.0	23.5	14.5	45.7	13.9
December	21.5	25.9	17.1	43.0	15.9

B.2 Rainfall data

Table B-2: Average recurrence intervals generated by NetSTORM

Duration	Average Recurrence Interval (ARI)										
	1 - month	3 - month	6 - month	1 - yr	2 - yr	5 - yr	10 - yr	25 - yr	50-yr	100-yr	200-yr
Event	8	25.4	33.2	33.7	48.2	61.6	71.9	86.5	98.7	112	127
1-hour	3.52	7	9.64	12.2	18	21.4	23.1	25	26.2	27.1	27.9
6-hour	6.6	14.3	20.1	20.6	28.6	37	44.1	55.3	65.4	77.5	91.8
24-hour	8	20.6	30	24.8	40.1	55.5	67.9	86.6	103	122	144

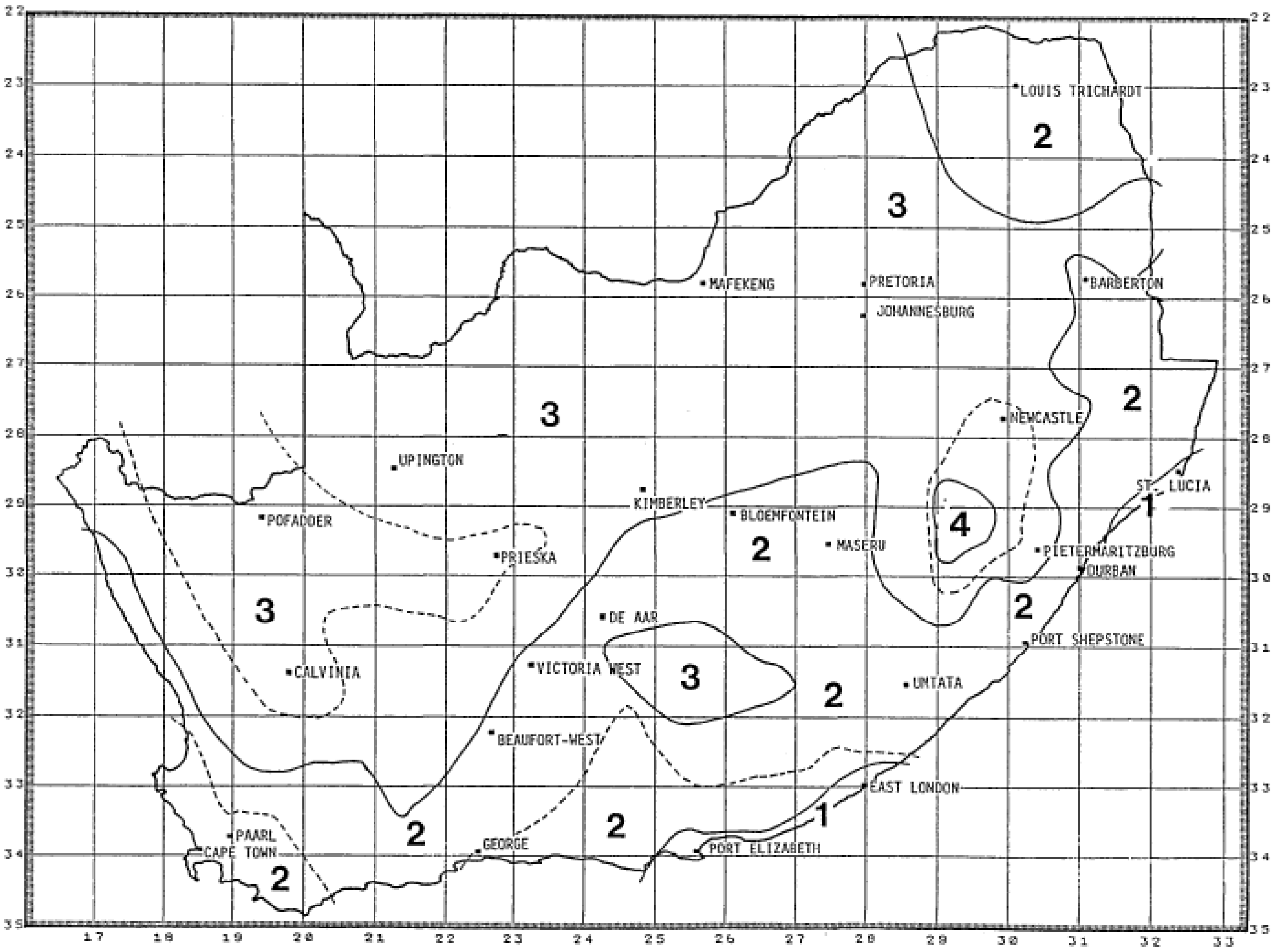


Figure B-1: Regionalisation of synthetic rainfall distributions (Schmidt, Schulze & Dent, 1987)

