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Modelling the impact of SuDS for stormwater quality management in the Bongani River catchment, Knysna

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degree of Master of Science in Engineering in Civil Engineering

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Abstract

The Bongani River is a primary pollutant source of stormwater runoff discharging into a shallow portion of the Knysna Estuary known as the Ashmead Channel (Harvey, 2019), situated on the southern coast of South Africa along the Garden Route. The Ashmead Channel is experiencing continuous macroalgal blooms which threaten the ecosystem's biodiversity (Human *et al.*, 2016; Claasens *et al.*, 2020). Furthermore, the recurring algal blooms have impacted – and will continue to impact – the aesthetic appearance and intrinsic value of the ecosystem goods and services provided by this environment (Allanson, 2010). The Herald Reporter (2019) highlighted that SANParks and the public are concerned about pollution and have expressed their desire to improve the quality of stormwater runoff entering the Knysna Estuary.

One of the ways to improve the quality of stormwater in the Bongani River is to introduce Sustainable Drainage Systems (SuDS) into the catchment area to aid in improving stormwater management. SuDS aim to achieve holistic management of water quantity and flooding, water quality and surface water pollution, public amenity and community inclusion, and the conservation and protection of biodiversity (Armitage *et al.*, 2013; Woods Ballard *et al.*, 2015).

The feasibility of reducing nutrient loads using SuDS was investigated by developing a hydrological model of the Bongani River. The base model, alongside several intervention scenarios, was developed in PCSWMM (Personal Computer Stormwater Management Model). Flow data collected during the study were used to calibrate the base model. Additionally, water quality was integrated into the models using event mean concentration (EMC) wash-off parameters for Total Nitrogen (TN) and Total Phosphorus (TP), which were estimated from an analysis of grab samples. The calibrated model was designated as the Current Scenario and was compared to the following additional scenarios:

- Pre-development Scenario – the Current Scenario modified to represent, as closely as reasonably possible, the likely state of the site before human development.
- Settlement Upgrade Scenario – incorporating the potential upgrading of the low-income areas to that more akin to typical suburban conditions.
- Tributary Management Scenario – incorporating a detention wetland on the western tributary and a retention wetland on the eastern tributary of the Bongani River to manage pollution from the low-income settlements.
- Bongani Wetland Upgrade Scenario – incorporating a constructed wetland near the discharge point as a regional control for the entire catchment.

The evaluation of the five scenarios was undertaken in two ways:

- In terms of flow quantity which was based on the reduction of flow volume and maximum flow rate in a 20-year timeseries. The Bongani Wetland Upgrade Scenario performed best with reductions of total volume by 77% and maximum flow rate by 71%, with the Settlement Upgrade Scenario and Tributary Management Scenario following, respectively.

- In terms of water quality which was based on the theoretical reduction of TN and TP loads over five consecutive 2-year periods. The Bongani Wetland Upgrade Scenario also performed best with reductions of 78% for TN and 77-78% for TP, followed by the Settlement Upgrade Scenario with reductions of TN by 66-75% and TP by 70-74% and the Tributary Management Scenario with reductions of 47-51% for TN and 47-52% for TP. All three of the scenarios achieved the pollutant reduction objectives described in the literature. However, the solutions would need to be combined to achieve the pollutant levels seen in the Pre-development Scenario, which compared with the Current Scenario, was 89% lower for TN and 90% lower for TP.

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Supplementary material

The following google drive link contains the supplementary material for this research. It contains PCSWMM files, Microsoft Excel documents, and a collection of pictures from the study area.

https://drive.google.com/drive/folders/1sz7pzP0XAZRVsjeFn_T6TPvVbyKint7X?usp=sharing

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List of Acronyms and Abbreviations

AMSL	Above Mean Sea Level
CFU	Colony Forming Units
DEA	Department of Environmental Affairs
DWA	Department of Water Affairs
DWAF	Department of Water and Forestry
EC	Electrical conductivity
HRT	Hydraulic retention time
KBP	Knysna Basin Project
ISE	Index of Simulated Efficiency
N	Nitrogen
NGO	Non-government Organisation
NCDOT	North Carolina Department of Traffic
NSE	Nash-Sutcliffe Efficiency
P	Phosphorus
PCSWMM	Personal Computer Stormwater Management Model
RGRDC	Reseau Geodesique de la Republique Democratique du Congo
RP	Return period
SuDS	Sustainable Drainage Systems
SRP	Soluble and Reactive Phosphorus
TAN	Total Ammonia Nitrogen
TKN	Total Kjeldahl Nitrogen
TOxN	Total Oxidised Nitrogen
TIN	Total Inorganic Nitrogen
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
UCT	University of Cape Town
UK	United Kingdom
US	United States of America
US EPA	United States Environmental Protection Agency
WHO	World Health Organisation
WQV	Water Quality Volume
WQCV	Water Quality Capture Volume
WSUD	Water Sensitive Urban Design
WWTW	Wastewater Treatment Works

Glossary

Attenuation	The reduction or slowed release of the force, effect, or intensity of an event.
Deterministic model	A model that always gives the same exact set of outputs for a particular set of inputs.
Diffuse pollution source	The build-up of pollutants from agriculture and/or urban areas washed off from indirect sources into a stream or water body during a storm event from multiple locations.
<i>Escherichia coli</i> (<i>E. coli</i>)	A gram-negative, anaerobic, rod-shaped, coliform bacterium of the genus <i>Escherichia</i> that lives in large numbers in the intestines of mainly warm-blooded organisms.
Eutrophication	The process of nutrient enrichment of waters which results in the stimulation of an array of symptomatic changes amongst which are the increased production of algae and aquatic macrophytes (plants), deterioration of water quality, and other changes that interfere with water uses.
Hydrological model	A hydrological model is a simplification of a real-world water-related system that aids in understanding, predicting, and managing water resources. Both the flow and quality of water are commonly studied in hydrological models.
Index of Simulated Efficiency (ISE)	A statistical index used to evaluate the performance of hydrological models by comparing observed and predicted values from a model. It is calculated as the ratio of the sum of squared differences between observed and predicted values to the sum of squared differences between observed values and the mean of the observed values.
Intermittent dry period	The dry period between rainfall events.
Land use	Land use is the term used to describe the use of land by humans and represents the development practices in a certain place or area.
Nash-Sutcliffe Efficiency (NSE)	A performance metric for evaluating the accuracy of hydrological models measuring the similarity between the observed and modelled data ranges from negative infinity to 1, with 1 indicating perfect symmetry and values nearer to 0 being poor agreement.
Nutrient	A nutrient is a chemical compound or substance used by an organism to function, grow, and reproduce.
pH	A logarithmic-scale measure of the acidity/basicity of an aqueous solution, inversely represents the concentration of hydrogen ions in solution.
Point pollutant source	A location where there is a direct flow of pollutants into a stream or water body.
Return period	The likelihood of occurrence of a particular event. A 1-year return period (RP) event is an event that is equalled or exceeded once a year on average over a long period of time, similarly, a 2-year RP event is equalled or exceeded once in two years on average over a long period of time.
Peri-urban	Denoting an area adjacent to an urban area.
Pollutant	A particular substance that is in excess in a particular environment.
Water quality	The suitability of water for a respective usage with respect to its physical, chemical, and biological characteristics.

1. Introduction

This research project investigated the Bongani River catchment's water quality problems, which discharges stormwater runoff into the Knysna Estuary, Knysna, South Africa. A hydrological and water quality model was developed to evaluate potential stormwater management interventions that could aid in reducing the transfer of pollutants from the catchment into the Knysna Estuary.

1.1 Research context

The Garden Route is located in South Africa's southern Cape region (Figure 1-1). Its main tourist attractions include estuaries, coastlines, mountains, forests, and amenities found in settlements like the town of Knysna (Marker, 2003). In southern Africa, estuaries are considered the most threatened ecosystem because of human-related activities (Branch *et al.*, 1985; Allanson, 2000; Van Niekerk *et al.*, 2020).



Figure 1-1: Knysna locality map (Bing map roads, n.d.)

The Knysna Estuary is a major tourist destination on the Garden Route and is seen as a driving economic force of the Knysna Municipality (GAPP Architects, 2017) (Figure 1-2). Classified as an estuarine bay, it is one of the rarest estuarine types in South Africa (Royal Haskoning DHV, 2017). It contains at least 40% of South Africa's total estuarine faunal and floral biodiversity (Allanson, 2000). Its biodiversity includes its seagrass meadows and intertidal saltmarsh vegetation (Figure 1-3), which are excellent carbon sinks, and provide habitat, shelter and food for several fish, birds, mammals, and invertebrate species (Adams *et al.*, 2016).



Figure 1-2: The town of Knysna and the Knysna Estuary



Figure 1-3: Saltmarsh vegetation of the Knysna Estuary

The ecosystem within the estuary, however, is threatened, and its shallow eastern section, the Ashmead Channel, has been experiencing recurring macroalgal blooms which pose a threat to the ecosystem's biodiversity (Russel, 1996; Human *et al.*, 2016; Claasens *et al.* 2020) (Figure 1-4). Human *et al.* (2016) ascribe the blooms' recurrence to contaminated stormwater flowing into the channel from the Bongani River. However, in discussing reasons for the contamination of the stormwater, they mention only polluted industrial discharge. More research is thus needed to identify other pollutants in the stormwater.

Research undertaken by Harvey (2019) identified the Bongani River (Figure 1-5) as a source of nutrient-rich and biologically contaminated stormwater whose flow contributes to the Ashmead Channel. Therefore, there is a need to understand the pollution levels within the Bongani River and what interventions could be implemented to reduce the impact on the biodiversity and amenity value of the Ashmead Channel and the Knysna Estuary.



Figure 1-4: Ashmead Channel’s macroalgal bloom and a warning about bacteria levels



Figure 1-5: The headwaters of the Bongani River catchment

Sustainable Drainage Systems (SuDS) – alternatively called Low Impact Development (LID) or Water Sensitive Urban Design (WSUD) – aim to achieve holistic management of water quantity and flooding, water quality, amenities, and biodiversity (Armitage *et al.*, 2013). Stormwater management initiatives such as SuDS offer potential ways of improving the water quality in the Bongani River.

1.2 Aims and objective

The overarching aim of this investigation was to evaluate stormwater management initiatives that would best manage the poor water quality from the Bongani River. This aim was achieved by developing a numerical model to analyse and evaluate the theoretical reductions of pollutant concentrations in the Bongani River to test the likely impact of various SuDS options. The research aligns with the Sustainable Development Goals (SDGs) put forward by the United Nations (UN) (2015) with the following goals relating to this research: (6) Clean water and sanitation; (11) Sustainable cities and communities; and (13) Climate action. Furthermore, the study relates to Commitment 19 of The New Urban Agenda as outlined by the UN (2017) which stated that there is a need to invest in protective, accessible, and sustainable infrastructure and services regarding water, drainage, stormwater management, and pollution.

1.3 Scope and limitations

The scope of the investigation encompassed:

- Site visits to Knysna with sampling and testing 12 sites across the Bongani Catchment over six months commencing February 2019. Six sites were replaced in a second six-month period with new locations to understand the pollutant origins better. The water quality testing included an assessment of inorganic Nitrogen (N), Phosphorus (P), and *Escherichia coli* (*E. coli*) to provide insight into water quality issues.
- Storm event data was collected for flow rate and water quality. The measurements of the fluctuations of stream flow and pollutant concentrations during storm events provided a better understanding of Bongani River's variation of water quality.
- A combined hydrological and water quality model was developed by collating rainfall, evapotranspiration, topography, the hydraulic network, and water quality data from a dataset from the Knysna Municipality. The model was then calibrated and verified.
- Upon completing the hydrological model, various SuDS interventions were introduced. Finally, the scenarios were assessed based on their theoretical pollutant load reductions.

Limitations of this research project were mainly attributed to data collection. The retrieval of continuous rainfall data, nutrient and sediment data and flow data is complex and comes with considerable uncertainty. Other limitations in the study included the availability of information relating to developing water quality treatment equations for SuDS.

1.4 Report layout

This chapter introduced the research project. The layout of the report is summarised below.

- Chapter 2 is a literature review of stormwater management and hydrological modelling.
- Chapter 3 is a site description of the Bongani River and its catchment area.
- Chapter 4 is an outline of the method followed in the research.
- Chapter 5 explains the collection of physical data during the research.
- Chapter 6 describes the development of the flow component of the hydrological model and elaborates on its calibration, validation, and verification.
- Chapter 7 presents the water quality and storm event data collected and describes the development of the water quality component of the hydrological model.
- Chapter 8 describes the stormwater management scenarios in the model.
- Chapter 9 is an overview of the results of the stormwater management scenarios.
- Chapter 10 entails the conclusions and recommendations of the research.

2. Literature review

The following chapter discusses the literature available for stormwater management on a global, regional, and local scale. It then addresses surface runoff quality, the natural mechanisms that manage the treatment thereof, and the stormwater management guidelines that aid with improving water quality. The emergence of SuDS in stormwater management is then discussed, and the different systems that aim to mitigate the impact of poor water quality are provided. Finally, a review of the various hydrological modelling software is presented as related to the design and evaluation of SuDS.

2.1 Stormwater management: a challenge for settlements

Stormwater management has been undervalued, resulting in the continued development of concretised drainage corridors, which unfortunately focus narrowly and primarily on the rapid removal of stormwater from roads and impervious urban surfaces (United States Environmental Protection Agency (US EPA), 1983; CCT, 2009; Department of Human Settlements, 2019; City of Cape Town (CCT), 2021). A significant source of pollution entering estuaries and oceans comes from the contaminants deposited upon pervious and impervious surfaces from anthropogenic and natural origins (Thurstan *et al.*, 2020; Liu *et al.*, 2019), however, sewage spills also pose a threat to downstream water quality (Human *et al.*, 2016). These contaminants build-up during intermittent dry periods to the point of saturation where further deposition of both gross pollutants (litter) and sediment is swept away, usually by wind (Di Modugno *et al.*, 2015; Costa *et al.*, 2021) or until they are transported during rainfall events by stormwater networks to downstream aquatic systems which, in excess, can cause problems for human health and quality of the environment (Ashton & Bhagwan, 2001; Barbosa *et al.*, 2012). The increased hardening of the urban landscape and the associated build-up of contaminants increases the concentrations of pollutants in stormwater runoff, which are then transported directly to downstream aquatic environments (Marsalek *et al.*, 2006; Rockström *et al.*, 2014; Palla & Gnecco, 2015).

Improving the quality of stormwater runoff requires a holistic approach to managing landscape infrastructure. ‘Water Sensitivity’ in terms of stormwater management focuses on the holistic balance of the social, economic, and environmental factors within and across catchment areas and can aid with improving stormwater runoff quality (Fisher-Jeffes *et al.*, 2017). Water Sensitive Urban Design (WSUD) and SuDS are approaches that can aid with the promotion and adoption of water sensitivity. WSUD aims to manage the water balance, maintain and, where possible, improve water quality, encourage water conservation, as well as maintain water-related environmental and recreational opportunities (Whelans *et al.*, 1994). SuDS may be considered as the stormwater component of WSUD focusing primarily on the stormwater management components of the urban water cycle. In addition, SuDS aim to address sustainability within the design of stormwater infrastructure and call for a shift in focus toward holistic management of surface water drainage.

2.1.1 Global stormwater challenges for settlements of the future

A challenge faced by developing urban areas is that of sustainable water and ecological resource management (Wong & Brown, 2008). It is vital to drive development towards areas with low biodiversity value to prevent further damage to fragmented ecosystems (Perrin *et al.*, 2009; Rebelo *et al.*, 2011). A shift from conventional to natural urban surface water management systems has great potential for effectively managing stormwater. Ward *et al.* (2012) highlighted water and environmental issues such as adapting to climatic extremes, reducing flood risk, managing increasingly stressed water resources, and improving water quality. Armitage *et al.* (2013) noted the following negative impacts of development as related to growing water and environmental concerns:

- The displacement of naturally free-draining areas with impermeable surfaces such as roads, concrete pipes, and paved areas. This ‘hard’ infrastructure increases runoff peaks and lowers the natural water table rather than allowing for natural processes.
- Losses in indigenous fauna and flora due to the impacts of increased pollution in surface water and historical changes to natural watercourses. Stormwater buffers that evolved in the landscape no longer function in the same way they did before development.
- Conventional urban drainage techniques have largely ignored the need to preserve and improve water quality which greatly impacts biodiversity and amenity.
- Compaction of sub-soil strata under urbanised environments has reduced infiltration and recharge into aquifers, decreasing the baseflow from aquifers into receiving watercourses.

Ecosystem services provide the key to supporting and sustaining communities (Table 2-1). These services from the natural world are economically valuable but forgotten to an extent in some modern development contexts (Millennium Ecosystem Assessment, 2005).

Table 2-1: Summary of the ecosystem services categories
(Millennium Ecosystem Assessment, 2005)

Categories	Description	Examples
Provisioning Services	Provision of goods	Water, Food, Raw materials.
Regulating services	Ecological processes contribute to economic production or cost savings.	Flood attenuation, base flow regulation, groundwater recharge, soil stability, water purification, carbon sequestration.
Cultural services	The value that is derived from the use or appreciation of biodiversity.	Spiritual, educational, cultural, recreational, existence.
Supporting services	Ecological processes that underlie or support the above three services.	Soil fertility, Pollination, Pest control.

2.1.2 Regional concerns for surface water drainage

An issue that needs to be addressed across the developing world is the vulnerability of both urban and rural communities to climate change and water scarcity (Rockström *et al.*, 2014). The impacts of rapid urbanisation need to be mitigated and controlled through the restoration and management of the ecosystem goods and services that most communities heavily rely upon for their livelihoods. Mihelcic *et al.* (2017) stress the application of disciplinary knowledge from mega-cities within developments with inherently different socio-economic constraints. Developmental problems in South Africa must be addressed within the context of the areas being considered. Appropriate consideration of the natural and public environments needs to be made with the in-context management and planning of both rural and urban settlements.

The *Integrated Urban Development Framework* of South Africa sets out a policy which aims to guide development toward more inclusive, resilient, and habitable settlements (Department of Cooperative Governance and Traditional Affairs (COGTA), 2016). It intends to address the unique context of South Africa's historically influenced spatial development challenges and the conditions separating cultural and ethnic groups. These challenging conditions have left a large portion of the population in overpopulated and underserved settlements, which have been relatively disregarded in terms of environmental and social conditions. South Africa's transition to water sensitivity needs to consider informal areas where higher densities of people live and where infrastructure advancement is often overlooked (Fisher-Jeffes *et al.*, 2017). COGTA (2016) projected that nearly three-quarters of the South African population will live in urban areas by 2030. Therefore, water-sensitive development in the periphery of urban areas is key to establishing intergenerational and social equity. It is, therefore, important that multifunctional, adaptive infrastructure is prioritised for investment.

Developing stormwater management objectives for a water system vary based on the prevalent conditions and context of the problem. The City of Cape Town (CCT) has developed a policy framework for mitigating urban stormwater impacts that seek to (CCT, 2009):

- Improve runoff water quality.
- Control stormwater runoff quantities and flow rates.
- Encourage natural groundwater recharge.

The objectives listed above focus on water quality and quantity of the urban water cycle, highlighting the importance of re-establishing natural watercourses. The link between a healthy urban water cycle and providing ecosystem goods and services to local communities may be realised through effective stormwater management practices such as SuDS. If an urban design can integrate inclusive and locally appropriate infrastructure solutions for managing stormwater whilst considering water quality and quantity, sustainable urban water management and water sensitivity can be established, as described by Armitage *et al.* (2013), UN (2015), Fisher-Jeffes *et al.* (2017), and UN (2017).

2.1.3 Sources of pollution affecting stormwater quality

Extensive literature on stormwater quality concerns with research about water quality management dating back to the 1950s (Müller *et al.*, 2020). Understanding the sources and mechanisms of urban pollutant transport in a catchment area is essential for addressing the management of stormwater quality (Zhao *et al.*, 2018; Fernandez *et al.*, 2019). There are two distinct types of pollutant sources in a stormwater system: point and diffuse (nonpoint) sources (Ashton & Bhagwan, 2001; The Civic Federation, 2007; Mahdi & Pagilla, 2021). Point source pollution arises from a location that is not being carefully monitored and/or managed. They range from industrial and commercial practices to zones where specific discharges are causing problems in the water quality downstream of that location, like mining (Department of Human Settlements, 2019). An example of point source pollution is a sewage manhole that leaks into a nearby stream, particularly during storm events.

Diffuse or nonpoint source pollution comes from many different sources and locations. It is related to human activities in various environments, even though each source individually may not pose a significant threat (Woods Ballard *et al.*, 2015). An example of diffuse source pollution includes pollutants that come from landscapes that have poorly managed municipal infrastructure, especially with regard to the management of sewage and solid waste.

First flush, or pollutant flushing, occurs when previously deposited solids or dissolved pollutants are mobilised and transported in a drainage system at the beginning of a storm event (Taebi & Droste, 2004). The first flush phenomenon is debated due to its variability, and there is no real consensus on its definition and how it is to be quantified (Czemiel Berndtsson, 2013). It has been suggested that a catchment's first flush can be quantified by the runoff volume required to reduce its pollutant concentrations to background levels. Because this runoff volume is quantifiable, it can be linked to the initial portion of stormwater runoff, which thus has higher pollutant concentrations than subsequent flows. However, not all storm events and catchment areas exhibit first flush effects (Bertrand-Krajewski *et al.*, 1998; Liu *et al.*, 2019). First flush events can result in heavily polluted runoff to streams, rivers, estuaries, bays, and oceans hence treatment thereof is recommended before discharge into downstream water bodies (Czemiel Berndtsson, 2013).

The mismanagement of stormwater infrastructure in developed urban areas has brought about concerns for communities downstream of them (Armitage, 2011; Department of Environmental Affairs and Development Planning, 2011; COGTA, 2016). Several issues compound the problem of stormwater management in settlements, such as their development without proper town planning, poor waste removal and lack of sanitation service provisions, poor considerations for waste and water management, hesitation from local authorities to provide proper sewerage, as well as tentativeness to relocate to better-serviced areas due to proximity to existing work and social support (Armitage, 2011). It was also highlighted by Armitage (2011) that the need for more skills, poorly directed local government expenditure on service delivery, fragmented communication between departments, and the lack of properly directed expenditure also contributes to the concerns for the future of communities.

An increase in urban development and water demand can be linked to an increase in wastewater generation, which, can enter the surface water environment. Episodic stormwater runoff events can convey sediment, chemicals, solid and biological pollutants, and nutrients of varying origins into seeps, streams, and rivers, draining into the downstream aquatic environments such as estuaries, lakes, and bays. Estuaries provide a nursery for life in the oceans as they house many fish species during their early phases of development. Surface water runoff dynamics can cause biological, chemical, and physical changes which directly affect the health of the nurseries that estuaries provide (Marker, 2003; Kirk Cochran, 2014). The increase in wastewater generation and the inadequate treatment also pose a threat to downstream water bodies, changing both the quality and quantity of water entering them. What once were ephemeral streams can be turned into perennial streams with peak flow rates or discharges at abnormal times. Streams with smaller seasonally variable discharges can increase in flow, both of which can impact the health of downstream aquatic ecosystems.

Urbanisation is generally linked to higher flow velocities and a more rapid rise of the flow rate – a steeper rising limb of the hydrograph – and more prominent flood peaks during storms due to shortened channels and reduced boundary roughness, which increases sensitivity to rainfall events, and reduction in infiltration and groundwater storage due to the increased development of impermeable surfaces (Barbosa *et al.*, 2012; Järveläinen *et al.*, 2017).

Examples of South African constraints for the effective management of stormwater quality include, but are not limited to, fragmented governance and coordination; underinvestment in stormwater and sewage infrastructure; nutrient-rich fertiliser in some agricultural practices, environmental damage; a decline in tourism and foreign investment; preliminary analysis and monitoring of contaminants in surface water; ageing municipal infrastructure; and a lack of enforcement of legislation, guides, and standards due to socio-political problems (van der Merwe-Botha, 2009). In addition, although many good stormwater related projects exist, a lack of financial support and capacity for continuation and management of the projects hinders long term prospects for innovation and sustainability (Department of Environmental Affairs and Development Planning, 2011; Armitage *et al.*, 2013; Fisher-Jeffes *et al.*, 2017).

Discerning the source of urban stormwater pollution is important because it determines the type of response required. This understanding can aid decision-makers with knowledge of whether management interventions are needed within the drainage system or if interventions lie in monitoring and curbing the most prevalent point source pollution contributors. Managing stormwater runoff involves removing pollutants from the stormwater system, and treating the most polluted portion of runoff can reduce water quality impacts on downstream water bodies. The following section involves a review of the literature on surface water quality.

2.2 Surface water runoff quality: characterising pollution

Stormwater runoff is the primary transport mechanism of most urban pollutants (Shaver *et al.*, 2007). Most of these pollutants occur as a mixture of physio-chemical constituents that depend on the type and intensity of anthropogenic influence, and the nature of the land uses in the catchment of interest. Land use is the term used to describe the use of land by humans and represents the development practices in a particular place or area. Pollutants are often found in a particulate form, where nutrients, organics and heavy metals are bound to sediment or organic material (Pitt *et al.*, 1995). Nutrient losses from the soil are directly linked to erosion processes which relate to high sediment loads during more significant rainfall events (Ramos and Martinez-Casanovas, 2016). Smaller storm events, however, often transport much of the annual pollutant loads of a catchment (Armitage *et al.*, 2013; Atlanta Regional Commission, 2016).

Eutrophication is the process of nutrient enrichment of waters resulting in increased production of algae and plants (Department of Environmental Affairs and Development Planning (DEADP, 2011). It is said to be one of the most ubiquitous environmental problems in inland surface waters, primarily due to the enrichment of nutrients, Nitrogen (N), and Phosphorus (P) (DEADP, 2011; Davidson *et al.*, 2014). The trophic state concept was first developed by Naumann (1919) and aimed to classify the relationship between a catchment and a lake. The trophic classification is related to the productivity of plants and algae in the aquatic environment, and that N and P are the primary determinants of their productivity (Naumann, 1929). Algae are one of many indicators of N sources in marine and estuarine environments and represent higher-than-normal nutrient loads (Ferrat *et al.*, 2003). The abundance of algae in nutrient-rich environments is attributed to their high nutrient uptake and ability to respond quickly to N spikes in the water column. As nutrient concentrations increase in stormwater runoff during storm events, suspension and transport of pollutants occur, providing nutrients for algal blooms. Table 2-2 presents the trophic states described in the *South African Water Quality Guidelines Volume 7: Aquatic Ecosystems* (Department of Water Affairs and Forestry (DWAf), 1996a).

Table 2-2: Environmental effects of trophic states
(Department of Water Affairs and Forestry (DWAf), 1996a)

Trophic state	Effects
Oligotrophic	Usually moderate levels of species diversity, low productivity systems with rapid nutrient cycling, no nuisance growth of aquatic plants or presence of blue-green algal blooms.
Mesotrophic	Usually high levels of species diversity, usually productive systems, nuisance growth of aquatic plants and blooms of blue-green algae, algal blooms may include species which are toxic to man, livestock, and wildlife.
Eutrophic	Usually low levels of species diversity, usually highly productive systems, nuisance growth of aquatic plants and blooms of blue-green algae, algal blooms may include species which are toxic to man, livestock, and wildlife.
Hypertrophic	Usually very low levels of species diversity, usually highly productive systems, nuisance growth of aquatic plants and blooms of blue-green algae, algal blooms may include species which are toxic to man, livestock, and wildlife.

2.2.1 Pollutants in stormwater runoff

Stormwater runoff pollution is a widespread concern in both the developing and developed regions of the world (US EPA, 1983; Wong *et al.*, 2000; Ashton & Bhagwan, 2001; Marsalek *et al.*, 2006; Barbosa *et al.*, 2012; Järveläinen *et al.*, 2017; Costa *et al.*, 2021). Understanding the types of pollutants impacting water quality has assisted in developing approaches that lead to the reduction of the transport of pollutants from their source. Pollutants that affect stormwater quality have been grouped in Table 2-3.

Table 2-3: Contaminants and their impacts on stormwater runoff quality
(Green Building Council of South Africa (GBCSA), n.d.; Kavka & Poetsch, 2002)

Contaminant group	Description and relation to stormwater runoff
Nutrients	Nutrients are found in a variety of forms. The sources of these pollutants vary from sewage overflows and organic wastes to industrial discharges and fertilizers from residential and agricultural runoff. Excess nutrients in stormwater (e.g., N and P) can promote rapid plant growth leading to eutrophication and ecology degradation if not appropriately managed. Excessive plant growth can cause oxygen depletion, negatively impacting the complex aquatic ecosystems in the larger receiving water bodies. Suppose invasive species are present (e.g., <i>Ulva spp.</i> and Kikuyu grasses). In that case, it is common for their populations to increase rapidly, posing a threat to indigenous riverine vegetation as well as the urban water cycle.
Total suspended solids (TSS)	TSS is composed of both organic and inorganic particulates in the runoff. In areas of higher turbidity, light penetration into the water can be reduced, leading to lower amounts of direct sunlight in the aquatic environment. Excess sedimentation could, in some cases, cause negative impacts on plant growth within the river substrate because of contaminants found in runoff. If contaminant and sediment levels are not controlled, the potential for negative impacts on riverine ecosystems is more likely as light penetration decreases, and contaminant levels increase in rivers and estuaries.
Litter	This type of contaminant is both visible and microscopic. It includes organic waste, plastics, glass, and many other refuse types. These contaminants enter the system almost entirely through urban runoff where there is insufficient provision for proper refuse disposal.
Toxic trace metals	Industrial chemicals enter the urban water cycle in various ways such as illegal dumping, accidental spillage from industrial sites, brake and clutch linings, and other roadway pollutants from transport networks.
Oils, greases, and surface pollutants	Toxic pollutants accumulate from rubber, fuel, transport networks and detergents from roadways and various domestic and industrial sources.
Biological pollution	Faecal indicator bacteria like total coliforms, faecal coliforms, <i>E. coli</i> , and intestinal enterococci are excreted by humans and warm-blooded animals. They can survive for some time in the aquatic environment. Due to ease of testing, <i>E. coli</i> and faecal coliforms are currently one of the most widely used indicators for assessing faecal pollution and are mainly caused by raw and treated sewage and diffuse impacts, e.g. from pasture lands. <i>E. coli</i> and faecal coliforms also indicate the potential presence of pathogenic bacteria, viruses, and parasites. They are usually measured in Colony Forming Units (CFU), which are counted in a 100 mL sample.

Methods that aim to tackle pollution have become more common as the management of urban drainage systems has become more sustainable. To contextualise the need for the shift towards a more sustainable approach to managing the quality of surface water, the level of contamination of the drainage system needs to be understood. Water quality guidelines provide context about the level of contamination for nutrient and biological components and can be used to determine the severity of the risk. There are several South African and international guidelines – by the Department of Water Affairs and Forestry (DWAF), the Department of Environmental Affairs (DEA), the Department of Water Affairs (DWA) and the World Health Organisation (WHO) – that are summarised in Table 2-4 concerning nutrient pollution – as total inorganic nitrogen (TIN) and soluble and reactive phosphorus (SRP) – and biological pollution – as *E. coli*.

Table 2-4: A summary of water quality guidelines for pollutants of interest

TIN (mg/L))	Conditions	Source
> 10	Hypertrophic	DWAF (1996a)
2.5 - 10	Eutrophic	
0.5 – 2.5	Mesotrophic	
< 0.5	Oligotrophic	
SRP (mg/L))	Conditions	Source
> 0.25	Hypertrophic	DWAF (1996a)
0.025 – 0.25	Eutrophic	
0.005 – 0.025	Mesotrophic	
< 0.005	Oligotrophic	
<i>E. coli</i> (CFU/100mL))	Conditions	Source
> 100,000	Excessively polluted	EU-Bathing water quality directive 2006/7/EEC (Kavka <i>et al.</i> , 2006)
< 100,000	Strongly polluted	
< 10,000	Critical pollution	
< 1,000	Moderately polluted	
< 100	Little pollution	
> 1000	Unacceptable	WHO (1989) & DWAF (1996b)
< 1000	Fine for irrigation	
< 500	Fine for recreation	DWAF (1996c) & DEA (2012)
0	Target for drinking	DWAF (1996d)

The nutrient concentrations and conditions provided in Table 2-4 are based on the water body's trophic state, which represents the ecosystem's health concerning its species diversity. Biological contamination, on the other hand, is linked to the level of pollution and the acceptability thereof. Therefore, understanding the levels of contamination of a waterbody can aid with developing targeted interventions that can reduce negative impacts on biodiversity downstream.

2.2.2 Natural stormwater management processes

Development has altered natural, self-sustaining drainage systems which has accelerated the degradation of natural water systems (Ashton & Bhagwan, 2001). The processes involved in natural water courses include vegetated seeps, streams, rivers, and wetlands that capture, store, and release water and its contents into receiving environments. Stormwater management can mimic processes that promote natural flow regimes and appropriate maintenance of stormwater quality in compromised catchment areas (Fletcher *et al.*, 2015; Khadka *et al.*, 2019). Therefore, it is important to understand the various pollution removal mechanisms to improve the management of pollutants in a stormwater network. Removal strategies that aid in stormwater quality improvements include (Wilson *et al.*, 2004; Woods Ballard *et al.*, 2007):

- Physical processes involving the settling, filtering, and suspension of pollutants are assisted by meandering streams, pools, rapids, and rocks on the stream bed. The reduced flow velocity in pools aids in sedimentation and filtration processes, whereas increased flow rates aid in oxygenation and suspension of pollutants for plants and microbes to treat.
- Chemical processes comprise pollutant removal by organisms. These naturally occur in healthy ecosystems with microbes biodegrading organic material, adsorption, nitrifying ammonium, and photosynthesis aided by ultraviolet light.
- Biological removal works alongside chemical removal in riverine environments. Plant uptake, biofiltration, and removal of nutrients and metals from stormwater runoff occur when enough vegetation and microbial growth occur. Vegetation and microbes naturally grow in the soil-substrate matrix or the stream flow however, their growth can be supplemented by an appropriate selection of stream and pond bed materials.

Stormwater runoff that is controlled by well-vegetated ecosystems can aid in mitigating water quality problems such as nutrient enrichment.

2.3 The shift toward sustainable urban stormwater management

Stormwater management, especially in urban areas, has become more complex as it has shifted away from solely the conveyance of stormwater away from settlements towards a more holistic approach (Fletcher *et al.*, 2015). Fletcher *et al.* (2015) noted that with the adoption of a more holistic approach since the 1980s, there had been rapid growth in the use of different but related terms worldwide. Examples include International Urban Water Management (IUWM), Water Sensitive Urban Design (WSUD), Sustainable Drainage Systems (SuDS), Best Management Practice (BMP), Stormwater Control Measure (SCM), Low Impact Development (LID), and Blue-Green Infrastructure (BGI) (Fletcher *et al.*, 2015; Lamond & Everett, 2019). Recent literature is increasingly using the term BGI, and although SuDS is still a term that is in use for stormwater management – particularly in South Africa.

SuDS aim to achieve holistic management of water quantity and flooding, water quality and surface water pollution, public amenity and community inclusion, and the conservation and protection of biodiversity (Armitage *et al.*, 2013; Woods Ballard *et al.*, 2015). Four main stormwater management strategies that can be adopted within SuDS – each linked to a point in the pollution train: good housekeeping, source control, local control, and regional control (Armitage *et al.*, 2013). It is good practice to combine multiple stormwater management methods to achieve more holistic treatment (US EPA, 2000; Anawar & Chowdhury, 2020). A treatment train is a combination of stormwater management interventions in series that aim to achieve better stormwater quality and quantity management (Armitage *et al.*, 2013; Fletcher *et al.*, 2015; Atlanta Regional Commission, 2016). An essential component of a treatment train is pre-treatment, which involves the removal of litter, sediment, and other coarse pollutants prior to downstream stormwater management systems (Hoffman *et al.* 2012). Using a treatment train can enhance system performance by combining pre-treatment for downstream interventions, reducing the impacts of stormwater runoff and its pollutant load (Hoffman *et al.*, 2012; Armitage *et al.*, 2013; Woods Ballard *et al.*, 2016).

There are several approaches to the design of SuDS, most of which are based on the management of various sizes of storm events. A storm event is a period when rainfall occurs. The probability that a specific threshold of rainfall or stream flow will occur is expressed as a return period (RP) defined as the average (mean) period in months or years that a specified threshold (intensity, rainfall depth, flow rate etc.) is exceeded. The most significant water quality pollution impacts generally occur during frequent, lower RP storm events (Perrin *et al.*, 2009; Armitage *et al.*, 2013; Woods Ballard *et al.*, 2016). Therefore, the Water Quality Volume (WQV) is a useful measure in SuDS design being the initial volume targeted for treatment. It is usually linked to the volume emanating from storms having a specified RP, such as 1-6 months, or total depth, such as 25 mm, that typically account for 85-90% of storm events (Armitage *et al.*, 2013; Atlanta Regional Commission, 2016). On the other hand, stormwater quantity management also involves the hydraulic control of larger, more infrequent volumes of stormwater. Retrofitting existing drainage systems with SuDS is also a vital part of the overall strategy for making towns and cities more resilient to the dangers of flooding and stormwater pollution (Woods Ballard *et al.*, 2015).

2.3.1 Stormwater management objectives

There are different objectives for the design of stormwater infrastructure which range from the management of smaller, more regularly recurring storm events to more significant storm events which convey larger volumes of stormwater on an infrequent basis. When designing a stormwater management system, it is important to consider the local hydrological cycle, ground conditions, the impact of different types of development (greenfield or brownfield), and compliance with the law (Armitage *et al.*, 2013). Therefore, SuDS comprise several unit processes as provided in Table 2-5.

Table 2-5: The management objectives of SuDS and their key unit processes
(Wilson *et al.*, 2004; Woods Ballard *et al.*, 2015)

Management objective	Key processes
Stormwater quantity	Rainwater harvesting, infiltration, retention, conveyance, long-term storage, and extended attenuation storage
Stormwater quality	Sedimentation, filtration and biofiltration, adsorption, biodegradation, volatilisation, precipitation, plant-uptake, nitrification, and photosynthesis.
Amenity	Health and safety, environmental risk assessment and management, recreation and aesthetics, and education and awareness.
Biodiversity	Protection, maintenance of habitat, monitoring.

Several criteria guide the selection of appropriate SuDS options (Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ) & Australian and New Zealand Environment and Conservation Council (ANZECC), 2000; Wilson *et al.*, 2004; Woods-Ballard *et al.*, 2007; Armitage *et al.*, 2013):

- i) Current and future land use characteristics.
- ii) Site characteristics and utilisation requirements.
- iii) Catchment characteristics upstream.
- iv) Stormwater runoff quantity (peak flow and flood volume) requirements.
- v) Stormwater runoff quality requirements.
- vi) Amenity needs.
- vii) Biodiversity goals and objectives
- viii) Terrestrial ecosystem health
- ix) Socio-economic considerations

Perrin *et al.* (2009) and Woods Ballard *et al.* (2015) stated that reducing post-development stormwater flow rates in a drainage system to levels similar to pre-development conditions was an effective way of addressing local water quality problems. However, targeting specific pollutants in smaller less frequent storm events is also motivated for in Australian and South African stormwater management policies (CCT, 2009; Melbourne Water, 2005; South Eastern Councils, 2013). Furthermore, the revised Red Book (Department of Human Settlements, 2019) states that the required capacity of stormwater management interventions can be determined by hydrologic simulation and their design can be determined using appropriate modelling software. Thus, comparing models of the current system with theoretical models in which interventions are imposed can effectively evaluate water quality improvements. Different authorities specify different objectives for stormwater management (Table 2-6).

Table 2-6: Various SuDS objectives for stormwater quality and quantity design

CCT (2009)		
SuDS objective		Greenfield, brownfield, and existing development sites located in catchments of sensitive receiving water systems
Improve runoff water quality		Design storm event for modelling = 1 in 6-month RP, 24h storm
		TP removal of 45%
		TSS removal of 80%
Control quantity and rate of runoff		To protect the stability of downstream channels
		Design storm event for modelling = 1 in 1-year RP, 24h storm
Victorian Stormwater Committee (1999), Melbourne Water (2005), and South Eastern Councils (2013)		
Criteria		Description
Manage stormwater discharge		Keep 1.5-year RP storm discharges at pre-development levels
Water quality treatment		TN removal of 45% TP removal of 45% TSS removal of 80% Gross pollutants (litter) removal of 70%
Atlanta Regional Commission (2016)		
Sizing criteria		Description
Water quality	Runoff reduction	Retain or reduce the runoff for the first 1 inch (25 mm) of rainfall, or to the maximum extent possible.
	Water quality volume (WQV)	Retain or reduce runoff of 85% of the storms in an average year. 1.2 inch (30 mm) of rainfall in Georgia, USA, varying elsewhere.
Water quantity	Channel protection	Provide extended detention of the 1-year RP 24hour storm event released over a period of 24 hours.
	Overbank flood protection	Peak discharge control of the 25-year RP storm.
	Extreme flood protection	Evaluate the 100-year RP 24-hour storm. Manage the effects with detention controls and floodplain protection.

The water quality objectives from CCT (2009) in Table 2-6 are a local policy and, like those from the Australian sources, focused on targeted pollutant management. Atlanta Regional Commission (2016) focuses on managing smaller storms in terms of quantity to improve water quality. Nonetheless, these objectives can be used to assess whether a stormwater management plan can appropriately improve stormwater control. A treatment train can help with this control of stormwater and improve the likelihood of both the quality and quantity objectives being met. A treatment train comprises several stormwater management interventions. The priority of a SuDS treatment train is water quality treatment during low flows and attenuation and volume control during high flows (Armitage *et al.*, 2013; Woods Ballard *et al.*, 2015). The SuDS components considered in a stormwater system depend on design criteria and how the drainage system is integrated with development and landscape. The components can convey or store runoff depending on the design requirements.

2.3.2 Stormwater management controls

The SuDS components in a stormwater management treatment train can be grouped in different ways. ARMCANZ & ANZECC (2000) refer to two measures within runoff management: runoff source controls and structural controls. Armitage *et al.* (2013) grouped SuDS into four complementary components: good housekeeping; source controls; local controls; and regional controls. Managing stormwater at the source was recommended as the best approach to improving quality and quantity management (ARMCANZ & ANZECC, 2000; Armitage *et al.*, 2013; Woods Ballard *et al.*, 2015; Atlanta Regional Commission, 2016). Source control implies that if stormwater runoff management is adopted across private and public developments in a catchment area, the amount of pollution entering the drainage system is minimised on a larger scale than managing stormwater runoff using a single regional or structural control. It was also noted that it is generally easier and more cost-effective to control pollution at the source. The following are the four SuDS components discussed by Armitage *et al.* (2013):

- Good housekeeping aims to ensure that as much as possible is done to minimise the amount of pollution being released into the environment that will subsequently be transported by runoff to other sensitive environments downstream (Armitage *et al.*, 2013). Good housekeeping intends to ensure that private, public, and municipal operations, industries, and services are performed in ways that minimise contamination of the stormwater systems (US EPA, 2005).
- Source controls aim to manage pollution as close to their source as possible, usually at the site of concern. However, they can be challenging to implement holistically unless people are motivated by policy and are adopted on a broad scale.
- Local controls are generally implemented as a treatment measure that follows source controls such as soakaways, rain gardens and rainwater harvesting systems. Local controls include SuDS components like infiltration trenches, swales, bio-retention areas, and in some cases smaller ponds and wetlands.
- Regional controls are the final stage of a stormwater management treatment train and encompass detention and retention ponds and wetlands, which manage runoff from several developments. Regional controls are usually located in low-lying areas of catchments within municipal land, large private developments, or protected areas (Melbourne Water, 2005; Armitage *et al.*, 2013).