Appendix C: Sieve Analysis results

C.1 Sieve Analysis Equations

Equations C-2 and C-3 were used to calculate the Coefficient of Uniformity, C_u, and Coefficient of Curvature, C_c, respectively (British Standards Institution, 1990).

$$C_u = \frac{D_{60}}{D_{10}} \tag{C-2}$$

$$C_c = \frac{{D_{30}}^2}{D_{60}\ x\ D_{10}} \tag{C-3}$$

where D_{60}= a diameter of which 60% of the sample is smaller (mm); D_{10}= a diameter of which 10% of the sample is smaller (mm); and D_{30}= a diameter of which 30% of the sample is smaller (mm)

C.2 Van Der Kemps Kloof Site

Table C-1: Van Der Kemps Kloof soil datasheet

Location	Van Der Kemps Kloof Site
Date Tested	30th September
Tested By	AMNA
Weight of the container	316.8
Weight of the container +Dry Soil	681.8
Weight of the Dry Sample	365

Sieve Opening Diameter (mm)	**Mass of Empty Sieve (g)**	**Mass of Sieve + Soil retained (g)**	**Mass of soil retained (g)**	**Percentage Retained %**	**Cumulative Retention %**	**Percentage Passing %**
4.750	437.7	454.0	16.3	4.5	4.5	95.5
2.000	400.4	420.9	20.5	5.7	10.2	89.8
0.600	333.5	369.7	36.2	10.0	20.1	79.9
0.425	296.4	338.2	41.8	11.5	31.7	68.3
0.300	278.3	336.1	57.8	15.9	47.6	52.4
0.150	263.1	395.6	132.5	36.6	84.2	15.8
0.075	256.8	302.6	45.8	12.6	96.8	3.2
pan	460.0	471.5	11.5	3.2	100.0	0.0
		Total weight	362.4			

Table C-2: Van Der Kemps Kloof USCS Grain Size Range

RESULTS - USCS Grain Size Range					
% Gravel	4.5	**D60 (mm)**	0.360	**Cu= D60/D10**	3.11
% Sand	92.3	**D30 (mm)**	0.208	**Cc=D30^2/D10*D60**	1.04
% Fines	3.2	**D10 (mm)**	0.116		

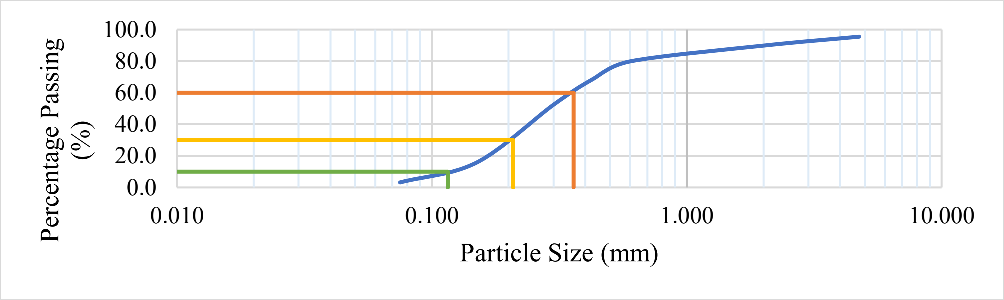


Figure C-1: Van Der Kemps Kloof site Particle Size Distribution Curve

C.3 Chatty 10 Site

Table C-3: Site 10 (Chatty) soil datasheet

Location	Chatty 10 Site
Date Tested	30th September
Tested By	AMNA
Weight of the container	309.9
Weight of the container +Dry Soil	632.9
Weight of the Dry Sample	323

Sieve Opening Diameter (mm)	Mass of Empty Sieve (g)	Mass of Sieve + Soil retained (g)	Mass of soil retained (g)	Percentage Retained %	Cumulative Retention %	Percentage Passing %
4.750	437.7	441.6	3.9	1.2	1.2	98.8
2.000	400.4	436.2	35.8	11.1	12.3	87.7
0.600	333.5	413.8	80.3	24.9	37.2	62.8
0.425	296.4	332.3	35.9	11.1	48.3	51.7
0.300	278.3	315.4	37.1	11.5	59.8	40.2
0.150	263.1	333.3	70.2	21.7	81.5	18.5
0.075	256.8	300.3	43.5	13.5	95.0	5.0
pan	460.0	476.3	16.3	5.0	100.0	0.0
		Total weight	323			

Table C-4: Site 10 (Chatty) USCS Grain Size Range

RESULTS - USCS Grain Size Range					
% Gravel	1.2	**D60 (mm)**	0.555	**Cu= D60/D10**	5.41
% Sand	93.7	**D30 (mm)**	0.229	**Cc=D30^2/D10*D60**	0.92
% Fines	5.0	**D10 (mm)**	0.103		