The primary difference between local and regional controls is scale. Local controls manage surface water downstream of a particular site or sub-catchment and essentially function as pre-treatments for more significant downstream stormwater management initiatives. Regional controls, however, receive runoff from more catchments. Table 2-7 summarises the principal SuDS options.

Table 2-7: A summary of the various SuDS controls

SuDS control	Description
Green roofs	Green roofs are areas of vegetation installed on buildings to soak up rainfall. Their benefits include aesthetics, biodiversity, enhanced building performance and the reduction of surface water runoff (Woods Ballard <i>et al.</i> , 2015; Atlanta Regional Commission, 2016).
Soakaways	Soakaways are a strategy used to infiltrate runoff and use excavated pits filled with porous media to detain and store runoff (Armitage <i>et al.</i> , 2013; Woods Ballard <i>et al.</i> , 2015).
Rainwater and stormwater harvesting	Rainwater and stormwater harvesting encompass the collection, storage, and utilisation of rainfall and runoff, respectively. Rainwater harvesting collects rainfall from local impervious areas whereas stormwater harvesting involves the collection of water from stormwater runoff (Perrin <i>et al.</i> , 2009; Armitage <i>et al.</i> , 2013; Atlanta Regional Commission, 2016).
Permeable paving	Permeable paving is a load bearing pervious surface cover which also acts as a stormwater treatment practice, for example concrete block pavers (CBPs) laid on top of granular or stone base that can temporarily store stormwater runoff. (Perrin <i>et al.</i> , 2009; Armitage <i>et al.</i> , 2013).
Filter strips	Filter strips are used to manage shallow overland stormwater runoff through vegetative filtering and are most effective as pre-treatment components in a treatment train (Debo & Reese, 2003; Woods Ballard <i>et al.</i> , 2015).
Infiltration trenches	Infiltration trenches are excavated trenches that can aid temporary stormwater storage and groundwater recharge; they are usually filled with a granular material of an acceptable void ratio while they are generally lined with a geotextile to separate the trench media and the surrounding soil (Hobart City Council, 2006; Woods Ballard <i>et al.</i> , 2015).
Swales	Swales are shallow vegetated channels with gently sloped sides which replace kerbs or impervious drainage lines with grass-lined stormwater transport corridors (Mays, 2001; Parkinson & Mark, 2005).
Bio-retention areas	Bio-retention areas are shallow landscaped depressions that can reduce runoff rates and treat pollution through infiltration into soil covered by carefully selected vegetation. They can be used as a source or local stormwater control and are most effective at delivering interception and infiltration but can also provide self-irrigating landscape features and habitats for biodiversity (Woods Ballard <i>et al.</i> , 2015).
Detention basins	Detention basins are temporary storage basins that manage excess stormwater during periods of higher than usual rainfall and, because they are usually empty, can be used for other landscape features like parks (Armitage <i>et al.</i> , 2013; Atlanta Regional Commission, 2016).
Retention ponds	Unlike detention basins, retention ponds always contain water, additionally they are designed to cater for considerable temporary quantities of stormwater, slowing it down, allowing it to mix with ponded water, and releasing the treated stormwater at a reduced rate (Armitage <i>et al.</i> , 2013; Atlanta Regional Commission, 2016).
Constructed wetlands	Constructed wetlands are ponds designed with shallow areas partially or entirely covered by aquatic vegetation. They provide a habitat for wildlife and can be highly effective in removing pollutants (Armitage <i>et al.</i> , 2013; Atlanta Regional Commission, 2016).

Although there is a wide range of available SuDS, retrofitting larger SuDS initiatives at a municipal scale where catchment areas are already relatively developed is common. Therefore, the following sections detail the local and regional controls. Good housekeeping, however, is also a critical aspect of holistic stormwater management and is also included in the part of the literature review that follows.

2.3.2.1 Good housekeeping

According to US EPA (2005), good housekeeping can help ensure a reduction in the amount and type of pollution that: (1) collects on streets, parking lots, open spaces, and storage and vehicle maintenance areas and is discharged into local waterways; and (2) results from actions such as environmentally damaging land development and flood management practices or poor maintenance of storm sewer systems. Suppose the level of service of infrastructure is shown to be both viable and valuable. In that case, the potential for homeowners to act on noble causes such as collecting rainwater can be boosted (Armitage *et al.*, 2013).

Another component of good housekeeping is community education which, according to ARMCANZ & ANZECC (2000), can play a significant role in improving stormwater quality. They observed that the many individual actions and impacts at various locations across various land uses in a catchment contribute to the pollution of stormwater. Community education was highlighted to be a process used to create awareness of issues, enhance people's knowledge, understanding, and skills, influence people's values and attitudes, and encourage more responsible behaviour (ARMCANZ & ANZECC, 2000). Good housekeeping reduces the intensity of pollution entering a stormwater drainage system and is critical for the benefits of downstream SuDS interventions.

2.3.2.2 Swales

Swales (Figure 2-1) are an alternative to concrete pipes and channels and provide increased roughness and infiltration while creating a visually aesthetic green corridor. The flow velocities tend to be slower than with the impervious alternatives, and the vegetation helps filter suspended material and encourage the deposition of silt. They are often used as low-grade pre-treatment systems and are generally suitable for road runoff and recreational areas (Melbourne Water, 2005; Armitage *et al.*, 2013; Woods Ballard *et al.*, 2015). There are various types of swales, including wet, vegetated, and dry (InfoDrainage, 2020a). The two main types are:

- Vegetated dry swales can be used to convey or attenuate stormwater. They are helpful for infiltrating stormwater through a drainage bed and may use an underdrain to convey excess stormwater to a designated outlet (Armitage *et al.*, 2013; Woods Ballard *et al.*, 2015).
- Wet or bio-retention swales use marshy conditions to mimic a wetland or biofiltration system. They are used primarily in areas of low soil permeability or a high water table (Melbourne Water, 2005; Armitage *et al.*, 2013; Woods-Ballard *et al.*, 2015).

Considerations for the design of swales include treatment performance, vegetation, flow control, site characteristics, treatment performance, sizing of overflow areas, space for recreation, and drafting a monitoring and maintenance plan (NCDOT, 2014). In addition, groundcovers are often used for sediment removal and erosion protection. Shrubs can be used for screening on the banks,

glare reduction and aesthetic value, whilst trees can be used for shade and character (Melbourne Water, 2005). A summary of the design features of swales can be found in Appendix E.2.

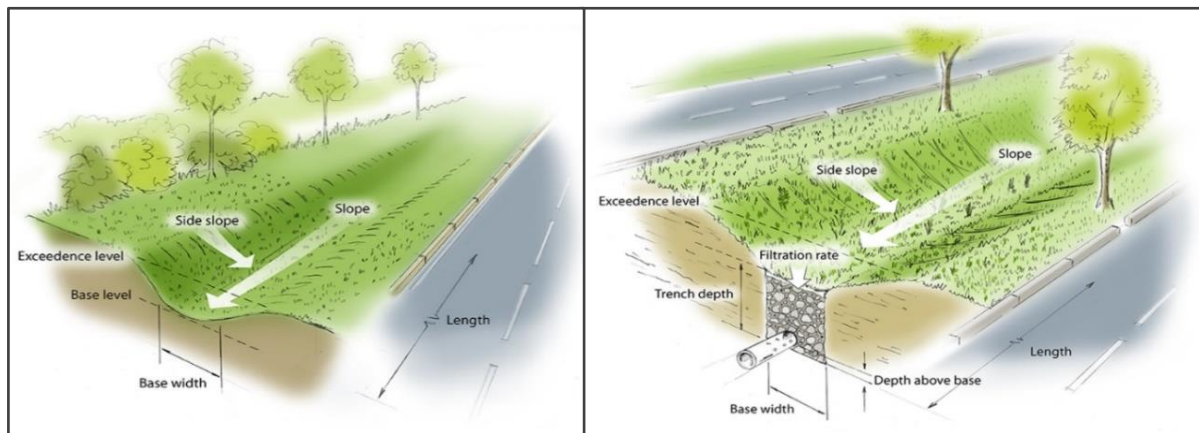


Figure 2-1: A swale with and without a perforated underdrain (InfoDrainage, 2020a)

2.3.2.3 Bio-retention areas

Bio-retention areas (Figure 2-2) are landscaped depressions typically employed to manage the initial stages of storm events through natural processes, especially infiltration and interception storage (Woods Ballard *et al.*, 2015).

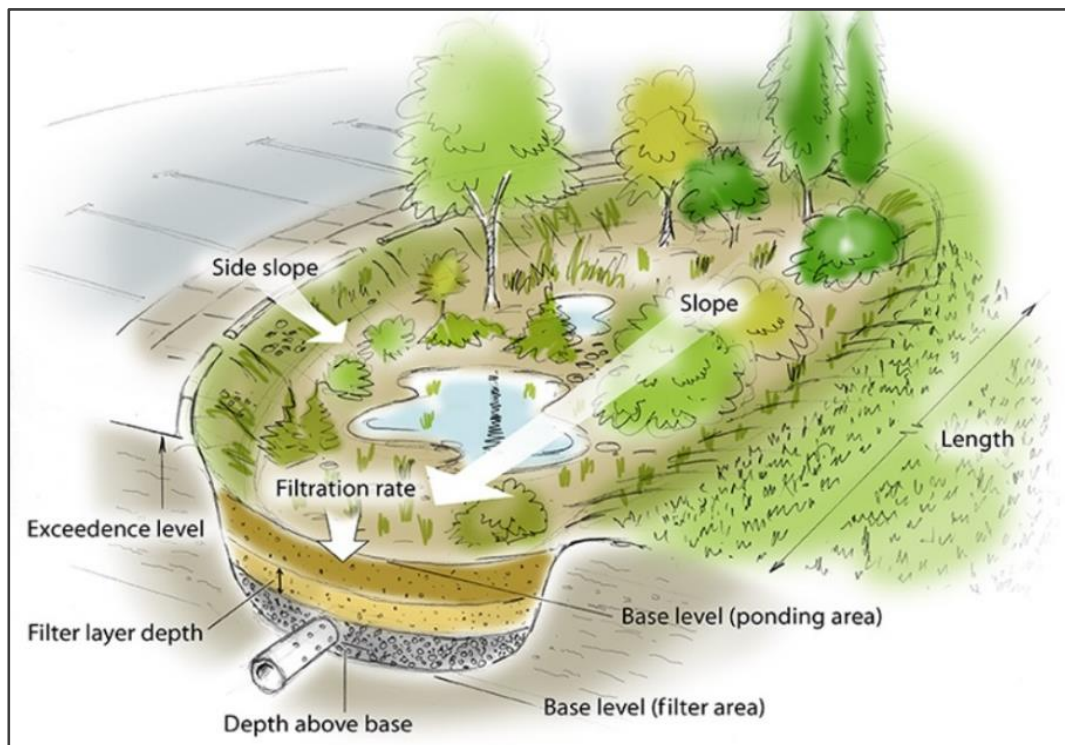


Figure 2-2: A bio-retention system (InfoDrainage, 2020b)

Alternative names for bio-retention areas include biofiltration basins, bio basins, biofilters, rain gardens, bio-swales or biofiltration swales (InfoDrainage, 2020b). The primary processes involved include filtration (capturing contaminants in vegetation, soil, or geotextiles); absorption (biological uptake); sedimentation (sediment deposition due to lower energy in the system, a result of lower flow velocities); infiltration (stormwater penetration into the ground); and detention (temporary storage of stormwater). Bio-retention areas are highly adaptable and use the principles of infiltration, surface roughness, soil moisture retention, as well as storage of excess stormwater runoff aiding in flood attenuation particularly adjacent to impermeable areas. A summary of the design features of bio-retention areas can be found in Appendix E.2.

Rain gardens are bio-retention areas that do not contain underdrains. Street planters are a type of bio-retention area that can be utilised to increase infiltration in urban areas where impervious surfaces are high in concentration (Atlanta Stormwater Commission, 2016).

2.3.2.4 Detention basins

Detention basins (Figure 2-3) store excess stormwater during higher-than-usual rainfall (Woods Ballard *et al.*, 2015). The captured stormwater will either infiltrate into the ground, evaporate, or drain into downstream watercourses or stormwater infrastructure at a regulated rate.



Figure 2-3: A dry detention basin (SusDrain, 2020a)

The efficacy of a detention facility is governed by the detention time and, thus, the storage volume of the system. Important design considerations involved with detention areas include local catchment hydraulics and hydrology; implementation of appropriate safety structures like the prevention of steep embankments around the pond perimeter; upstream pre-treatment systems such as a forebay to retain sediments; and the sizing of outlet structures from the pond (Armitage *et al.*, 2013). A design feature summary of detention basins can be found in Appendix E.2.

2.3.2.5 Retention ponds

A retention pond (Figure 2-4) is a stormwater structure with a permanent body of water, and its primary treatment mechanisms are sedimentation and biological uptake. They have medium to high pollutant removal capabilities and are typically more effective treatment systems than detention basins (Armitage *et al.*, 2013; Woods Ballard *et al.*, 2015). Introducing a planted narrow bench around the perimeter of the pond can aid in restoring aquatic life and enhancing contaminant control. Another important consideration is that of indigenous wildlife, which can help maintain local biodiversity in the surrounding landscape. A summary of the design features of retention ponds can be found in Appendix E.2.



Figure 2-4: A retention pond (Outerspacegardens.co.uk, 2018,)

2.3.2.6 Constructed wetlands

Although retention ponds and constructed wetlands (Figure 2-5) are similar, retention ponds are usually less vegetated and are implemented primarily for water quantity management. Constructed wetlands, on the other hand, are preferred if there is a focus on improving water quality and biodiversity. Wetlands can store surface water in two ways: temporarily and permanently. Temporary wetlands are ideally empty within 24 hours of a storm event and are vegetated to be able to accommodate both dry and wet periods, whereas permanent wetlands always have water. Usually, there is a trade-off between maximising retention time and storm flow storage and the emptying thereof. Constructed wetlands aim to create an environment where the water quality of stormwater can be enhanced prior to receiving water. In addition, they can create habitats which are not only nurseries for aquatic biodiversity but also can provide visual enhancement of the landscape (Woods Ballard *et al.*, 2015; Atlanta Regional Commission, 2016).



Figure 2-5: A free flowing and ponded wetland system on the left and right respectively
(Green, 2012)

The pollutant removal efficiency of constructed wetlands has been found to depend upon hydrologic variables such as climate, hydraulic loading rate, pollutant loading rate, hydraulic retention time (HRT), water depth, size, age, vegetation type, density, and management (Toet *et al.*, 2005; O’Geen *et al.*, 2010). A key design parameter of a constructed wetland is its HRT, which is the mean amount of time that water spends in a water body and is calculated by dividing the mean volume of the waterbody by the mean outflow rate (Davis, 1995).

Ponded wetlands ideally consist of four zones: the inlet zone; the shallow vegetation zone; the deep outlet zone; and the high-flow bypass channel (Armitage *et al.*, 2013). There are many types of constructed wetlands, several of which are provided in Table 2-8.

Table 2-8: Types of wetlands (Armitage *et al.*, 2013; Atlanta Regional Commission, 2016)

Type of wetland	Description
Shallow wetland	Shallow marsh stores WQV
Extended detention shallow wetland	Upstream storage of some WQV
Pocket wetland	Small contributing area, small wetland
Pond-wetland systems	Wet pond flows into a shallow marsh downstream
Submerged gravel wetland	Treatment cells with subsurface flows
Wetland channel	Implemented in a widened channel with a meander

Wetlands, ponds, and a few other SuDS components require pre-treatment to ensure that they function optimally (Armitage *et al.*, 2013; Woods Ballard *et al.*, 2015; Atlanta Regional Commission, 2016). Pre-treatment can be achieved by using forebays, filter strips or other SuDS source controls. A summary of the design features of wetlands is given in Appendix E.2.

2.3.2.7 Forebays: pre-treatment for downstream controls

Forebays are pre-treatment components for stormwater management systems (Figure 2-6). Alternate names associated with forebays include silt, sediment/sedimentation forebays, traps, or basins. Forebays generally operate by reducing flow velocities and encouraging sediments to settle out of the water column, thus protecting downstream stormwater management controls from being overloaded or smothered (Melbourne Water, 2005). Some of the key design features of forebays are provided in Appendix E.2.



Figure 2-6: Forebays at a development in Parklands, Cape Town, South Africa

A mixture of SuDS components in combination is important in developing the solutions. The number of components in the treatment train depends on the sensitivity of receiving water bodies, contributing catchments size, and the expected pollutant concentrations (Table 2-10).

2.3.2.8 SuDS summary

The SuDS components discussed in this section are valuable for the management of stormwater runoff. Table 2-9 summarises the advantages and limitations of key SuDS options. Good housekeeping is not included in the summary; however, it should precede other SuDS options and could be considered a necessary component of a SuDS treatment train.

Table 2-9: Advantages and limitations of selected SuDS (Armitage *et al.*, 2013)

Swales	
Advantages	Limitations
Inexpensive and more aesthetic than concrete structures.	Impractical in steep and very gradual topographies.
Effective infiltration of runoff.	High surface area in comparison to other systems.
Delay runoff peaks and retain sediment.	Maintenance is key to mitigating unwanted debris, foul odours, and breeding mosquitoes.
Bio-retention areas	
Advantages	Limitations
Can easily be incorporated into varying landscapes.	Require relatively gradual slopes.
Effective attenuation of stormwater runoff.	Frequent maintenance required.
Easy retrofitting and good aesthetics.	Maintenance is key to mitigating unwanted debris, foul odours, and breeding mosquitoes.
Detention areas	
Advantages	Limitations
Temporary storage aiding in flood peak attenuation.	Low removal of dissolved pollutants and pathogens.
Easy to maintain and inexpensive construction costs.	Can take up large amounts of valuable urban space.
Multiple alternative purposes in the dry season.	Unsuitable in areas with high water tables.
Retention ponds	
Advantages	Limitations
Large flood storage and effective pollutant removal.	Health and safety concerns.
Promotes biodiversity and can provide amenity.	Maintenance is key to mitigating unwanted debris, foul odours, and breeding mosquitoes.
Can be seen as a landscape feature, creating a sense of place that may not have existed prior.	Requires a sealed bottom or sufficient base flow to keep a permanent pool.
Constructed wetlands	
Advantages	Limitations
Effective design can benefit aesthetics and amenity.	Negligence can enrich nutrients and pathogens.
Provides an effective strategy for preventing stormwater runoff contamination.	Inflows need to be controlled effectively as excessive flooding with a long duration can be detrimental to the aquatic vegetation.
Flood control structures can be retrofitted as wetlands.	Wetlands are usually restricted to flatter areas.

A mixture of SuDS components in combination is important in the development of the solutions. The number of components in the treatment train depends on the sensitivity of receiving water bodies, contributing catchments size, and the expected pollutant concentrations (Table 2-10).

Table 2-10: Recommended number of components in a treatment train
(Woods Ballard *et al.*, 2007)

Catchment Characteristic	Receiving water sensitivity		
	Low	Medium	High
Roofs only	1	1	1
Residential roads, parking areas, and commercial zones	2	2	3
Refuse collection areas, industrial areas, highways, loading areas, and truck stops	3	3	4

2.3.3 Stormwater quality: pollutant removal

Reducing pollutant loads in stormwater systems requires appropriate design and maintenance but depends on the characteristics and concentrations of the incoming pollutants. The removal ranges for SuDS in Table 2-11 can aid their selection (Armitage *et al.*, 2013; Carvallo Aceves *et al.*, 2017).

Table 2-11: Pollutant removal percentage ranges of a few SuDS initiatives (Minton, 2002; Debo & Reese, 2003; Wilson *et al.*, 2004; NCDWQ, 2007; Woods-Ballard *et al.*, 2007)

SuDS option	TN removal (%)	TP removal (%)	TSS removal (%)
Bio-retention areas	40-50	50-60	50-80
Infiltration trenches	25-60	60-80	70-80
Swales	30-90	25-80	60-90
Enhanced dry swales	50-90	30-80	70-90
Infiltration basins	55-60	60-70	45-75
Constructed wetlands	30-60	30-40	80-90
Extended detention shallow wetlands	50-60	30-40	60-70
Detention basins	20-60	20-70	45-90
Retention ponds	30-50	30-50	75-90

The link between pollutant removal and HRT was investigated in a study undertaken by Toet *et al.* (2005). They found that pollutant removal improved with an increase in the retention time of the respective wetland systems. The pollutant removal data they provided was seen to follow a first-order decay rate. Equation 2-1 represents a first-order decay relationship between pollutant removal and HRT.

$$\frac{A}{A_0} = e^{-k * HRT} \quad \text{Equation 2-1}$$

Where: A = Amount of pollutant remaining in the system (kg); A_0 = Initial amount of pollutant in the system (kg); k = pollutant removal coefficient; and HRT = hydraulic retention time (h^{-1}).

Two types of TN and TP pollutant removal data are reported in the literature:

- i) Pollutant removal values for varying HRTs like those provided by Toet *et al.* (2005) for a study in Texel, Netherlands. They collected pollutant removal data from a sewage treatment wetland evaluating the effect of four different HRTs (0.3, 0.8, 2.3, and 9.3 days) on the removal of TN and TP in the wetland (Table 2-12).

Table 2-12: TN and TP removal in a constructed wetland with respect to varying HRTs
(Toet *et al.*, 2005)

HRT (Days)	HRT (Hours)	TN Fractional Removal	TP Fractional Removal
0	0	0	0.000
0.3	7.2	0.143	0.019
0.8	19.2	0.243	0.151
2.3	55.2	0.414	0.255
9.3	223.2	0.631	0.481

- ii) Pollutant removal coefficients (k -values) were found for both TN and TP in studies completed by Tanner *et al.* (1995) and Wittgren & Maehlum (1997). A pollutant removal coefficient for TN was also found in a study by Gajewska *et al.* (2020). The k -values found in the literature for TN and TP are provided in Table 2-13.

Table 2-13: Pollutant removal constants (k -values) for TN and TP reductions with respect to HRT in constructed wetlands

TN		TP	
k-value	Reference	k-value	Reference
0.0067	Tanner <i>et al.</i> (1995)	0.0058	Tanner <i>et al.</i> (1995)
0.0025	Wittgren & Maehlum (1997)	0.0117	Wittgren & Maehlum (1997)
0.0022	Gajewska <i>et al.</i> (2020)		

The pollutant removal data information about how TN and TP are removed from constructed wetlands with respect to HRT, which can be useful when inferring pollutant removal in a model.

2.4 Evaluating SuDS in hydrological models

This section describes what hydrological modelling entails in the context of SuDS design, the available models, and discusses the complexities of modelling a catchment area. Hydrological models are necessary for water and environmental resource management (Gayathri *et al.*, 2015). They are mathematical representations of the processes involved in the converting climate inputs such as precipitation, solar radiation, and wind through surface and subsurface transfers of water and energy into hydrological outputs like flow in rivers (Hughes, 2004; Rossman & Huber, 2016a).

2.4.1 Hydrological models for stormwater management applications

Hydrological models can be used to evaluate the performance of stormwater management interventions. However, the assessment for large-scale catchments remains challenging because of spatial resolution and the accessibility of calibration data (Krebs *et al.*, 2014). Nonetheless, many studies have highlighted the importance of hydrological modelling for urban stormwater management (Liu *et al.*, 2010; Niazi *et al.*, 2017; Hossain *et al.*, 2019). Hallouin *et al.* (2018) describe four attributes of terrestrial ecosystems that directly affect freshwater resources:

- Quantity
- Quality
- Location
- Timing

Hydrological modelling can represent these attributes in a sophisticated way, although there will always be uncertainty regarding the data representing the respective attributes. For example, rainfall will vary spatially – at separate locations in a catchment – as well as temporally – at different times across a catchment – and no data collected from specific points in the catchment will be able to adequately represent these variations in space and time (Smithers, 2012; Hallouin *et al.*, 2018). Therefore, it is thus important to deal with the components contributing to uncertainty and quantify it in deterministic models (Hughes, 2004; James, 2005). Different modelling techniques provide various levels of quantification of uncertainties. Although computing power and modelling software has become more sophisticated, data availability and other forms of error need to be mitigated and reported. Different modelling philosophies will also change the type and amount of uncertainty and error in the outputs of a model.

It is important to differentiate between event-based and continuous timeseries-based hydrological modelling. The differences between the two are provided in Table 2-14.

There is inherent complexity in rainfall-runoff processes and therefore in the models used to estimate runoff rates and volumes. There is a need to incorporate the rainfall-runoff

fundamentals along with sensitivity analyses that allow modellers to understand the range of possible responses and variations in the model (Shaver *et al.*, 2007). The extent to which the model attempts to represent the many and diverse processes that affect the response of runoff to rainfall and other characteristics of the landscape is termed model complexity (Hughes, 2004). To an extent, the more variables it considers, the more complex a model is, likely to be.

Stormwater management interventions in practice are usually designed for drainage and flood control using representative RP storm events for which the identification criteria vary in different regions (CCT; 2009; Woods Ballard *et al.*, 2015; Atlanta Regional Commission, 2016). Limitations for using storm events for design include, but are not limited to, the assumption that the frequency of the design flood is the same as that of the input rainfall and that they consider the probabilistic nature of rainfall but do not consider the probabilistic nature of the parameters that represent the catchment conditions (Smithers, 2012).

Table 2-14: Differences between event- and continuous timeseries-based hydrological models (Rossman & Huber, 2017; Smithers, 2012; James, 2005; Goel *et al.*, 2000)

Event-based model	Continuous timeseries-based model
Uses a rainfall input that contains distinct storm event return period (RP) rainfall depths.	Assesses the hydrological model using a continuous dataset of rainfall data collected from a nearby rainfall gauge.
Has a defined duration for the rainfall event, although multiple storm events can be run (e.g., different RP storm events with a duration of 24-hours).	The historic time period depends on the length of time for which data was collected from the rainfall gauge, however, synthetic datasets can be generated.
Usually used in design for the sizing of various SuDS developments.	Provides an opportunity to investigate the impact of numerous storm events of varying scales across different seasons, allowing for investigation of the effect of first flush for example.
Response of catchment can only be assessed for the storm event RPs run in the model.	Provides a more comprehensive assessment of a catchment areas response.
Storm event rainfall data for different RPs can be acquired without a rainfall gauge being present in close proximity of the catchment area.	Can generate distinct RP storm events which could be used for design purposes.

Hydrological models can model water quality concerning pollutant build-up and wash-off processes for different land uses (Rossman & Huber, 2016b). Different land uses exhibit different pollution levels; for example, a well-vegetated woodland contributes fewer harmful pollutants than a construction site. Interpreting the types of pollutants from each land use that can be modelled is important for understanding the pollution problem of a catchment and the impact of its discharge on receiving waters. According to Roose (2000), nitrogen is a significant component in proteins such as nucleic and amino acids, while phosphorus is an essential building block in metabolic processes and the conversion and transferal of energy, making them two of the most critical macronutrients in vegetation growth. According to Leutnant *et al.* (2018), stormwater quality models are usually calibrated using observed pollutographs. They observed that

calibration results for continuous pollution modelling are highly uncertain because current models still rely on oversimplified concepts of pollutant accumulation (build-up) and wash-off.

The effectiveness of SuDS can be evaluated in several ways, such as benefit-cost analysis, social return on investment, and risk-benefit analysis. Each of these techniques assesses the impact of a stormwater system upgrade across its life cycle. However, the complexity of estimating real long-term benefits, returns, risks and costs is high due to the range of stakeholders involved in such projects (Millar & Hall, 2012; David *et al.*, 2013).

2.4.2 Available hydrological models

A challenge faced by hydrological modellers is to find the best ways of integrating international developments of conceptual models, mathematical techniques, and software-related approaches to local modelling practices (Hughes, 2004). As a result, many models have been developed to represent parts of the hydrological cycle; a summary of some of the better-known models is provided in Table 2-15.

Table 2-15: Software models for urban stormwater management (Rangari *et al.*, 2018)

Program	Developed by	Public domain	Comments
HEC-HMS	US Army Corps of Engineers	Yes	Developed to replace HEC-1 with additional capabilities such (2D) hydrologic modelling, single or multiple storms.
SWMM	US EPA	Yes	Single event or continuous simulation of stormwater runoff quantity and quality.
PCSWMM	CHI	No	Runs on the SWMM engine allowing for single event or continuous simulation of stormwater runoff quantity and quality with capabilities of modelling multiple scenarios and enhancements around the inputs and outputs.
XP-SWMM	XP Solutions	No	Comprehensive software package for modelling stormwater, sanitary and river systems, used to develop link-node (1D) and spatially distributed hydraulic models (2D).
MIKE URBAN	DHI Water and Environment	No	A flexible system for modelling and design of water distribution networks, waste water and stormwater. Contains a database for storing network as well as hydraulic modelling data.
ILLUDAS	British Road Research Laboratory	Yes	Uses time-area methods to generate hydrographs from directly connected paved and previous areas.
MUSIC	e-Water	No	Tool used for demonstrating the performance of stormwater quality treatment systems in urban areas.

The Storm Water Management Model (SWMM) was first developed as a public domain software in the computer language FORTRAN by the US EPA in 1971 at much the same time as the Clean Water Act in the US (Metcalf & Eddy, 1971). It is made up of a series of blocks: Executive, Runoff, Transport, Storage, and Receiving water. SWMM 5 was released in 2005 and is the graphical user interface of SWMM, re-written in the C language (Niazi *et al.*, 2017). It is highly regarded as a robust piece of software due to its long open-source history and well-supported commercial options (Niazi *et al.* 2017).

PCSWMM is an enhanced version of SWMM that assists with dynamic rainfall-runoff modelling. It simulates urban runoff quantity and quality for multiple scenarios enabling comparisons of rainfall events, and improvements and upgrades to an existing urban stormwater network. In addition, PCSWMM offers a limited number of SuDS applications (called LIDs in the program) to manage stormwater runoff volumes and the pollutants being transported within those flows.

3. Site description

This section reviews the available data on the Knysna Estuary and the eutrophic Ashmead Channel, the shallow north-eastern section of the Knysna Estuary, into which the Bongani River and the Knysna Municipal Wastewater Treatment Works (WWTW) discharge. It provides background material on the intrinsic value of the Knysna Estuary, provides context about previous research on Ashmead Channel, and describes the weather, landscape characteristics, biodiversity, and amenity value, and the tributaries and streams of the Bongani Catchment.

Estuaries in the Cape Floristic Region in South Africa are extremely rich in plant and animal diversity, attracting visitors, sustaining livelihoods, and uplifting the community (Coastal & Environmental Services (CES), 2007). The Knysna Estuary has been classified as South Africa's most important estuary in terms of conservation priority (Human *et al.*, 2016), supporting an ecosystem with several fish, birds, mammals, plants, and invertebrate species, each with significant roles and importance in the overall ecosystem (Van Niekerk & Turpie, 2012; Human *et al.*, 2020). The estuarine vegetation is exposed to a high degree of photosynthetic radiation, leading to abundant and diverse Eelgrass meadows and saltmarsh banks. This can be partially attributed to the fact that the estuary is the most light-transparent along the southern Cape coast, if not throughout the entire coast of South Africa, due to the marine influence of the bay regime (Allanson, 2000; Marker, 2003). The endemic and endangered Knysna Seahorse (*Hippocampus capensis*) is exclusively found along the Garden Route. The only other estuaries supporting the species are in Plettenberg Bay and Sedgefield respectively, with both roughly 30 km away from the town of Knysna (Figure 3-1).

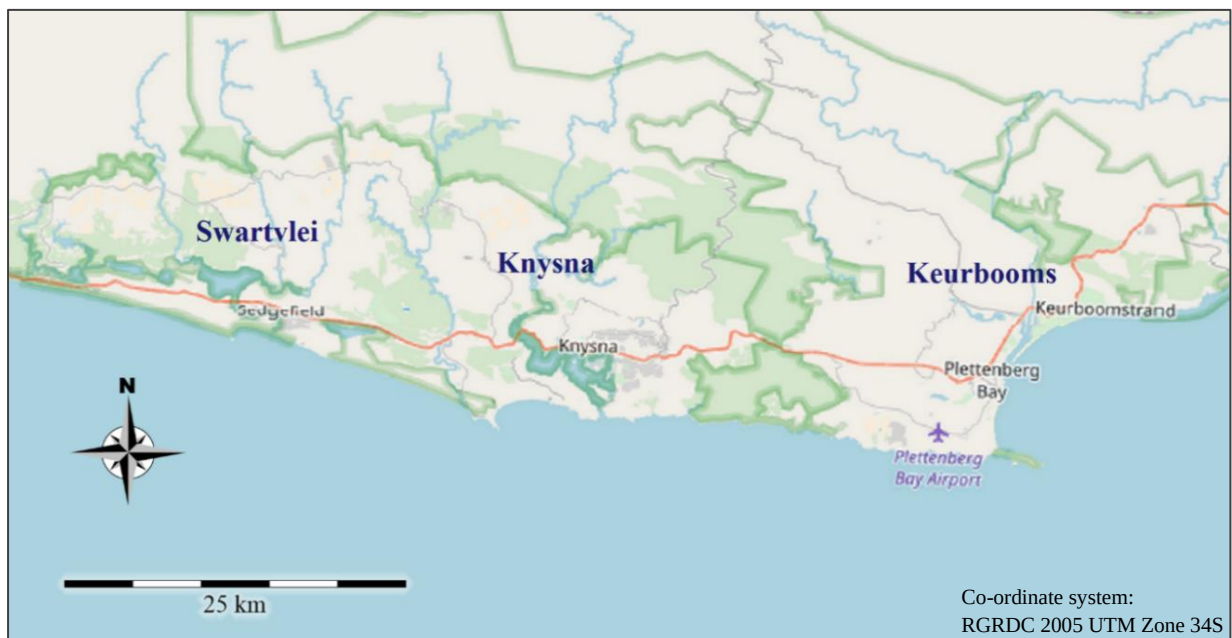


Figure 3-1: Estuaries inhabited by the Knysna Seahorse along the Garden Route including the Knysna Estuary in the centre (Open Street Map roads, n.d.)

3.1 The state of Knysna's rivers and streams

The streams and rivers draining into the Knysna Estuary are under considerable anthropogenic stress (Winter *et al.*, 2016). Harvey (2019) investigated the water quality along the north-eastern shores of the Knysna Estuary from the Salt Stream to the Bigai Stream, focusing on stormwater discharges (Figure 3-2). She gathered data on inorganic nutrients (ammonium, nitrites, and nitrates) which make up total inorganic nitrogen (TIN), soluble and reactive phosphorus (SRP), sediments as total suspended solids (TSS), and *Escherichia coli* (*E. coli*) to identify which stormwater discharges were polluting the Knysna Estuary.

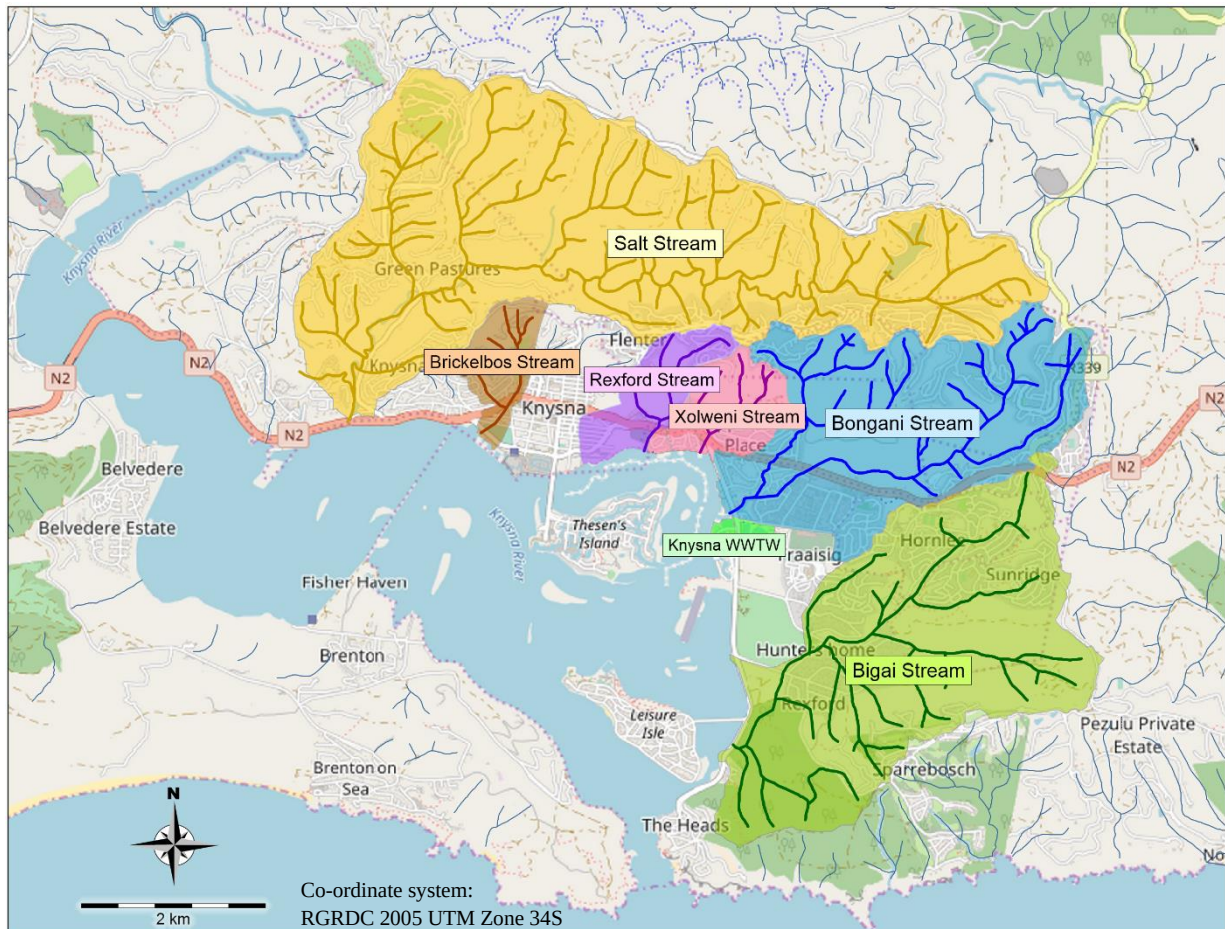


Figure 3-2: Knysna Estuary's north-eastern catchment areas
(Bing map roads, n.d.; Knysna Municipality, n.d. a)

The state of the streams and rivers entering the Knysna Estuary is critical for the provision of ecosystem goods and services, according to Mander & Van Niekerk (2013). They evaluated the current health of the systems in terms of their ecosystem services and determined that the Knysna River and the streams that enter the Knysna Estuary from the west were in better condition than, notably, the Salt and Bongani Rivers to the east because the land use in the west is less developed than the east which comprises industrial complexes and peri-urban settlements.

3.1.1 The drainage systems of the Knysna Estuary

The Knysna Basin is the 480 km² catchment area of the Knysna River, a sixth-order stream, the highest category of medium streams (Bravard & Petit, 2009). The Salt River is the second largest tributary of the Knysna Estuary, with a catchment area of about 1530 ha, draining suburbia, the Simola Golf Estate, Afromontane Forest, and plantations. The Bigai River has a catchment area of 910 ha, draining low to high-income suburbia, and is controlled at its downstream section by a 2 km long silted wetland consisting of primarily *Phragmites* reed beds. The Bongani River has a catchment area between 630 and 650 ha, depending on how much of the saltmarsh habitat is included. The effluent of the Knysna WWTW combines with the Bongani River in the saltmarsh upstream of the Ashmead Chanel. The other small streams entering the north-eastern parts of the estuary include the Brickelbos Stream and the Long Street Canal which drain into the Knysna Estuary and the Queen Street Canal, the Rexford Stream, and the Xolweni Stream, which drain into the Ashmead Channel.

3.1.2 The Knysna Estuary and the threats to its biodiversity

The Knysna Estuary is the South African stronghold for the eelgrass *Zostera capensis*. These eelgrass meadows have been shown to support a variety of invertebrate and fish species for habitat, shelter, foraging sites, and nurseries whilst providing other ecosystem services like carbon sequestration (Adams, 2016). However, the estuary is on a negative trajectory of change due to issues such as urban sprawl in Knysna which has led to an increase in the quantity of pollution and stormwater flow rates and volumes with the increase in the impervious land area (DWA, 2009). Most of the freshwater entering the Knysna Estuary is derived from the Knysna River, its tributaries, and several streams along the estuary's edge (Largier *et al.*, 2000). The streams on the northern and eastern shores of the estuary, including the Bongani, Bigai and Salt catchments, are degraded, have poor ecosystem services, and have been considered a burden on the estuary (Mander & Van Niekerk, 2013). Sediment transport into the estuary has also caused problems historically – primarily due to the sediment losses during the construction of golf courses (Russel, 1996; Allanson, 2000).

An estuary's ecological health depends on a blend of freshwater from the rivers, streams and the saline water brought in by the ocean's tides (Largier *et al.*, 2000). Nevertheless, little information is available on the smaller drainage networks discharging into the Knysna Estuary (Mander & Van Niekerk, 2013; Winter *et al.*, 2017). Stormwater runoff discharging into the estuary from the northern and eastern catchments arises from urban areas and their peripheries. These catchment areas are poorly understood freshwater sources of the Knysna Estuary (CES, 2007). The lack of information about the drainage networks around the estuary is a concern for the protection and prosperity of the ecological health of the biodiversity within and around the estuary (Marker, 2003; Allanson *et al.*, 2010; Human *et al.*, 2016). Thus, it is crucial that research is conducted in the most polluted catchment areas to help understand the threats they bring to the Knysna Estuary (CES, 2007; Winter *et al.*, 2017; Harvey, 2019).

3.1.3 Concerns for the Ashmead Channel: the green tide

The national importance of biodiversity in the Knysna Estuary calls for a better understanding of the negative impacts threatening it (Van Niekerk & Turpie, 2012; Adams *et al.*, 2016; Claasens *et al.*, 2020). Anthropogenic impacts on the Knysna Estuary's aquatic ecosystem include litter, faecal matter, agricultural fertiliser, erosion, illegal dumping, and industrial contamination – all of which have negative implications for the downstream water resource (CES, 2007). Combined, these impacts increase the risk of chronic eutrophication by algal blooms in response to spikes of nutrients. The problem is especially noticeable along the eastern coastline of the Knysna Estuary, particularly along the Ashmead Channel, where a recurring 'green tide' is causing concerns for its local biodiversity (Human *et al.*, 2016). This 'green tide' (Figure 3-3) is a periodically persisting opportunistic macro-algae bloom primarily consisting of *Ulva lactuca* (*Ulva* spp.) (Human *et al.*, 2016; Claasens *et al.*, 2020). The bloom was first identified in the summer of 2014/2015 in the intertidal zone of the estuary (Allanson *et al.*, 2016).