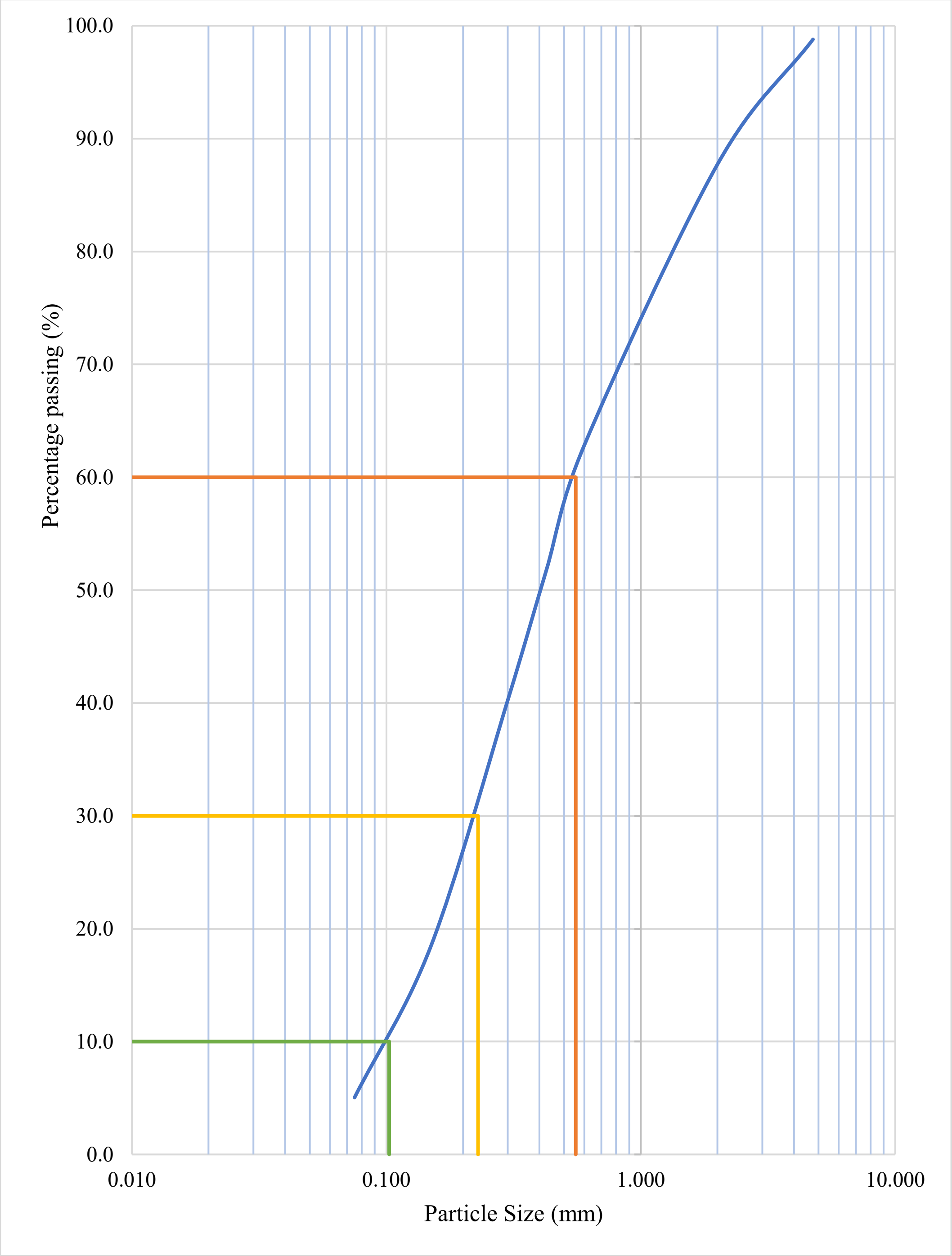


Figure C-2: Site 10 (Chatty) Particle Size Distribution Curve

C.4 Booysen Site

Table C-5: Booysen site soil datasheet

Location	Booysen Site
Date Tested	30th September
Tested By	AMNA
Weight of the container	301
Weight of the container +Dry Soil	515.6
Weight of the Dry Sample	214.6

Sieve Opening Diameter (mm)	**Mass of Empty Sieve (g)**	**Mass of Sieve + Soil retained (g)**	**Mass of soil retained (g)**	**Percentage Retained %**	**Cumulative Retention %**	**Percentage Passing %**
4.750	437.7	441.4	3.7	1.7	1.7	98.3
2.000	400.4	431.2	30.8	14.4	16.2	83.8
0.600	333.5	392.6	59.1	27.7	43.8	56.2
0.425	296.4	319.7	23.3	10.9	54.8	45.2
0.300	278.3	303.1	24.8	11.6	66.4	33.6
0.150	263.1	301.2	38.1	17.8	84.2	15.8
0.075	256.8	279.9	23.1	10.8	95.0	5.0
pan	460.0	470.6	10.6	5.0	100.0	0.0
		Total weight	213.5			

Table C-6: Booysen site USCS Grain Size Range

RESULTS - USCS Grain Size Range					
% Gravel	1.7	**D60 (mm)**	0.794	**Cu= D60/D10**	7.23
% Sand	93.3	**D30 (mm)**	0.269	**Cc=D30^2/D10*D60**	0.83
% Fines	5.0	**D10 (mm)**	0.110		

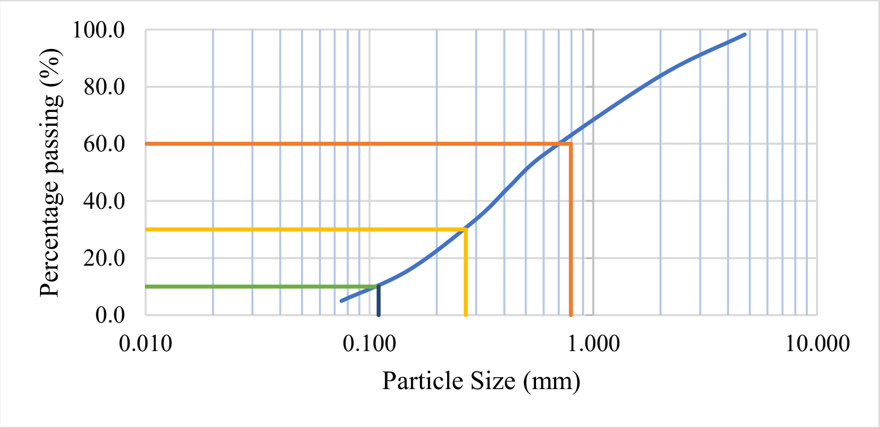


Figure C-3: Booysen site Particle Size Distribution Curve

C.5 Chatty 6 Site

Table C-7: Site 6 (Chatty) soil datasheet

Location	Chatty 6 Site
Date Tested	30th September
Tested By	AMNA
Weight of the container	255.6
Weight of the container +Dry Soil	686.1
Weight of the Dry Sample	430.5

Sieve Opening Diameter (mm)	**Mass of Empty Sieve (g)**	**Mass of Sieve + Soil retained (g)**	**Mass of soil retained (g)**	**Percentage Retained %**	**Cumulative Retention %**	**Percentage Passing %**
4.750	437.7	523.5	85.8	19.9	19.9	80.1
2.000	400.4	451.0	50.6	11.8	31.7	68.3
0.600	333.5	393.0	59.5	13.8	45.5	54.5
0.425	296.4	328.2	31.8	7.4	52.9	47.1
0.300	278.3	318.2	39.9	9.3	62.2	37.8
0.150	263.1	355.5	92.4	21.5	83.6	16.4
0.075	256.8	310.8	54.0	12.5	96.2	3.8
pan	460.0	476.5	16.5	3.8	100.0	0.0
		Total weight	430.5			

Table C-8: Site 6 (Chatty) USCS Grain Size Range

RESULTS - USCS Grain Size Range					
% Gravel	19.9	**D60 (mm)**	1.158	**Cu= D60/D10**	10.35
% Sand	76.2	**D30 (mm)**	0.245	**Cc=D30^2/D10*D60**	0.46
% Fines	3.8	**D10 (mm)**	0.112		

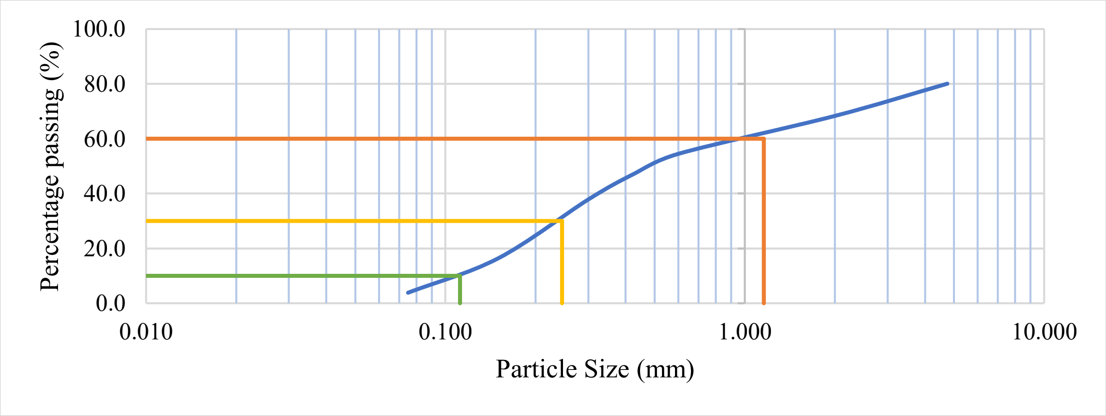


Figure C-4: Site 6 (Chatty) Particle Size Distribution Curve

C.6 Chatty 2 Site

Table C-9: Site 2 (Chatty) site soil datasheet

Location				Chatty 2		
Date Tested				30th September		
Tested By				AMNA		
Weight of the container				296.2		
Weight of the container +Dry Soil				500		
Weight of the Dry Sample				203.8		
Sieve Opening Diameter (mm)	**Mass of Empty Sieve (g)**	**Mass of Sieve + Soil retained (g)**	**Mass of soil retained (g)**	**Percentage Retained %**	**Cumulative Retention %**	**Percentage Passing %**
4.750	437.7	479.1	41.4	20.3	20.3	79.7
2.000	400.4	423.3	22.9	11.3	31.6	68.4
0.600	333.5	375.8	42.3	20.8	52.4	47.6
0.425	296.4	311.8	15.4	7.6	60.0	40.0
0.300	278.3	295.1	16.8	8.3	68.2	31.8
0.150	263.1	296.3	33.2	16.3	84.5	15.5
0.075	256.8	278.5	21.7	10.7	95.2	4.8
pan	460.0	469.8	9.8	4.8	100.0	0.0
		Total weight	203.5			