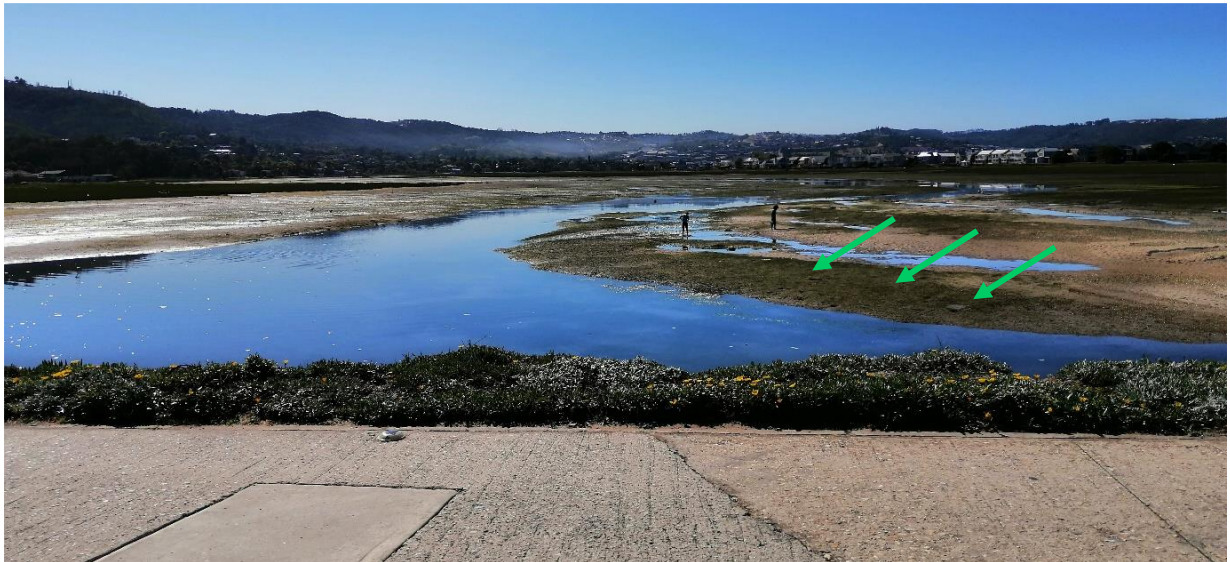


Figure 3-3: Ashmead Channel's macroalgal bloom shown from Thesen Island's causeway

The green tide has been exacerbated by high nutrient loads in surface water runoff, contaminated municipal discharge from the Knysna WWTW, and benthic flux from the anoxic sediment in the Ashmead Channel (Adams *et al.*, 2016; Human *et al.*, 2016; Claasens *et al.*, 2020). A major concern with the abundance of the blooming algal species is that it threatens the *Zostera capensis* beds, the indigenous intertidal Seagrass vegetation upon which many of the species found within Ashmead Channel and the Knysna Estuary depend (Berglund *et al.*, 2003; Burkholder *et al.*, 2007). The influx of nutrients into the channel and contaminated benthic flux from anoxic sediments have ensured persistent eutrophication and the loss of the local Seagrass meadows within Ashmead Channel. This loss of indigenous biodiversity will continue to have repercussions on the fauna and flora of the channel (Human *et al.*, 2016).

3.1.4 Knysna Estuary's polluted eastern shores

Water samples from 18 sites were collected and tested along the eastern shores of the Knysna Estuary in 2018 in research conducted by Harvey (2019) to investigate water quality issues around that part of the estuary. The samples were tested for pH, conductivity, turbidity, and nutrients – ammonium, nitrites, nitrates, and phosphates which make up inorganic N and P – and sediments as total suspended solids (TSS). The proposed water quality objectives for the Knysna River, which were also assumed to apply to the small drainage networks around the Knysna Estuary, were gazetted for public comment by the Department of Water and Sanitation (DWS) in 2018. They include the requirement that median total inorganic N (TIN) values be less than 0.7 mg/L (DWS, 2018). The median TIN concentrations at all sites measured by Harvey (2019) – except a section of the Brickelbos Stream – exceeded this recommended water quality objective. Furthermore, the DWAF guidelines also noted that within *‘unimpacted, well-oxygenated waters, most (>80%) of the inorganic N should be present as nitrate; and that typically, ammonium concentrations should be below 0.1 mgN/L, or less than 20% of the inorganic N present’* (DWAF, 1996a). However, measurements from Harvey (2019) found that ammonium concentrations made up a disproportionate amount of the TIN concentrations exceeding 20% – with many sites exceeding 70% – indicating that most of the sites were not meeting the recommended objectives.

Harvey (2019) revised her sampling and testing locations once the major concerns for the eastern shoreline were better understood. The revised sampling and testing sites shifted the focus to the Salt, Xolweni, Bongani, and Bigai catchments. The data showed that Ashmead Channel and its contributing catchments were likely being polluted by high nutrient loads from various upstream peri-urban settlements from Xolweni in the west to Hornlee in the south-east (Figure 3-2). The Bongani River was of the greatest concern because of its elevated pollutant concentrations – excessive TIN, SRP, and *E. coli* concentrations – and deteriorating drainage and sewage infrastructure. The nutrient concentrations were eutrophic and, in some cases, hypertrophic for much of the research period (Harvey, 2019). Furthermore, the investigation revealed that TIN and SRP were higher than samples measured by Russel (1996) and SSI (2012). Additionally, the measured *E. coli* concentrations from Ashmead Channel, the Bongani River and the upper Bigai Stream were generally greater than the limit for recreational use (< 500 CFU/100ml), which was indicative of a chronic, rather than intermittent, pollution issue. In particular, the Bongani River's persistent nutrient contamination of the Ashmead Channel threatens the estuarine biodiversity and the benefits of its ecosystem services (Adams, 2016).

3.2 Characterising the Bongani River catchment

This section describes the geographical features of the Bongani River catchment. A summary of the local climatic conditions is provided, after which the geology and soil characteristics are described. A summary about the biodiversity, economy, and amenity value of the Bongani River catchment follow before a description of the stream network.

3.2.1 Climate and weather

Knysna is classified as a Cfb climate according to the world map of Köppen-Geiger climate classification (Kottek *et al.*, 2006; Forest, 2020). This means that it has a ‘Cool Summer [C]’, its precipitation classification is ‘Fully Humid [f]’, and that its main climate is ‘Arid [b]’. Climates like that of Knysna exist in coastal north-eastern Argentina, south-western Patagonia, much of mainland Europe, south-eastern Australia, New Zealand, coastal British Columbia in Canada, and parts of northern South America and Central America (Forest, 2020). This is significant because if local data that may be required is unavailable, data from areas with a similar climate are potential substitutes.

Knysna is warm and temperate, receiving significant amounts of rainfall throughout the year with a mean temperature of about 17°C and Mean Annual Precipitation (MAP) of about 670 mm (en.climate-data.org, n.d.). The seasonal mean temperatures are about 25°C in summer and 7°C in winter (Marker, 2003). Rainfall within the Knysna Basin is considered relatively high in the context of South Africa, which is a relatively dry country with a MAP of about 460 mm (South Africa Yearbook, 2015/2016). However, the rainfall is not constant across the basin – varying from a MAP of about 700 mm at the coast to about 1800 mm some 18 km inland over the central Knysna Basin. At the river’s source in the Outeniqua Mountains, it is less than 600 mm (Marker, 2003). Knysna is also vulnerable to extreme climatic events such as severe droughts and flood events, as witnessed in 1996 (Marker, 2003) and 2015 (Gosling, 2015) (Figure 3-4).



Figure 3-4: Knysna flooding in September 2015 (Fran Kirsten as cited by Gosling, 2015)

3.2.2 Geology and soils

The Knysna Basin has had a complex geological history (Marker, 2003). If the sand layers covering the clay become saturated, lubrication of the deposits can result in increased erosion posing as slope failure. Bongani River's headwaters are situated in the cover sands. From the headwaters, the streams flow across sandstone, shale, and siltstone before reaching the flatter portion of the landscape, comprising mudstone, sandstone, shale, and sandstone rock. The stream then flows into the estuary across the alluvium silt deposits of the Knysna Estuary (Figure 3-5).

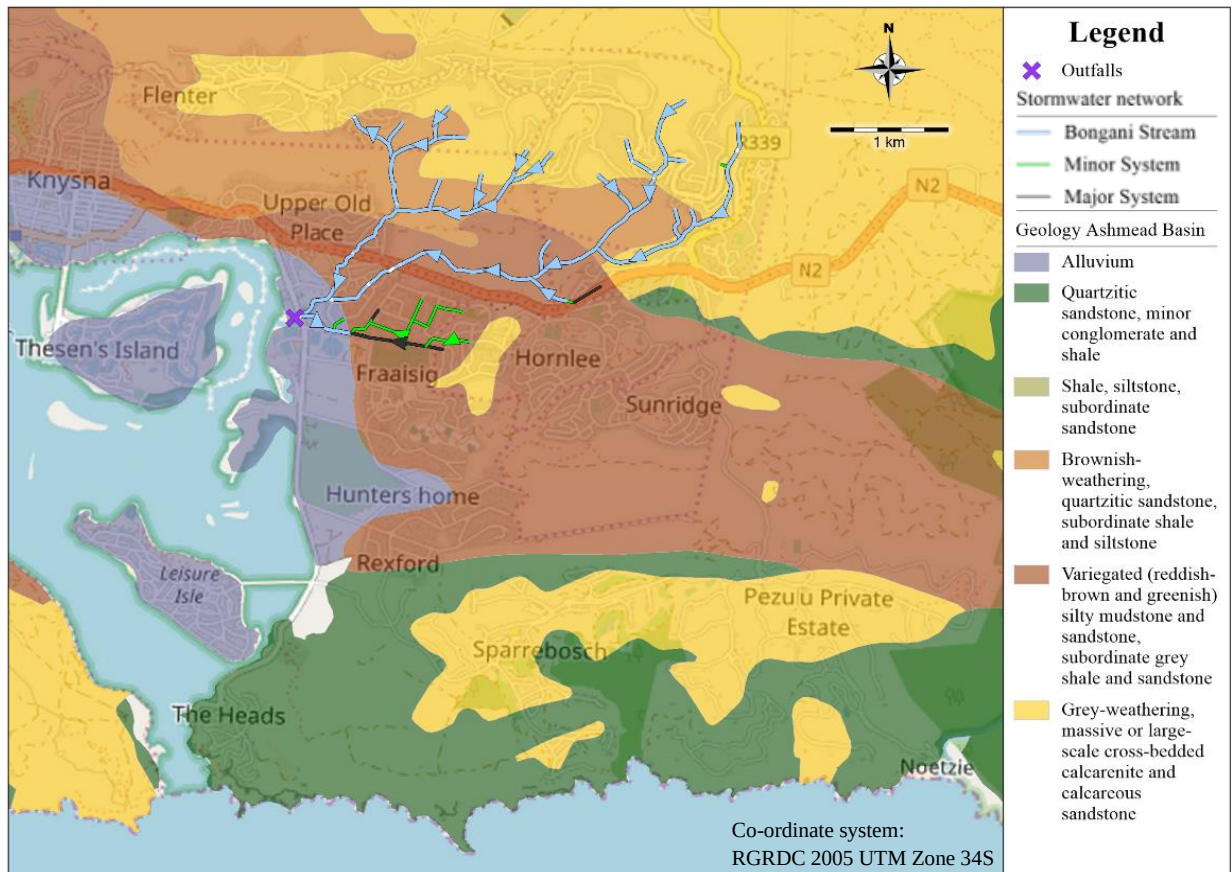


Figure 3-5: A geological map of the eastern Knysna Estuary
(Open Street Map, n.d.; Knysna Municipality, n.d. b)

The soil types that lie above the geology include (Land Type Survey Staff, 2006):

- Fixed dunes lie above the grey-weathering, massive or large-scale cross-bedded calcarenite and calcareous sandstone and variegated silty mudstone and sandstone, subordinate grey shale, and sandstone layer (depicted in yellow and maroon).
- The duplex soils on the mid-slopes lie above the brownish weathering, quartzitic sandstone, subordinate shale, and siltstone layers (depicted in orange).
- Alluvial valley deposits lie above the alluvium layer (depicted in blue).

3.2.3 Biodiversity

The southernmost patches of Afromontane Forest are found in the areas surrounding Knysna. Together with the Afromontane Forests of the Amatole Mountains, the vegetation type makes up its own ecoregion in South Africa (von Gadow *et al.*, 2016). Moreover, part of the Bongani Catchment supports Southern Cape Afrotemperate Forests (Figure 3-6) (Geldenhuys, 1991).

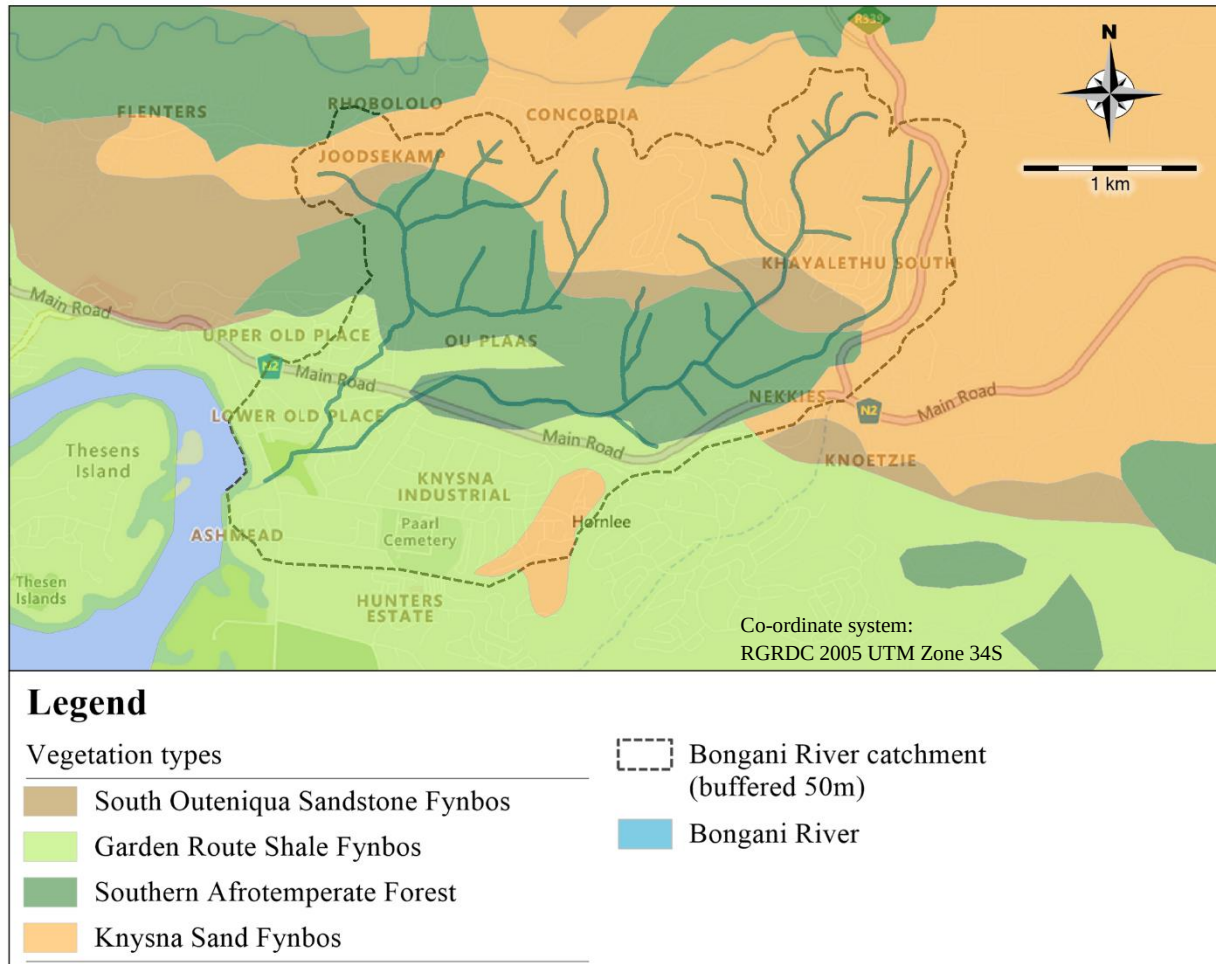


Figure 3-6: Vegetation map of the Bongani Catchment
(Bing Map Roads, n.d.; Knysna Municipality, n.d. c)

Three types of fynbos vegetation surround the Southern Afrotemperate Forest:

- The endangered Garden Route Shale Fynbos, which hosts endemic species such as *Cyphia georgica* and *Gladiolus roseovenosus* (Garden Route National Management Plan, 2010).
- The endangered Knysna Sand Fynbos, which is almost totally transformed, in urgent need of protection, and close to extinction (Lombard *et al.*, 2005; Mucina & Rutherford, 2006).
- The vulnerable South Outeniqua Sandstone Fynbos which has been largely transformed through plantations and agricultural developments (Golding 2002; Lombard *et al.*, 2005).

3.2.4 Economy and amenity

The timber from the Southern Afrotemperate Forests surrounding the estuary used to be the economic mainstay for Knysna. Forests are still typical in the surrounding catchments. However, instead of comprising indigenous trees, sizable areas of the land are devoted to Eucalyptus and Pine plantations managed and harvested by local landowners (CES, 2007; Mander & Van Niekerk, 2013). Nonetheless, large parts of the Knysna Basin still contain indigenous vegetation, including the Bongani Catchment, which supports roughly 250 ha of the Southern Afrotemperate Forest ecosystem. The remaining indigenous forest can be found in the Heidevallei area, which comprises the Bongani River and Old Place Stream catchments midsection. However, a concern for the ecosystem is that the streams that flow through these forests are regularly inundated with overflowing sewage and litter from the settlements in their headwaters.

Tourism is a significant contributor to the economy of Knysna (CES, 2007; GAPP Architects, 2017). The Knysna Estuary is a primary driver of this tourism, but the Bongani Catchment does not particularly promote or provide areas for inducing tourism. The tourism market in the Bongani Catchment includes township tours and the Knysna African Crafts Market, which is adjacent to the Bongani Wetland and Loerie Park (Figure 3-7). Besides the market, some commercial activity exists in the Knysna Industrial area. Ensuring that these spaces are well maintained can also create an environment for enhanced tourism and local recreational activities.



Figure 3-7: The Bongani Wetland, and the open space adjacent to the Knysna African Crafts Market, viewed from George Rex Drive

Public amenities such as parks in the area are limited. Apart from the market, Loerie Park, located adjacent to George Rex Drive, is primarily used for sports and social gatherings during public holidays and weekends. Two other sports fields in the catchment provide amenities: the Khayaletu sports field, which is adjacent to the Khayaletu Nature Reserve, and the Heidevallei sports field, which is adjacent to the N2 adjacent to the Bongani River.

3.2.5 Tributaries and stream network

The Bongani Catchment comprises three main tributaries that combine and flow into the Ashmead Channel: Old Place Stream, Bongani Stream, and Vigilance Canal (Figure 3-8).

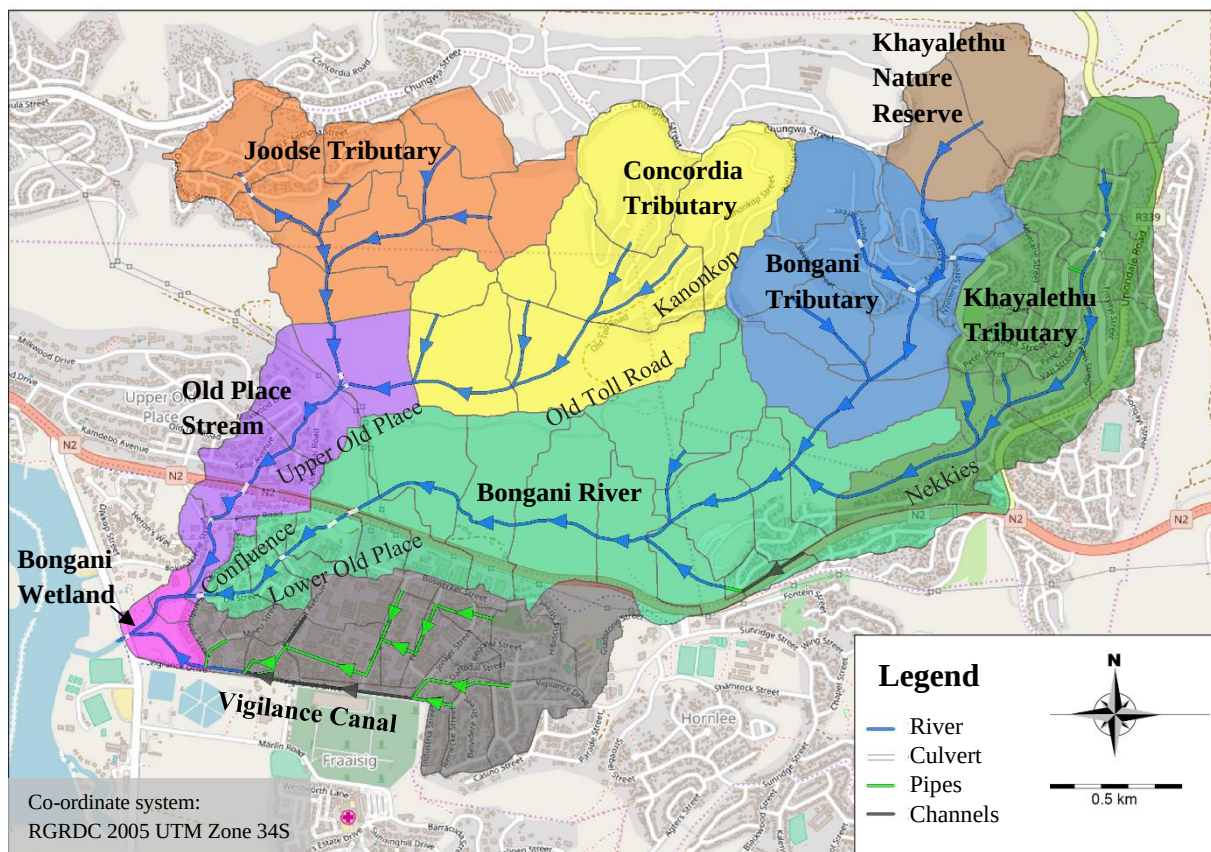


Figure 3-8: The tributaries of the Bongani River (Bing map roads, n.d.)