Table C-10: Site 2 (Chatty) USCS Grain Size Range

RESULTS - USCS Grain Size Range					
% Gravel	20.3	**D60 (mm)**	1.434	**Cu= D60/D10**	12.87
% Sand	74.8	**D30 (mm)**	0.284	**Cc=D30^2/D10*D60**	0.50
% Fines	4.8	**D10 (mm)**	0.111		

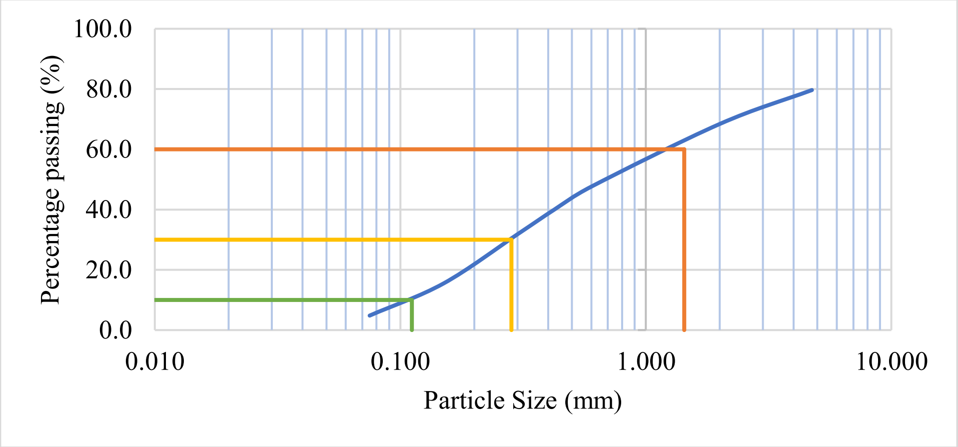


Figure C-5: Site 2 (Chatty) Particle Size Distribution Curve

Appendix D: Additional flow measurement techniques attempted during the project

D.1 Use of Chalk sticks

The first attempt to collect flow data was using chalk sticks that were identified as a simple, low-cost, low-risk and low-cost method. 8 mm thick and 32 mm wide wooden sticks, marked in 10 mm increments, were made from Meranti. A waterproof matte varnish was used to coat the wood to both protect it as well as providing a suitable surface that could be coated with chalk. Once the varnish application was complete and dry, the wooden sticks were coated with blackboard chalk and housed in perforated PVC trunking material, 40 mm wide and 16 mm thick. The chalk sticks were finally cut to the length of the culvert height, and contact adhesive or tape was used to attach the chalk sticks to the culvert wall, as shown in Figure D-1. During a storm, the rising water level washes off the chalk up to the water's surface. After the storm, the wooden rulers were pulled out vertically to remove them from the PVC housing. The peak depth was indicated by the high-water mark indicated by the chalk line visible on the wooden surface. The wooden surface was dried with a paper towel and re-chalked.

Selected locations with reasonably uniform flow were chosen for the application of the Manning equation (Equation 5-5) in the flow rate calculation from the depth measurements.

Figure D-1: Chalk stick placement

The flow depth data would have been collected biweekly at the sites shown in Figure 5-9. This frequency was determined by the NMU staff availability. The high-water mark and flow depth during the data collection were to be measured from all the sites. However, the chalk sticks and most of the PVC trunking material were stolen before the first set of measurements could be taken; hence, the measurement technique was abandoned.

D.2 Solinst Levelogger

A Solinst levelogger is an instrument used for measuring and recording water level changes in surface water bodies using pressure transducers. It can be programmed to record data at set intervals. A Solinst levelogger was installed at Site 2 (Chatty) (Figure 5-9), the effective outlet of the Chatty River Catchment. The Solinst levelogger was concealed within a casing which was hidden, as shown in Figure D-2, in an attempt to protect the instrument from theft.

Figure D-2: Solinst levelogger casing

The levelogger installed was used to measure the surface water level. The instrument measured total absolute pressure, ‘*L*’. The difference between the levelogger total pressure readings, ‘*L*’, and the barometric pressure in the column above the water level, *D*, was used to calculate the water pressure in column ‘*A*’, as shown in Figure D-3. A barologger, ‘*B*’, placed above the water level as shown at ‘*D’*, was used to collect barometric pressure for barometric compensation.