Old Place Stream consists of two smaller streams (Joodse Tributary and Concordia Tributary) that merge in the forest below the Old Toll Road, the road to the Green Waste Site (Figure 3-9).

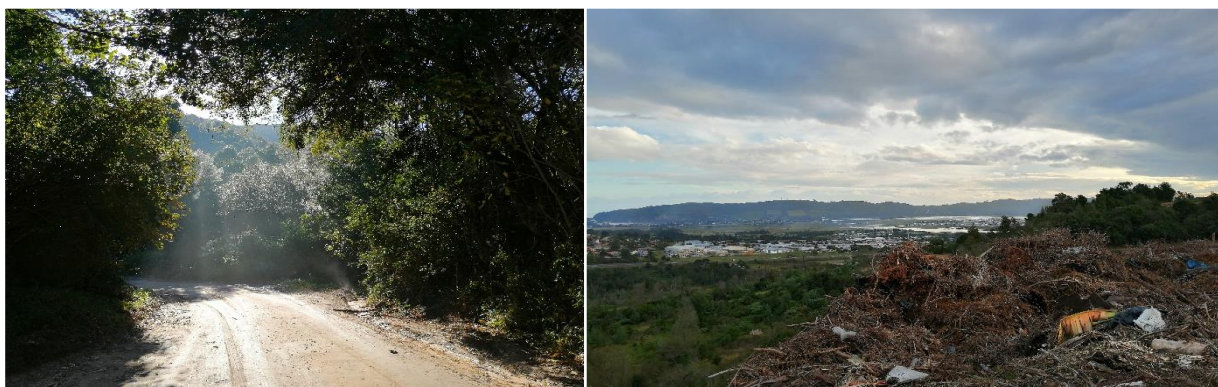


Figure 3-9: The Afromontane Forest and Green Waste Site along the Old Toll Road

The western tributary of Old Place Stream drains the settlement of Joodse Kamp (Figure 3-10), while the eastern tributary drains Concordia and Kanonkop.



Figure 3-10: The settlement of Joodse Kamp

The intermediate sections of these two catchments are made up primarily of Afromontane Forest, which is both steep and dense. The upper sections are made up of primarily low-income residential areas, which face problems like illegal dumping and sewage spills (Figure 3-11).



Figure 3-11: Concordia Tributary and an informal dump site upstream of its headwaters

After their confluence, the Old Place Stream flows downstream through the suburb of Upper Old Place, until it flows beneath the N2 highway and enters the suburb of Lower Old Place where it continues through formal residential areas to its confluence with the Bongani River, which occurs in the greenbelt between Lower Old Place and Knysna Industrial area.

The Bongani River is the major tributary or drainage line of the catchment. Upstream of its confluence with the Old Place Stream, the Bongani River consists of two smaller streams that merge at the top of the Heidevallei. The western tributary of this section of the Bongani River originates in the Khayaletu Nature Reserve in the east and drains through the low-income settlement of Bongani in the west (Figure 3-12).



Figure 3-12: The settlement of Bongani, as viewed from Judah Square

The eastern tributary of this section of the Bongani River drains the settlement of Khayaletu, which drains towards the Nekkies settlement adjacent to the N2 highway (Figure 3-13).



Figure 3-13: The settlement of Khayaletu (left) and an informal dump site in the settlement of Nekkies with the Afromontane Forest in the background (right)

Downstream of the confluence of the Bongani and Khayaletu Tributaries, the Bongani River flows through the indigenous Southern Afrotemperate Forest that spans from the Joodse Tributary to Nekkie and Kairo. From here there are two significant contributions of surface water runoff. The first is from the N2 highway, which has several stormwater outlets that drain northwards towards Heidevallei and the Bongani River. The other source of stormwater includes the seeps of Heidevallei from the north. Heidevallei is the valley through which the Bongani River flows prior to its crossing underneath the N2 highway and its emergence from the Afromontane Forest (Figure 3-14).



Figure 3-14: The N2 highway with the Heidevallei in the background

There were two threats to the Bongani River observed within the Heidevallei:

- The Knysna Green Waste Site (Figure 3-14) has two seeps that drain from the northern ridge of Heidevallei. The leaching of pollutants from the site is a potential source of groundwater and surface water contamination.
- The other concern in the Heidevallei is that of sewage overflows where a gradient change in the sewer system from steep to gradual causes sewage to overtop manholes during storm events and discharge sewage directly into the Bongani River (Figure 3-15).



Figure 3-15: Sewage overflow points and the resultant bacterial growth in the river

From the Heidevallei, the Bongani River flows beneath the N2 highway and through a second culvert downstream into a persistently foamed up plunge pool. The stream then drains from the pond, through Lower Old Place (Figure 3-16), before flowing through the Knysna industrial area.



Figure 3-16: The Bongani River as it flows into a small pond in Lower Old Place

The Bongani River continues to a grassed block channel adjacent to Uil Street, where a wooden bridge provides an opportunity for flow measurement. Downstream of the bridge, the stream flows beneath a culvert beneath Sandpiper Street, entering its final reach before the confluence with Old Place Stream, from which it flows into the silted up Bongani Wetland (Figure 3-17).

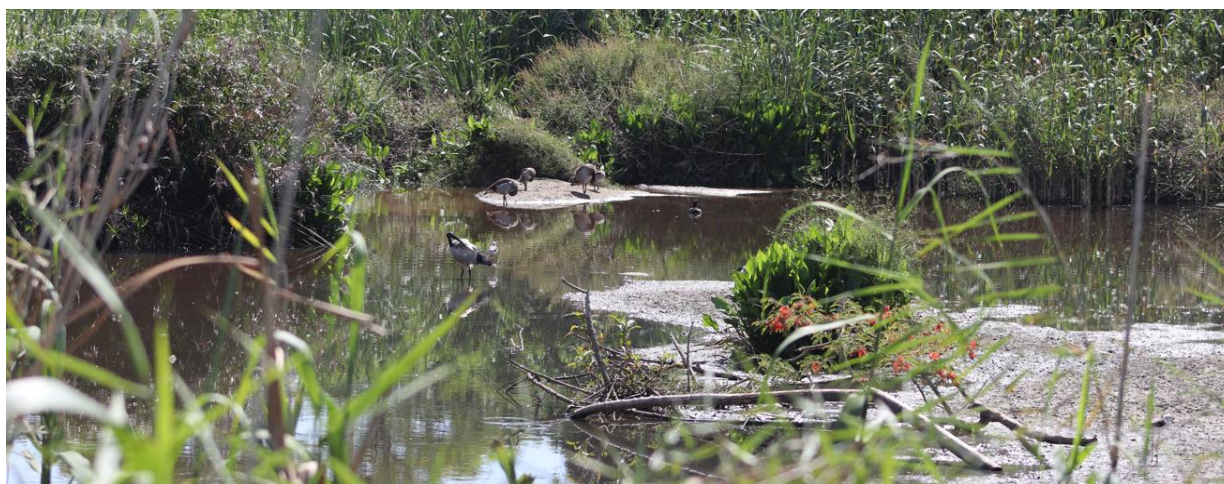


Figure 3-17: The Bongani Wetland

Vigilance Canal – the south-eastern tributary – is the most urbanised of the three major tributaries of the Bongani River. It drains most of the Knysna industrial area and receives stormwater from several concrete pipes which discharge into a concretized canal along Vigilance Drive. Vigilance Drive is the main arterial road connecting George Rex Drive and the settlement of Hornlee. The concrete canal along Vigilance Drive drains towards the Bongani Wetland in a vegetated channel, which begins downstream of Sandpiper Street (Figure 3-18).



Figure 3-18: Vigilance Canal flowing beneath Sandpiper Street

The outflow of the Bongani Wetland is controlled by six adjacent box culverts which cross beneath George Rex Drive (Figure 3-19). The final tributary merges with the Knysna WWTW effluent before flowing through the saltmarsh and into the Ashmead Channel.



Figure 3-19: The outflow of the Bongani River wetland beneath George Rex Drive

3.3 Concerns with current stormwater management in Knysna

Winter *et al.* (2016) discussed the rehabilitated dump site above the town of Knysna, which was cleared of alien vegetation and constructed into a recreational park area and reserve along the Brickelbos Stream. The Brickelbos Stream flows from the reserve through the town of Knysna, visible as a natural flow path through Riverwood Primary School at Trotter Street, before merging with a recently constructed conventional channel (Figure 3-20) (Winter *et al.*, 2016). This concrete channel is an example of the lack of consideration for more innovative and holistic solutions, such as sustainable drainage systems (SuDS), which provide more than just drainage.



Figure 3-20: An illustration of the missed opportunity for a SuDS approach in Knysna

The problems in the Bongani River are more concerning, with diffuse and point source pollution arising from the poorly serviced urban and peri-urban landscapes. Therefore, innovative, and sustainable interventions are required if the water quality problems in the Bongani River are to be managed. The pollution problems need to be addressed at their sources rather than relying on downstream interventions like litter traps or stormwater ponds, which may not be able to reduce the water quality impacts on the Ashmead Channel and the Knysna Estuary (Figure 3-21).



Figure 3-21: The stormwater management problems faced by the Bongani River

4. Method

This research aimed to evaluate stormwater management interventions that would best manage the poor water quality of the Bongani River. This was achieved by constructing a numerical model capable of describing the flow and water quality processes within the catchment. The steps taken included: selecting an appropriate modelling software; collecting various data for the model; developing the hydrological and water quality models; and investigating the potential impact of various SuDS interventions by evaluating the theoretical reductions of pollutant loads in the Bongani River upon their introduction. The following flow chart presents an overview of the method followed in the study (Figure 4-1).

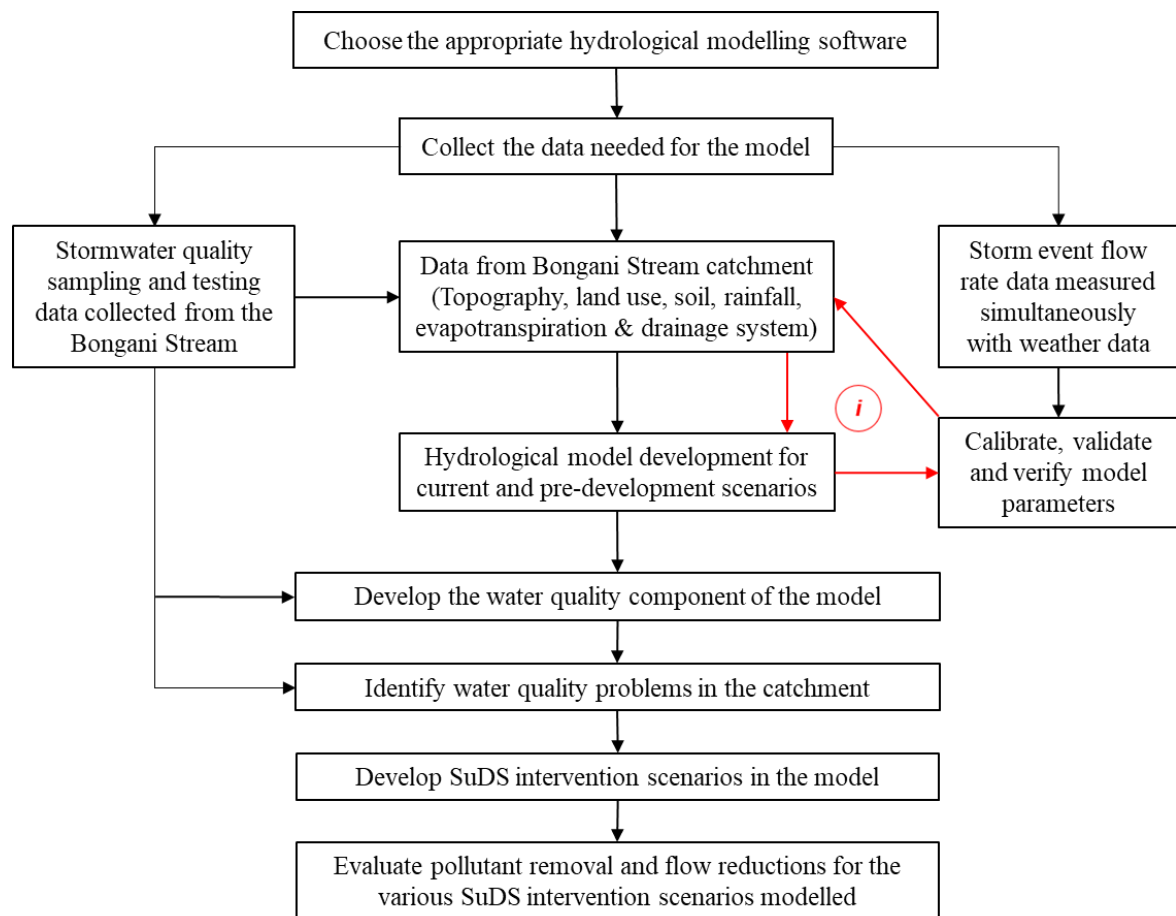


Figure 4-1: The method followed in the research

Water quality data collected by Harvey (2019) identified that the Bongani River catchment has a problem regarding nutrients and *E. coli* (Appendix A). This investigation continued the research into stormwater pollution in the Bongani River by measuring water quality by the concentrations of nutrients and sediments and counts of *E. coli* at key points throughout the catchment. In addition, the water quality data was used to identify problem areas and provide input into the water quality modelling for which a modelling software needed to be chosen.

4.1 Hydrological model selection and components

Appropriate modelling software needed to be identified for the Bongani River catchment's combined hydrological / hydraulic / water quality model.

4.1.1 Choosing appropriate modelling software

Several software alternatives were available for stormwater management applications (Section 2.4.2). The software alternatives were evaluated against various criteria, including cost, ease of use, technical support, and the ability to handle continuous flow and water quality simulation reliably. The SWMM engine was chosen because of its ability to run continuous models, which separates it from the other software options. The SWMM engine is continuously updated and universal, with many versions and a large user group (Hossain *et al.*, 2017). In the end, PCSWMM was selected for the modelling as it is widely used for assessing stormwater management interventions (Palla & Gnecco, 2015). It is supplied by Computational Hydraulics International (CHI) and uses an enhanced SWMM 5 engine, giving it good usability and functionality, incorporating a GIS engine that provides the tools for optimisation and comprehensive analysis of stormwater management applications and research (CHI, 2012).

4.1.2 Developing the model in PCSWMM

There were three distinct components to the model used to investigate the SuDS intervention scenarios:

- i) Setting up the hydrological / hydraulic flow model – collecting and processing geographic information system (GIS) data relating to weather, topography, land use, soil infiltration characteristics, and the surface water drainage system.
- ii) Calibrating and verifying the hydrological / hydraulic flow model – using flow rate data collected from the Bongani River to calibrate the most uncertain parameters of the model using the Sensitivity-based Radio Tuning Calibration (SRTC) tool, which allows for storm event and continuous time series calibration of the sub-catchment and conduit parameters which have inherent estimation errors. The calibration was evaluated using the following statistics: Nash-Sutcliffe Efficiency (NSE), Index of Simulated Efficiency (ISE), and R^2 . Once the model was calibrated, it was rerun to verify the calibration results.
- iii) Adding the water quality component – the flow of nutrients, which included constituents of nitrogen (nitrites, nitrates, ammonia, and total Kjeldahl nitrogen (TKN)) and phosphorus (soluble and reactive phosphorus (SRP) and total phosphorus (TP)), were measured during rainfall events to estimate wash-off event mean concentrations (EMCs) for TN and TP. These measured EMCs were compared with published wash-off EMCs to assess whether the parameters showed a reasonable correlation with those from the literature.

- iv) Once the model was calibrated and the water quality parameters estimated, the model was deemed complete. The ultimate step was to investigate and interpret the impact of different SuDS interventions on the water quality of the model of the Bongani River.

There are two main components in the PCSWMM program. The first is the runoff component which simulates continuous or event rainfall over multiple unique sub-catchments to generate runoff and pollutant loads at the outlet node of each sub-catchment. The second component is routing, which simulates the transport of runoff and its constituents through the model's conduits. Setting up the PCSWMM model required acquiring and interpreting GIS datasets available for the study site. This initially involved an investigation into available GIS datasets and their respective coordinate systems, which could contribute to the development of the model. In addition, several tabs, editors, and tools make up PCSWMM that were critical to the development of the model. Figure 4-2 outlines the general structure of a PCSWMM model.

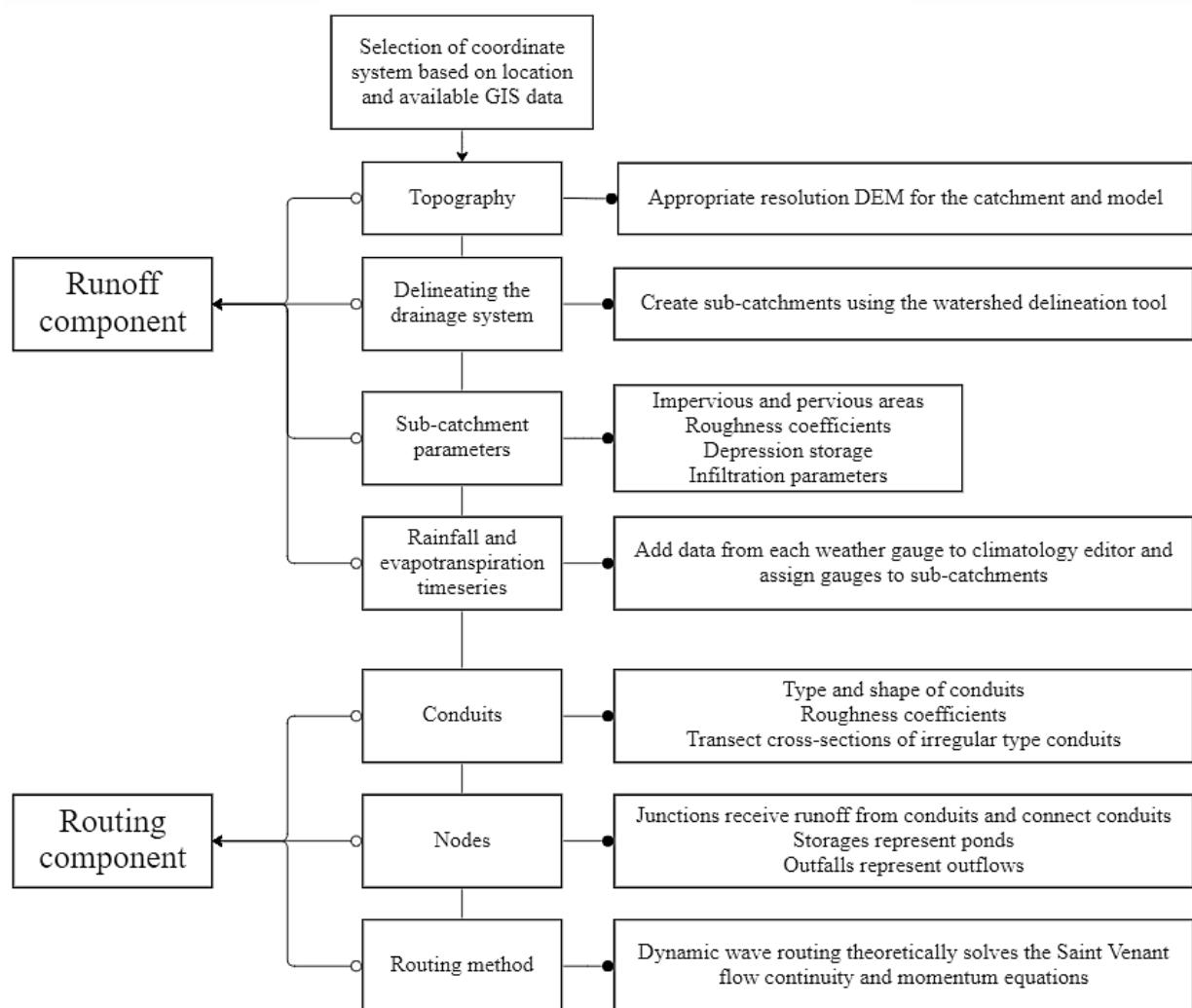


Figure 4-2: A generalised structure of a PCSWMM model (adapted from CHI, 2021)

4.1.3 Flow model development

The runoff component is made up of several parts. This section details these parts and their role in the functionality of the flow component of the hydrological model that was developed.

The topographical information in PCSWMM is represented by a digital elevation model (DEM) in a raster file format. A DEM is a grid of points on a two-dimensional plane at a particular interval with elevation values at each grid point. The PCSWMM software uses a DEM to delineate sub-catchments based on the desired discretisation level. The discretisation level is the area that PCSWMM will attempt to delineate the sub-catchments to during the delineation process. The tool used for the delineation is called the Watershed Delineation tool. The sub-catchments generated by the Watershed Delineation tool are comprised of three parts: pervious area, impervious area, and zero-impervious area. Each parameter is linked to a land use and includes a Manning's roughness coefficient and a depression storage. The zero-impervious area is the portion of the impervious area that does not have any depression storage. The pervious areas of the model have infiltration components linked to the soil type present. Three alternative soil infiltration models are available in PCSWMM: the Modified Green and Ampt, Modified Horton, and Curve Number methods. The Modified Green and Ampt infiltration model is generally the preferred method in modelling as it is a physics-based model that uses Darcy's Law and the Richards Equation to explain the infiltration of water through soil; which effectively describes the flow of water through porous media along a wetted front (Fitchett *et al.*, 2018; Rossman, 2015).

Long-term time series data for rainfall and evapotranspiration are necessary for continuous modelling. The climatology editor lets the user enter rainfall and evapotranspiration datasets into the model. Rain gauges can be set as inputs to different sub-catchments in the model, whereas evapotranspiration is the input combining surface water's evaporation and plants' transpiration.