Data was to be extracted from the data logger by connecting it to a PC using an Optical Reader or PC Interface Cable. However, at the time of collection, the logger at the effective outlet of the catchment, Site 2, was missing, indicating theft of the equipment.

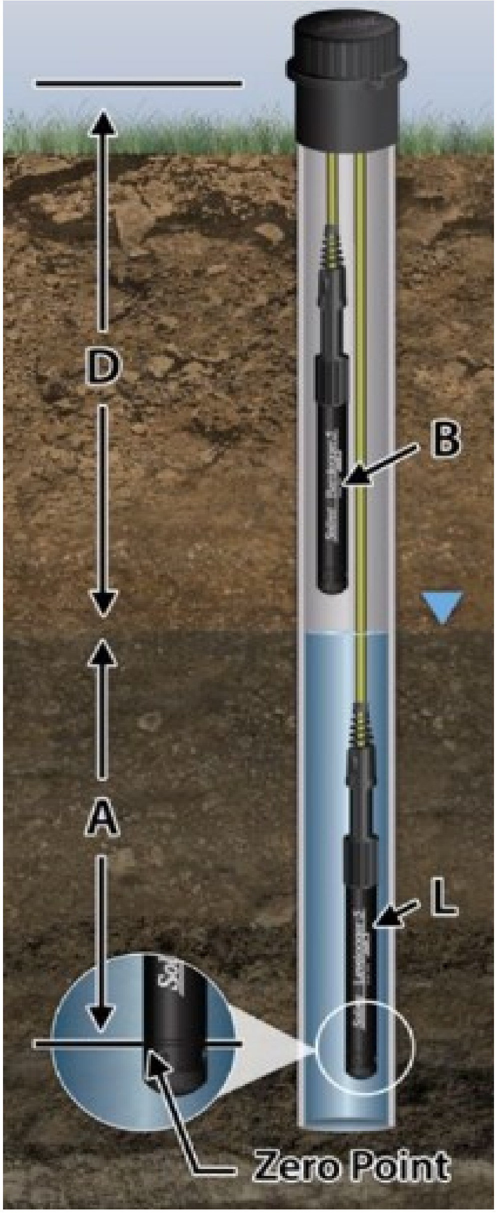


Figure D-3: Levelogger measurements (Solinst, n.d.)

A second attempt was made to measure flow with the flow at Site 2 and Site 14 using the Solinst Levelogger. However, the trapezoidal channel and outlet at Site 14 were filled with litter and rubble and there was overgrown vegetation in the channel (Figure D-4) which would have taken more than a week to clear making it very expensive. Furthermore, the team assigned, through DWS, to clear the channel highlighted the high-security risk associated with working at the site. Site (2) Chatty was therefore chosen as a flow monitoring location. Unfortunately, due to logistical issues, the process was unsuccessful.

Figure D-4: Overgrown channel and illegal litter dumping at Site 14 (Bethelsdorp) (September 2022)

Appendix E: Conceptual design considerations

Table E-1: Considerations for the conceptual design of wetlands and ponds (Townsville Council, 2011; Armitage *et al*., 2013; Woods-Ballard *et al*., 2015)

Parameter	Design consideration
Permanent water depth	1 – 1.2 m above the bottom of the pond
Temporary water depth	0.5 – 0.75 m
Water Quality Volume (WQV) depth	Maximum 1.75 m
Emergency overflow depth	250 – 400 mm
Maximum pond/wetland depth	2 m from the bottom of the pond
Minimum width-to-length ratio	Between 5:1 and 3:1
Bathymetry for wetlands	0-0.5 m – 50% of wetland 0.5-1.0 m – 30% of wetland 1.0-1.5 m – 20% of wetland
Duration of extended detention during a 1 in 6-month, 24-hour SCS design storm	24 hours