The land use editor enables the user to represent the various land uses of the sub-catchments in the model. Land use was applied in two distinct ways. The first application was the effect of land use on the rainfall-runoff relationship. This involved the development of a high-detail land use map which separates areas with inherently different percentage impervious and pervious areas, their depression storage, and their runoff speeds. The second application of land use was the effect it had on the pollutant wash-off characteristics across the catchment, which varies based on anthropogenic influences such as the presence of a road which receives pollutants from cars and wind or the presence of a natural area which has a lower impact on pollutant concentrations (Stein, 2008).

The routing component of a hydrological model includes the conduits, junctions, and storages that make up the model's hydraulic network. Additionally, irregular conduits can be used to represent river cross-sections and are generated by the Transect Creation tool, which uses a DEM to acquire cross-sections at defined intervals along the conduit in the model. Conduits are split by junctions where the cross-section or bed slope varies, and storages represent ponds

or depressed areas that attenuate stormwater along the model's hydraulic network. Ponds were given tabular storage curves, which assign areas to the different depths of a pond.

4.1.4 Flow model calibration, validation, and verification

Model calibration and verification in PCSWMM are achieved using the SRTC tool. This allows for the use of measured data to assess the model's sensitivity to variations in model parameters and to adjust parameters to better mimic the data collected from the drainage system. Calibration, validation, and verification can be described as follows in the context of the study:

- Calibration, which relies on observed data to adjust a model's parameters, is the process of minimising the difference between the modelled flow rate timeseries and the observed flow rate timeseries by varying parameters of considerable known uncertainty. The calibration process enables a modeller to alleviate the variability between what has been measured in the field and the model's outputs. This improves the modeller's confidence in the inputs and outputs of the model.
- Validation is the process that ensures that the model is representing the natural world as best as possible and helps with determining the credibility of its outputs. The validation process, which can include visual comparison, statistical analysis, or cross-validation, helps a modeller assess the performance of a model and how well it represents reality, which is especially important if the model is being used for decision-making or for informing stakeholders. The validation process relies heavily on the data collected from the field and the process used by the modeller. The validation process ensures that the model best mimics the processes occurring in the real world and involves checking the statistical indices and graphs to evaluate whether the calibration of the selected parameters is appropriate using datasets independent of those used in the calibration process. In PCSWMM, this is accomplished by running the model multiple times to assess the calibration outcomes by comparing computed and measured flows and uncertain parameters, which are adjusted within predefined limits.
- Verification is an important part of the model development process and is usually conducted with calibration and validation. The verification process ensures that the model produces or predicts the right outcomes based on the relationships of the input and output variables built into the model. The verification process does not rely on or compare to the real-world process. Instead, its purpose is to confirm that the model is functioning as the modeller intended it to when it was created. Once the model is calibrated and validated by the modeller, the model can be rerun to verify that the changes made to the inputs are as expected.

The evaluation of the calibration is undertaken by ensuring that the statistics chosen for measuring the model's validity are within acceptable ranges. The statistical indices that were used

to evaluate the calibration process included: the Index of Simulated Efficiency (ISE), Nash-Sutcliffe Efficiency (NSE), and the coefficient of variation (R^2). If the indices were within the acceptable ranges for the calibration and validation time series, and for a third set of observed flow level time series for verification, then the model would be deemed acceptable for use. Section 6.3 provides more details about the calibration, validation, and verification process that was undertaken.

4.1.5 Water quality model

PCSWMM has the potential to utilise different pollutant build-up and wash-off functions that represent the build-up of pollutants from various land uses in the catchment and the wash-off – the suspension and transport – of the built-up pollution. The build-up on a particular surface is at a rate with a limit (Rossman & Huber, 2016b). This accumulation of pollutants can be described by the mass of the pollutant per unit area of impervious area or unit curb length; however, for microbial pollutants, the number of organisms is used. Build-up options include the following functions:

- Power build-up simulates the accumulation of pollutants proportionally to time raised to some unit/power until a maximum limit is achieved.
- Exponential build-up follows an exponential growth curve that approaches the maximum limit. Saturation build-up begins at a linear rate, constantly declining over time until a saturation value is reached.

Wash-off options include the following functions:

- Exponential wash-off involves the removal of pollutants that have built up and increases exponentially with an increase in surface runoff. This function requires build-up as it depends on the accumulated amount of pollutant.
- Rating curve wash-off relates to the flow rate raised to some power representing the proportional relationship between the flow rate and the wash-off of a pollutant.
- EMC wash-off relates the flow rate to measured pollutant concentrations and assumes that all storms have the same storm wash-off concentrations. Therefore, using build-up for rating curve and EMC wash-off functions can be useful to establish the maximum mass of pollutants that could be removed during a storm (Rossman & Huber, 2016b).

The pollutant editor comprises the different pollutants being modelled, including the build-up and wash-off parameters. The EMC wash-off method was chosen due to data availability.

4.1.6 SuDS modelling

Once the calibrated hydrological model was developed and the water quality component added, SuDS could be investigated. The following SuDS (LID) controls are available in PCSWMM:

- Bio-Retention areas
- Infiltration Trenches
- Permeable Pavements
- Rain Barrels
- Vegetative Swales
- Rain Gardens
- Green Roofs
- Rooftop Disconnections.

Other alternatives for modelling SuDS interventions include using a conduit with a high roughness or using a storage to represent a pond or wetland. The junction or storage can be given a pollutant removal fraction or equation representing the likely impact of the SuDS intervention on the concentration or load of pollutants passing through that point in the model.

The details of the development of the flow model component are provided in Chapter 6, the water quality model component in Section 7.3, and the SuDS scenarios modelled in Chapter 8.

4.2 Methods of collecting data

Considerable data collection was needed to set up and calibrate the hydrological and water quality components of the model of the Bongani River catchment. Furthermore, data was needed to understand where water quality was poor in the catchment. Therefore, there were several types of data collected in the study:

- Weather data for setting up the hydrological component of the model.
- Geographic information system (GIS) data for setting up of hydraulic network components of the model.
- Landscape processes that make up the inputs that represent the physical processes that occur within the model's hydrological and hydraulic network component.
- The collection of storm event flow rate data for calibrating and verifying the hydrological and hydraulic components of the model.
- Water quality data for adding the water quality component into the model, interpreting the pollution problems present, and informing the development of interventions.

4.2.1 Data needed for the model

The data inputs required for developing the hydrological and hydraulic model are summarised in Table 4-1.

Table 4-1: Data requirements for the PCSWMM model

Data needed	Description of data	Source of information
Rainfall data	A continuous hydrological model requires a continuous rainfall time series from rain gauges situated within the catchment or as close to the catchment as possible.	SAWS provided rainfall data for three sites close to the catchment. The three continuous time series overlapped for at least 20 years.
Evapotranspiration	The conversion of temperature data to evapotranspiration data. Evapotranspiration represents the escape of water from the system from evaporation and transpiration.	The temperature data was acquired from the Knysna Meer weather site at Thesen Island and was converted using the Hargreaves Equation.
Digital Elevation Model (DEM)	Topographical data is represented by points on a grid. Each point has a height assigned and are collectively used to delineate the sub-catchments and drainage pathways.	A 5m DEM provided by Knysna Municipality (n.d. d) was used.
Land use	Land use links the hydraulic parameters involved with runoff and the coefficients that represent water quality characteristics for the functionality of the model's sub-catchments.	Various aerial maps were used to create a GIS shapefile with representative land uses in the catchment that represented different runoff characteristics.
Soil maps	A GIS overlay of the soils present across the sub-catchments is used to determine the distribution of soils.	Knysna Soils PDF from Land Type Survey Staff (2006).
Infiltration parameters for the Modified Green & Ampt method	The Modified Green & Ampt infiltration method requires the soil type's initial moisture content, hydraulic conductivity, and suction head at the wetting front.	Modified Green & Ampt parameters for the soil types present were acquired from Rawls <i>et al.</i> (1983).
Stormwater system	The stormwater system is characterised by the size, shape, slope, and hydraulic parameters of the conduits of the model, which can be open channels or pipes.	The stormwater system was retrieved from a map provided by Harvey (2019), who acquired it from Knysna Municipality (n.d. e).
Vegetation map	The pre-development representation of which vegetation types would have covered the catchment.	Knysna Vegetation Map (Knysna Municipality (n.d. c).
Water quality data	Estimates for EMC wash-off parameters for TN, TP, and TSS.	Acquired from sampling and testing and literature.
Flow rate data	Measured flow rate data from the stream.	Flow data available from Harvey (2019) was supplemented by data collected from water-level sensors installed in key locations.

4.2.2 Weather data

A total of six rainfall gauges provided rainfall data for the eastern side of the Knysna Estuary (Figure 6-2). The South African Weather Service (SAWS) collects rainfall data for five gauges in the region at recording intervals of between 5 minutes and daily. Additionally, SAWS collects wind and temperature data for two of those gauges (SAWS, 2020). Moreover, daily rainfall data have been collected since the beginning of 2017 at a private rainfall gauge in Upper Old Place.

The weather data from the five SAWS gauges and the private gauge were measured at 8 am daily. Three of the rain gauges provided complete rainfall data; however, several of the rainfall gauges provided unpatched data, meaning that there were some gaps in the rainfall records. A description of each rainfall gauge and the data available at each follows:

- The Knysna TNK rainfall gauge (SAWS Climate# 0014063 4) has an elevation of 30 m above mean sea level (AMSL) and is located at the Old Gaol, a museum of Knysna's old prison. It has been collecting daily rainfall data since 01/01/1900, but the data was unpatched meaning that there were periods during which there was no data collected.
- The Knysna Meer weather gauge (SAWS Climate #0014033 2) is located at SANParks on Thesen Island. It has been in operation since 01/01/1990 providing unpatched daily rainfall data until 01/01/2017, when it was upgraded to provide hourly data. The gauge was upgraded again on 18/04/2018 to a five-minute gauge providing rainfall depth, wind direction and atmospheric pressure.
- The Concordia BOS rainfall gauge (SAWS Climate# 0030090 3) is located beyond the headwaters of Concordia Stream, on a hillside in the Salt Stream's headwaters at an elevation of 246 m AMSL. It has been operating since 01/09/1910 providing unpatched daily and monthly rainfall data.
- The Kruisfontein BOS rainfall gauge (SAWS Climate# 0014183 7) is located beyond the eastern boundary of the Bongani Catchment at the Kruisfontein forestry outpost, which is located at 220 m AMSL. It has been operating since 01/03/1987 providing unpatched daily and monthly rainfall data.
- The Knysna WWTW weather station (SAWS Climate# 0014123 3) is located upstream of the Knysna WWTW at an elevation of 54 m AMSL. It was the only sub-daily rainfall gauge within the Bongani River catchment, providing hourly rainfall data, wind direction, temperature, and air pressure since 01/07/1996.
- The Upper Old Place private rainfall gauge is in the suburb of Old Place. It has been operating since 01/01/2017, providing a complete record of daily and monthly rainfall data.

4.2.3 Landscape and land use data

The nature of a landscape directly affects the rainfall-runoff relationship in a catchment as rainfall storage and speed of overland flow is controlled by the type of landscape it interacts with. Landscapes, when in a natural state with uncompromised soil and indigenous vegetation, manage the quantity and quality of water that flow from them, which directly links to the geological landscape and the climate the ecosystem has been exposed to. However, the quantity and quality of runoff has changed due to humans' development and use of landscapes. As a result, runoff characteristics have been altered, with some land uses having negatively impacted the quality and quantity of runoff, such as in a highly impervious industrial area. In contrast, other land uses

like a garden or park generally maintain similar runoff quality and quantity to natural conditions. Land use was thus used to differentiate runoff quantity and quality characteristics for different areas across the Bongani River catchment in the PCSWMM model.

Landscape data was represented in the PCSWMM model using soil infiltration, runoff, and water quality parameters. A soil map was used to differentiate the infiltration characteristics in the model. In contrast, land use maps were developed to represent and differentiate the runoff and water quality characteristics of the various land uses. The development of land use maps was done in two parts, one for the flow component and the other for the water quality component:

- A land use map was first developed at a high-level of detail to incorporate the runoff parameters in the flow component of the model. The parameters included: percentage imperviousness, depression storage for impervious and pervious areas, Manning's roughness coefficients for overland flow for impervious and pervious areas, and zero-impervious area percentages.
- A simplified land use map was then used for the water quality component of the model and provided a more general characterisation of the landscape. This was done for two reasons: firstly, because modelling the water quality of many land uses introduced unnecessary complexity into the model, and secondly, because the water quality data that was collected was representative of contributing catchment areas which were made up of multiple land uses according to the high-level of detail land use categorisation.

4.2.4 Storm event data collection

Some of the data needed for a thorough calibration, validation, and verification of the model was unavailable or limited; for instance, there needed to be more flow data available. Therefore, storm event data needed to be collected from the Bongani River, which comprised the following:

- Flow rate data for the calibration, validation and verification of the hydrological model were collected from flow sensors installed at three locations in the Bongani River catchment selected on the grounds of their practicability and representativity; this is described further in Section 5.1.
- Storm event grab samples to show the variation of water quality during a storm event. This provided information about the relationship between rainfall and pollutant concentrations.

Calibrating a hydrological model requires flow rate data from several storm events in the stormwater system being modelled. Therefore, predicting suitable storm events was essential for the collection of storm event data from the Bongani River catchment to ensure that flow rate and water quality data were attained during the storm events that occurred during the research. Weather prediction websites were used to evaluate the likelihood of a storm event occurring in

Knysna. The websites used included yr.no, windy.com, and weather.com to provide information about upcoming storm events, with predictions available for between 7 and 14 days.

Alternative options for measuring continuous flow rate include gauging weirs, pressure meters, acoustic Doppler current profilers, and ultrasonic flow level sensors. However, there were no weirs on the Bongani River, and pressure meters and acoustic Doppler current profilers were difficult to acquire. Ultrasonic flow level sensors were thus chosen due to the availability of the technology for the device and the ease of setting up beneath bridges identified within the river's cross-section.

The ultrasonic flow level sensors were designed and built for the project and measured the water level in the channel at 30-minute intervals. The sensor was connected to a circuit powered by 8 x 3.3V batteries which were connected to a 5V boost converter and a GPS/GPRS micro-controller that communicates with the ultrasonic sensor and the server through a GSM module. This measured flow level was sent to the cloud via Thingstream.io, where it could be exported to Microsoft Excel. The flow level was then subtracted from the sensor's height above the bottom of the channel to obtain flow depth. Figure 4-3 shows the ultrasonic flow level sensor's configuration.

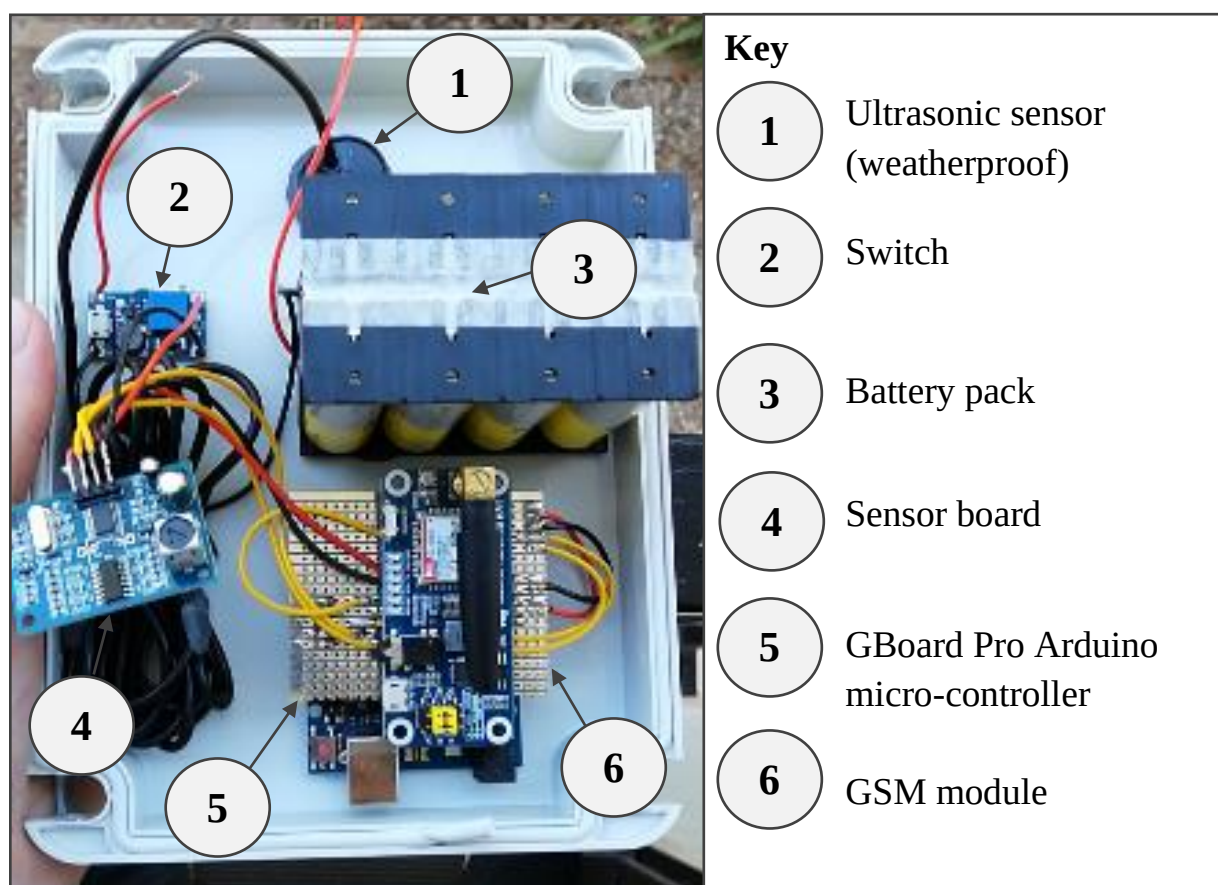


Figure 4-3: The ultrasonic flow sensor setup used to measure flow level

The ultrasonic flow level sensors measure depth, but flow rate was needed to calibrate the hydrological model. Therefore, a method for calculating the flow rate from the flow level collected was required. The Slope-Area Method is a widely accepted method for converting depth to flow in a uniform channel using Manning's Equation (Equation 4-1) (Manning, 1891).

$$Q = \frac{A^{5/3} \cdot P^{2/3} \cdot S^{1/2}}{n} \quad \text{Equation 4-1}$$

Where: Q = flow rate (m^3/s); A = cross-section flow area (m^2); P = wetted perimeter (m); S = slope (m/m); and n = Manning's roughness coefficient.

Uniform flow only exists for steady flow in prismatic channels, which have constant shape, roughness, and slope. Therefore, one appropriate uniform flow section was selected for each of the tributaries of the Bongani River catchment for flow estimation. When significant rainfall events (usually predictions larger than 10mm) were predicted by the weather forecasting websites, the flow sensors were turned on by the researcher to ensure that the ultrasonic flow level sensors captured the storm event flow data.

The time of concentration is the response time of a catchment and represents the amount of time taken for the entire upstream catchment to contribute stormwater runoff to that point in the catchment (The South African National Roads Agency SOC Limited (SANRAL), 2013). The calculation for the time of concentration from the Rational Method was used to estimate the response time of the catchment (Equation 4-2). The times of concentration for each of the three tributaries are summarised in Table 4-2.

$$T_c = \left(\frac{0.87 \cdot L^2}{1000 \cdot S_{av}} \right) \quad \text{Equation 4-2}$$

Where: T_c = Time of concentration (hours); L = Length of the longest flow path (m); S_{av} = Average slope as calculated by Equation 4-3.

$$S_{av} = \frac{H_{L85} - H_{L10}}{1000 \cdot (0.75) \cdot L} \quad \text{Equation 4-3}$$

Where: H_{L85} = Elevation height at 85% of L from the point of interest (m); H_{L10} = Elevation height at 10% of L from the point of interest (m).

Table 4-2: The time of concentrations of the three tributaries of the Bongani River

Tributary	Time of concentration (T_c) (minutes)
Bongani River	38
Old Place Stream	19
Vigilance Canal	17

Observed timeseries can be used to interpret the response time of a catchment, however, it would vary across different events due to the spatial and temporal variation of rainfall in a catchment.

The ultrasonic sensor flow level measurements were collected at 30-minute intervals to preserve the unit's battery life, which meant there was a risk that the sensors could miss the peak flow levels at each measurement location. Therefore, an alternative method was required to measure the peak flows for the flow sensor locations. The collection of maximum flow level data was thus undertaken using a secondary method denoted the chalk stick method, which was also used by Harvey (2019). The chalk stick method involved the use of the following components:

- The plastic trunking used to encase the chalk sticks was glued to the wall of the culvert with an easily removable cover so that the chalk sticks could be re-chalked when needed.
- The chalk sticks were placed within the trunking with a reusable putty adhesive.
- During a storm event, the water level would rise, washing off the chalk to the maximum flow depth.
- The chalk stick flow level data was compared with the flow sensors and functioned as a backup in the case of failure or theft.

It was important to hide the flow measurement devices to prevent theft, which is why they needed to be placed within culverts or beneath bridges. A depiction of the equipment used in the chalk stick method is provided in Figure 4-4.



Figure 4-4: Chalk stick measurement device beneath George Rex Drive

The geometric properties of some of the channels were measured by Harvey (2019) using a dumpy level survey. However, more locations needed to be surveyed, so all the channels where flow level was measured in the study were surveyed to acquire their cross-section and slope. This ensured that the cross-sections were up to date with the flow levels measured.

A dumpy level, tripod, and incremented survey staff (Figure 4-5) were used to measure the cross-sections using the rise and fall method. Once the survey was conducted and geometric

properties acquired, the flow depths measured by the flow sensors were converted to flow rate. Finally, the area and wetted perimeter were calculated from the flow depth based on the surveyed cross-sections (See Appendix C.1).