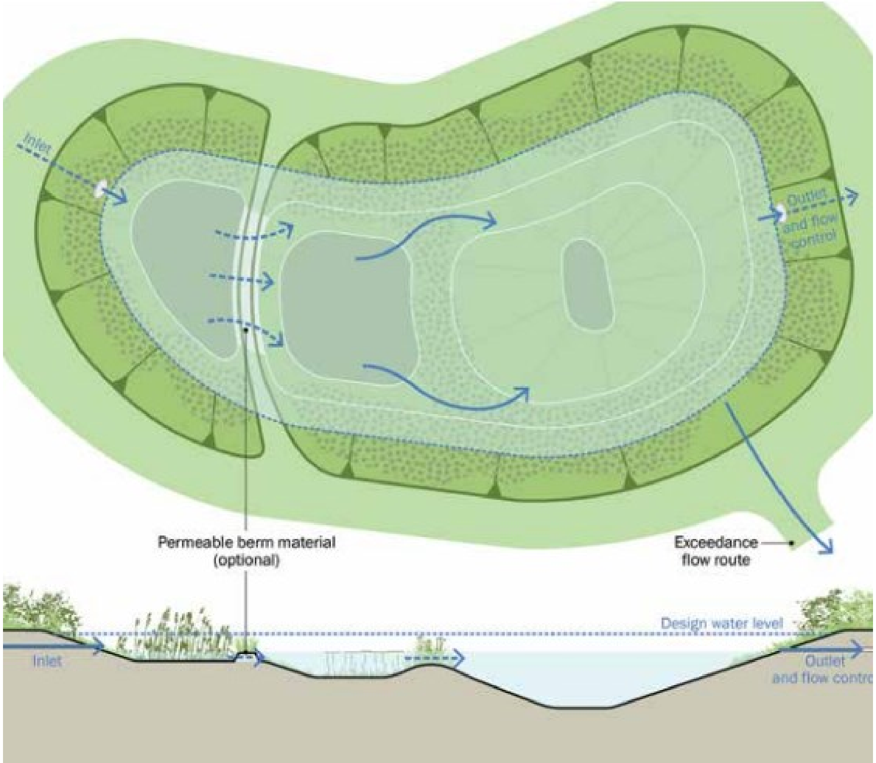


Figure E-1: Simple plan and profile details of a pond

Appendix F: A brief overview of the restoration of estuaries in South Africa

Estuaries and coastal seas have been the focal point of human settlement and marine resource use throughout history (Lotze *et al.*, 2006). According to the National Biodiversity Assessment carried out in 2011, there are approximately 300 functional estuaries in South Africa (Nel, 2014), with the majority of the larger, important estuaries report as being "fair" to "poor quality" (Van Niekerk & Turpie, 2011). Approximately 1% of South African estuarine areas experience minimal pollution (Nel, 2014).

As of 2011, it was reported that the health of the estuaries is currently being threatened by flow modification, habitat modification, fishing and pollution influenced by climate change, urbanisation and anthropogenic activities such as overfishing (Van Niekerk & Turpie, 2011). Other factors are the emergence of invasive plants and desalination (Van Niekerk & Turpie, 2011). Key pollutants of estuaries in South Africa are derived from municipal wastewater, industrial wastewater, stormwater runoff and agricultural runoff (Nel, 2014). These factors negatively impact the ecosystem services of the South African estuaries, making their restoration a priority. The continuation of overfishing and pollution due to land-based activities may lead to negative consequences on the well-being of local communities (Bodin *et al.*, 2013).

Estuaries are globally the most productive habitat types and ecosystems. The ecosystem services provided by estuaries include the provision of refuge and feeding areas for many species, nursery functions for coastal fisheries, and flood regulation (Nel, 2014). Furthermore, they offer sea storm protection, freshwater flows to the marine environment, replenishment of nutrients and organic material to coastal habitats, carbon sequestration, safe bathing areas and cultivation of plants for biofuels, food and building (Van Niekerk & Turpie, 2011). Estuary services, if managed well, can also be a source of revenue for communities and local governments through higher land rates from elevated property values (Van Niekerk & Turpie, 2011). However, despite being one of the most threatened habitats in South Africa, they are poorly protected (Nel, 2014).

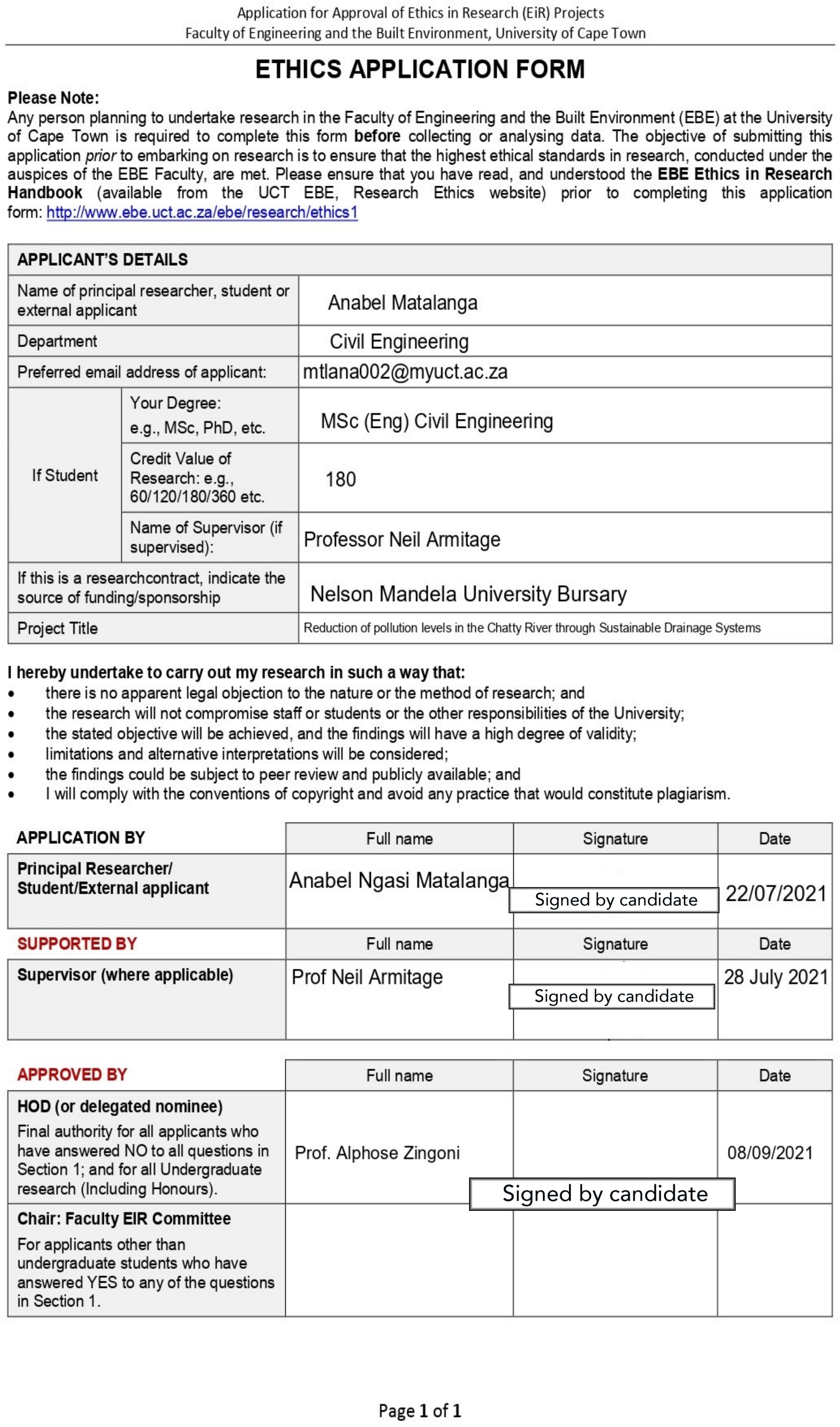
National legislation has aided in managing pressures on estuaries, for example through ecological flow requirements stipulated in the National Water Act (Act 36 of 1998) and Estuary Management Plans under the Integrated Coastal Management (Act 24 of 2008) (Adams & Riddin, 2019). However, a strong collaboration between key government departments, from the local to the national level, is required for integrated estuarine management (Van Niekerk & Turpie, 2011). Management decisions should be converted into implementation programmes to be closely monitored (Nel, 2014). Finally, evaluation and feedback should be carried out and attention given to strategies and conclusions of restoration evaluation (Morandi *et al.*, 2014).

Despite efforts made to ensure proper management of estuaries, there are still some knowledge gaps that limit the efficiency of their management. Some of these gaps include: the quantification of the modification in freshwater flow to the coast on a watershed scale; the quantification of invasive species in the estuaries; a systematic record of discharge into estuaries;

data regarding the value of estuaries; climate change; sediment structure of estuaries; and up to date surveys of the fish and bird fauna of estuaries amongst others (Van Niekerk & Turpie, 2011).

Although the estuaries are declining in health, they are resilient systems, and restoring them to a well-functioning, productive state is still possible (Van Niekerk & Turpie, 2011). Furthermore, their restoration and appropriate management will contribute to ecosystem resilience and adaptation to climate change.

Appendix G: Ethics Approval



ETHICS APPLICATION FORM

Please Note:
Any person planning to undertake research in the Faculty of Engineering and the Built Environment (EBE) at the University of Cape Town is required to complete this form **before** collecting or analysing data. The objective of submitting this application *prior* to embarking on research is to ensure that the highest ethical standards in research, conducted under the auspices of the EBE Faculty, are met. Please ensure that you have read, and understood the **EBE Ethics in Research Handbook** (available from the UCT EBE, Research Ethics website) prior to completing this application form: http://www.ebe.uct.ac.za/ebe/research/ethics1

APPLICANT'S DETAILS		
Name of principal researcher, student or external applicant		Anabel Matalanga
Department		Civil Engineering
Preferred email address of applicant:		mtlana002@myuct.ac.za
If Student	Your Degree: e.g., MSc, PhD, etc.	MSc (Eng) Civil Engineering
	Credit Value of Research: e.g., 60/120/180/360 etc.	180
	Name of Supervisor (if supervised):	Professor Neil Armitage
If this is a researchcontract, indicate the source of funding/sponsorship		Nelson Mandela University Bursary
Project Title		Reduction of pollution levels in the Chatty River through Sustainable Drainage Systems

I hereby undertake to carry out my research in such a way that:

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

APPLICATION BY	Full name	Signature	Date
Principal Researcher/ Student/External applicant	Anabel Ngasi Matalanga	Signed by candidate	22/07/2021
SUPPORTED BY	Full name	Signature	Date
Supervisor (where applicable)	Prof Neil Armitage	Signed by candidate	28 July 2021

APPROVED BY	Full name	Signature	Date
HOD (or delegated nominee) Final authority for all applicants who have answered NO to all questions in Section 1; and for all Undergraduate research (Including Honours).	Prof. Alphose Zingoni	Signed by candidate	08/09/2021
Chair: Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the questions in Section 1.			

Page **1** of **1**