Figure 4-5: Dumpy level, tripod, and incremented survey staff

4.2.5 Monthly water quality data collection

Grab samples were taken from 18 sites across the Bongani River catchment over the period of a year to indicate the general water quality. The sampling and testing was completed with the help of the Knysna Basin Project (KBP), a local non-government organisation (NGO). The focus of the sampling and testing was on biological and nutrient contaminants because of Ashmead Channel's current eutrophic state and *E. coli* concerns (Harvey, 2019). The pollutants that were tested for were limited to ammonium and ammonia, nitrites, nitrates, orthophosphates, and *E. coli*. The equipment needed for the water quality samples included: glass and plastic bottles, gloves, ice bricks, a cooler box, water quality testing kits, and a sampling stick to retrieve difficult-to-reach samples. Additionally, OHAUS® hand-held probes were used to obtain in-situ water quality measurements for temperature, EC, and pH (Figure 4-6).



Figure 4-6: OHAUS® hand-held probes for Temperature, EC, and pH

Each OHAUS® hand-held probe was first rinsed with distilled water and then calibrated before each field trip using standard procedures provided in the pen meters user's guide (OHAUS, 2019). The calibration of each probe was undertaken as follows:

- The EC pen meter was calibrated using a pre-defined calibration standard with an EC of 1413 $\mu\text{S}/\text{cm}$.
- The pH pen meter was calibrated using standard buffer solutions of pH 4, 7 and 10, with the pen meter being rinsed with distilled water before submerging it in the following buffer solution.

The monthly water quality data was a primary input for the water quality component of the model of the Bongani River catchment. Water quality can be modelled in PCSWMM using either wash-off or build-up and wash-off coefficients. Wash-off coefficients are representative of the concentrations of pollutants in stormwater runoff. On the other hand, build-up coefficients require site-specific data to be collected and analysed to determine the parameters that represent the build-up of pollutants on the surface of various land uses. Within PCSWMM, there are three wash-off model coefficients: exponential, logarithmic, and event mean concentration (EMC). EMC runoff coefficients are the most widely used primarily because the measured water quality data can be directly used to estimate the parameters without needing build-up (Rossman & Huber, 2016b).

Build-up coefficients were not readily available locally – neither for Knysna nor South Africa – and added additional uncertainty to the water quality model. Therefore, the decision was made to use only the EMC wash-off method for the model.

EMC wash-off parameter coefficients needed to be estimated for the water quality component of the model. Published EMC wash-off parameter coefficients were available, and several sources were used to establish a baseline for comparison of estimated EMC wash-off coefficients for various land uses and pollutants (Table 4-3).

Table 4-3: Published EMC wash-off coefficients

Source	EMC data provided
US EPA (1983)	TKN, TP, TSS
Coleman (2001)	TSS
Pitt & Maestre (2005)	NH ₃ , TO _x N, TKN, SRP, TP, TSS
Welsh (1991)	TN, TSS
DDE (2014)	TKN, TP, TSS
Järveläinen <i>et al.</i> (2017)	TKN, TP, TSS

The development of the water quality model required the following data inputs:

- Water quality was measured monthly and during storm events by collecting grab samples.
- The mean of the measured water quality data was used to estimate EMC coefficients for the land uses represented in the global scale land use map of the Bongani River.
- The published data (Table 4-3) for nutrients TN and TP were compared to land uses from the simplified land use map to assess their validity.

4.3 Developing the SuDS intervention scenarios

This section presents the method followed for developing the SuDS interventions chosen for the model. The SuDS interventions envisioned were drawn from case studies, literature, and the availability of open space within the Bongani River catchment. The Current Scenario was duplicated and edited to develop new scenarios that represented the SuDS interventions. The only changes that were made in each scenario were the alterations made for each SuDS option. PCSWMM has the capability to model SuDS in two distinct ways:

- LID controls, which are synonymous with SuDS, include the modelling of swales, bio-retention areas, infiltration trenches, rain gardens, green roofs, rooftop disconnections, and rainwater tanks. Pollutant removal occurs through the infiltration and/or storage of a portion of the stormwater runoff entering them.
- Using storages, nodes, and/or sub-catchments to represent a pond, wetland, or swale theoretically. Treatment functions can then be assigned to storages and nodes to remove a portion of the pollutants passing through them. These treatment functions can be related to HRT, water depth, or other hydraulic parameters within the storage or node.

The SuDS were developed considering the water quality volume (WQV) as well as for the flows of large and infrequent storm events to manage stormwater quality and quantity. There are multiple methods available for calculating WQV, with two methods used, which are both detailed in Appendix E.1:

- i) The water quality volume (WQV) method from Armitage *et al.* (2013); and
- ii) The water quality capture volume (WQCV) method from Mile High Flood District (2019).

Local data for treatment functions using HRT was unavailable; hence, data from international literature was collected and used. The SuDS interventions were modelled by adapting conduits and storages in this study and were given treatment functions relating to HRT obtained from Gajewska *et al.* (2020), Toet *et al.* (2005), and Tanner *et al.* (1995). More details about the treatment functions used are provided in Section 4.3.1.

The SuDS intervention scenarios in the model were focused on managing diffuse source pollution rather than point source pollution. Point source pollution can be more readily identified and fixed by the local authority, provided sufficient monitoring of the system is undertaken. Furthermore, these events are primarily stochastic and are challenging to model. Therefore, for example, the model did not incorporate sewage overflows from places in the Bongani River catchment that had system failures, even though the problem of sewage flows into the Bongani River are a considerable ongoing problem.

The SuDS intervention scenarios were developed with two aims:

- To reduce surface water runoff volumes from the storm events to the point where their runoff was comparable with the pre-development scenario; and
- To reduce TN and TP by 45% and TSS by 80% at the outfall of the system in those same events (in accordance with targets from CCT (2009), South Eastern Councils (2013), Melbourne Water (2005), and Victorian Stormwater Committee (1999).

4.3.1 SuDS interventions considered

The Current Scenario and the Pre-development Scenario represented the past and present state of the catchment and were the baseline for the following SuDS scenarios developed in the model:

- The Settlement Upgrade Scenario involved improving poor infrastructure in the peri-urban settlements. This scenario represented the improved management of sewage, stormwater, and solid waste that could reduce pollution stemming from peri-urban areas.
- The Tributary Management Scenario included an extended detention wetland which was envisaged for an open area in Old Place that could store and treat runoff during storm events. The scenario also included a constructed wetland in the Heidevallei adjacent to the N2 highway to manage the runoff catchments' major tributary.
- The Bongani Wetland Upgrade Scenario was a constructed wetland upstream of George Rex Drive. Several wetland options were investigated at Bongani Wetland: a detention wetland, a cascading wetland, a meandering wetland, and a generic constructed wetland.

4.3.2 Pollutant treatment functions

The pollutant treatment functions in the constructed wetlands modelled were a key aspect of the research. The treatment of pollutants in SuDS is highly variable and under-researched. It can be linked to climate, hydraulic and pollutant loading rates, hydraulic retention time (HRT), water depth, size, age, vegetation type, density, and system management (O'Geen *et al.*, 2010).

This research aimed not only to develop and model SuDS interventions but to investigate the theoretical pollutant reduction of nutrients identified as TN and TP using various equations that link HRT to pollutant removal. Studies by Gajewska *et al.* (2020), Toet *et al.* (2005), and

Tanner *et al.* (1995) provided data linking HRT and pollutant removal in constructed wetlands. In addition, there were two types of data found that linked HRT with pollutant removal. The first were k-values for first-order decay functions from the literature (Table 2-13), and the second was measured pollutant removal data concerning various HRTs.

Toet *et al.* (2005) measured and reported on the pollutant removal data for TN and TP concerning HRT. The pollutant removal for TN and TP was graphed with HRT to estimate the respective coefficients (k-values) using the principle relating pollutant removal and HRT as described by Equation 2-1. The graphed data is shown in Appendix E.8. The functions in Table 4-4 provide the upper and lower limits used from the k-values acquired from the literature.

Table 4-4: Pollutant removal equations in constructed wetland and retention ponds

Pollutant	Fractional removal lower (FR)	FR upper
Total nitrogen (TN)	$FR = 1 - \text{EXP}(-0.002 * \text{HRT})$	$FR = 1 - \text{EXP}(-0.007 * \text{HRT})$
Total phosphorus (TP)	$FR = 1 - \text{EXP}(-0.003 * \text{HRT})$	$FR = 1 - \text{EXP}(-0.0012 * \text{HRT})$

The pollutant removal equations were used for the SuDS intervention scenarios that included wetlands. Further details of the different SuDS scenarios can be found in Chapter 8.

4.4 Data analysis

There were two sets of analyses undertaken in the study:

- i) To understand and interpret the water quality sampling and testing results, for the data collected during the monthly sampling and testing and for the data collected during storm events.
- ii) To assess the SuDS intervention scenarios developed in the model.

4.4.1 Water quality data analysis

The water quality analysis was a part of developing the water quality component of the model of the Bongani River catchment. However, it was also used to understand and explain the quality of water that was measured during the sampling and testing. The water quality data analyses are detailed in Chapter 7, and two assessments were undertaken:

- i) Water quality data from the monthly sampling and testing (See Section 7.1).
- ii) A summary of the flow rate and water quality data from a storm event (See Section 7.2).

4.4.2 SuDS intervention scenarios assessment

The SuDS intervention scenarios that were created needed to be assessed to determine their efficacy as solutions for improving the water quality of the Bongani River. The Pre-development Scenario was established to represent, as closely as possible, the baseline water quality in the catchment, and besides the objectives provided by CCT (2009), South Eastern Councils (2013), Melbourne Water (2005), and Victorian Stormwater Committee (1999), was the objective that the other scenarios aimed to achieve. The results of the SuDS intervention scenarios are detailed in Chapter 9 and were assessed in three ways:

- i) Using the flow rate results of the 20-year timeseries where the flow volume and maximum flow rate were compared amongst the different scenarios (See Section 9.1).
- ii) Using an analysis of the TN and TP pollutant load reductions over the ten years between the 31st of December 2009 and the 31st of December 2020 (See Section 9.2).
- iii) By comparing the flow hydrograph and the TN and TP pollutographs of a representative 6-month RP storm event that occurred on the 23rd of July 2006 (See Section 9.3)

The final part of the research entailed the conclusions and recommendations, which refer to the uncertainty and limitations of the data collection and PCSWMM modelling, the recommendations for the Bongani River catchment, and recommendations for research similar to this study.

5. Flow level and water quality data collection

This section details the collection of stormwater quantity and quality data from the Bongani River catchment. The field data collected during the research comprised the following components:

- The flow level and water quality data collected during storm events.
- The monthly water quality samples that were collected and tested.

5.1 Storm event data collection

Historical streamflow data from the Bongani River catchment was unavailable prior to the flow data collected by Harvey (2019) in 2018. Only two continuous flow level datasets were measured during the study and comprised data from the Bongani River at Uil Street (Bongani Stream Sensor) and beneath a culvert along the Vigilance Canal (Old Vigilance Canal Sensor) (Figure 5-1). James (2005) recommended that observed flow timeseries should be used for calibration of any hydrological model to improve its reliability. Consequently, it was deemed necessary to continue measuring flow data from the Bongani River.

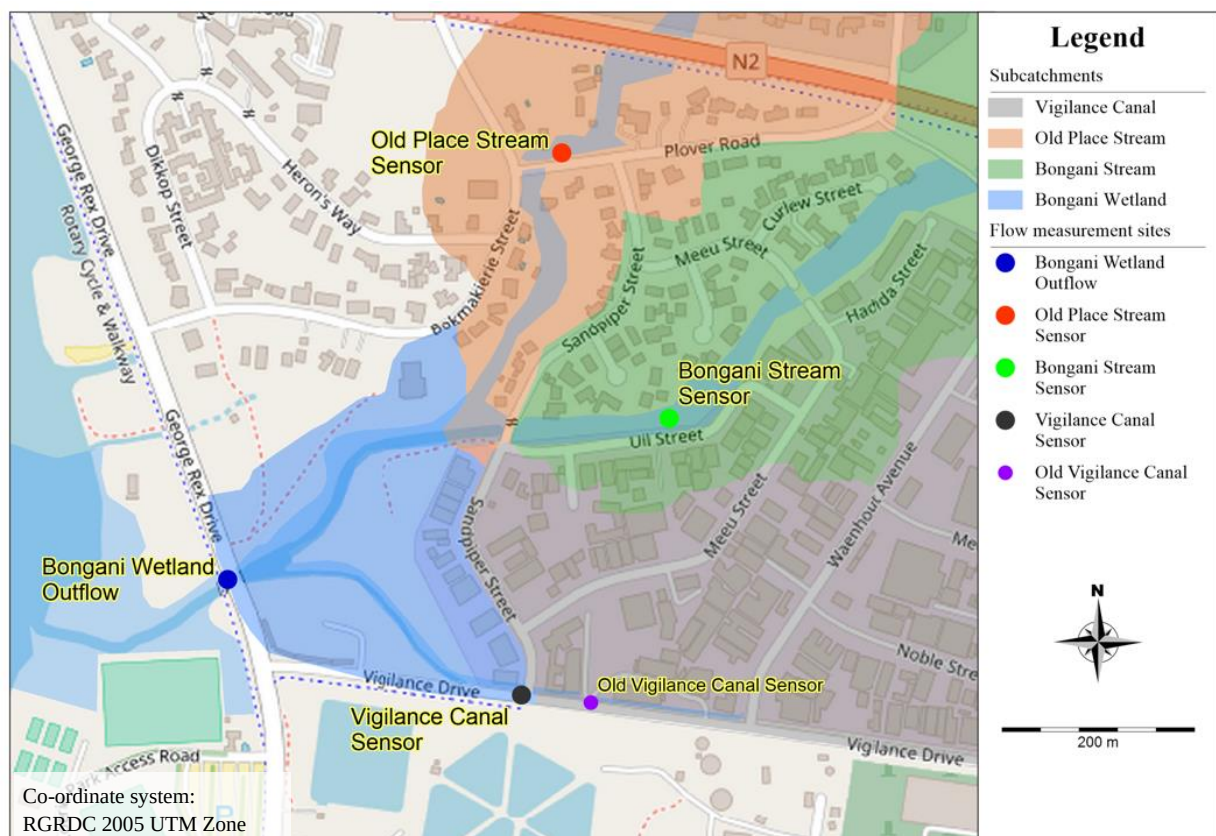


Figure 5-1: The flow measurement sites with the sub-catchments named after the streams that flow through them (Open Street Map, n.d.)

Water quality data was also collected concurrently with the flow data measurements to provide information about the variability of water quality during storm events. This information would prove valuable for assessing the difference between the loads of different pollutants such as nutrients and suspended particles as pollutant concentrations in stormwater are dynamic and continuously changing. The collection of storm event flow data followed the method provided in Figure 5-2.

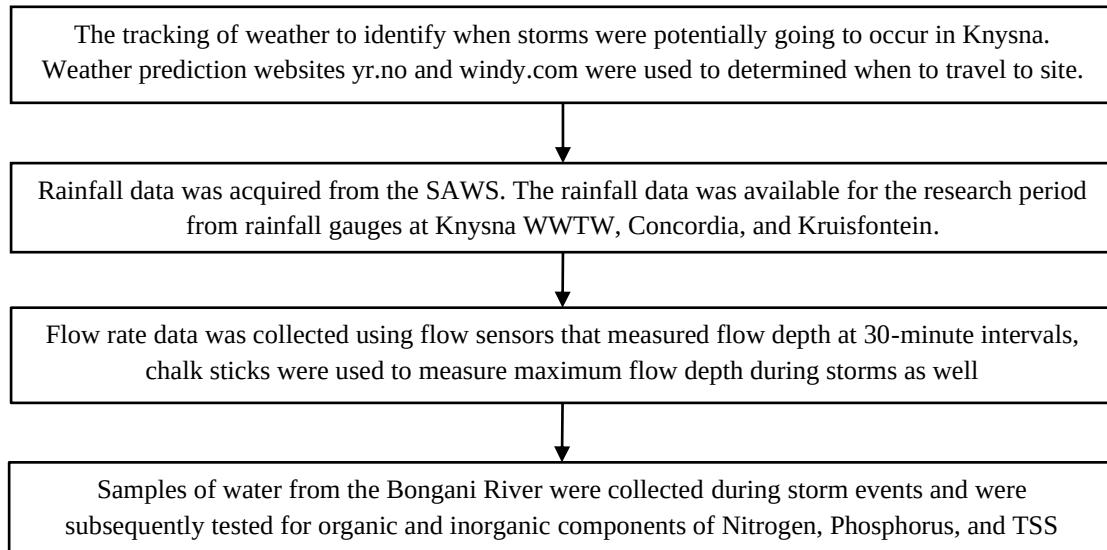


Figure 5-2: Storm event data collection flow chart

5.1.1 Flow level measurement

The types of flow measurement devices and their respective locations in the Bongani River catchment are described below:

- A flow sensor private bridge adjacent to Plover Road (Old Place Stream Sensor).
- A chalk stick within the culvert beneath Plover Road.
- A flow sensor beneath the wooden bridge adjacent to Uil Street to the north of the Knysna Industrial area (Bongani River Sensor).
- A flow sensor within the culvert beneath Sandpiper Street adjacent to Vigilance Drive (Vigilance Canal Sensor).
- Three chalk sticks beneath George Rex Drive that drain the Bongani Wetland towards the Ashmead Channel (Bongani Wetland Outflow).

The Bongani River Sensor was situated along Uil Street at the Bongani 10 sampling site and provided viable data for storm event flow rate and water quality (Figure 5-3).



Figure 5-3: The footbridge under which Bongani River Sensor (Bo 10) was located

The Vigilance Canal Sensor was in the Knysna Industrial area along Vigilance Canal at the Bongani 12 sampling site. Harvey (2019) had collected some flow rate data for a location slightly upstream, but the canal at that location is uneven which could affect the accuracy of the measured flow rate, so the flow sensor was moved to the downstream culvert beneath Sandpiper Street as shown by the red arrow in Figure 5-4.



Figure 5-4: Vigilance Canal Sensor location (Bo 12) beneath Sandpiper Street Culvert

The Old Place Sensor was in Lower Old Place located at the Bongani 7 sampling site under a private bridge (Figure 5-5).



Figure 5-5: Old Place Stream Sensor (Bo 7) beneath a private bridge

The three locations discussed above were to be used for the calibration of the hydrological model. The flow sensors at these three locations were used to measure continuous flow level particularly during storm events.

5.1.2 Storm event water quality data

The samples were taken at predetermined intervals using plastic bottles which were placed in a cooler box to preserve them for testing which took place in the Water Quality Laboratory at UCT (Figure 5-6). They were tested using standard operating procedures with a Thermo Fisher Scientific GalleryTM Discrete Analyser which measures for various water quality parameters. All samples were first vacuum filtered through a 0.45µm membrane filter paper to reduce turbidity which can interfere with colorimetric analysis (Hach, 2013). The samples and required reagents were then placed into sample cups and inserted into the Discrete Analyser. The analyser performed automatic dilutions where the concentrations could not be measured.



Figure 5-6: Sample bottles from a storm event that were measured in the Water Quality Laboratory at the University of Cape Town

The samples collected during the storm events were tested for the following nutrients:

- Soluble and reactive phosphorus (SRP) – which are orthophosphates (PO_4^{3-})
- Total phosphorus (TP) – which measures particulate and dissolved phosphorus
- Total ammonium nitrogen (TAN) – including Ammonia (NH_3) and Ammonium (NH_4^+).
- Total oxidised nitrogen (TOxN) – including nitrites (NO_2) and nitrates (NO_3^-)
- Total Kjeldal nitrogen (TKN) – TKN is a measurement of the total concentration of organic nitrogen and NH_4^+ . An acid digestion process is used to break down the sample such that TOxN can be measured as NH_4^+ along with the NH_4^+ that was already in the sample.

The SRP concentrations were measured using a colorimetric method which determines the concentration of a chemical in a solution with the aid of a colour reagent. The orthophosphates are reacted with the reagent's ammonium molybdate and ascorbic acid before the absorbance of the compound formed was measured by the discrete analyser (Thermo Fisher Scientific Inc., 2015c). Similarly, the TP concentrations were measured as SRP using the same method, however the first step of the process involves acid digesting the samples to convert organic P to SRP.

The TAN tests also use a colorimetric method; NH_4^+ in the sample reacts with hypochlorite ions, and then with salicylate ions in the presence of sodium nitroprusside, forming from a compound whose absorbance is measured spectrophotometrically. The analyser calculates the NH_4^+ concentration – as N – from the measured absorbance relative to a calibration curve (Thermo Fisher Scientific Inc., 2015a). Similarly, TKN is measured as TAN using the same method, but the first step of the process is to acid digest the sample to convert organic N to NH_4^+ .

The TOxN concentrations were measured via the colorimetric hydrazine method; the nitrate in the sample is reduced to nitrite by hydrazine, and then undergoes a series of other reactions until it forms a pink compound. Like the TAN test method, the absorbance of this compound is measured and the TOxN concentrations are calculated based on a calibration curve that relates absorbance to concentration (Thermo Fisher Scientific Inc., 2015b).

Suspended and dissolved particles in stormwater can be measured in three different ways: total dissolved solids (TDS); Total settleable solids (TSS); and Total solids (TS). The TDS OHAUS® pen meter that was available for use was out of range for the site, so TDS was not measured. TSS was measured by filtering the sample through a 0.45µm filter and weighing the solids left on the dried filter paper, whereas TS was measured by placing a known volume of sample in an oven and weighing the solids that are left behind after evaporation.

The storm event water quality data was later used as an input of the water quality model that was developed. The storm event water quality data was used in combination with the water quality data collected during the monthly sampling and testing. Before the water quality model could be developed, however, a hydrological model was required. The following section details the development of this flow model, and details the calibration thereof, which made use of the flow level data acquired from the three tributaries of the Bongani River catchment during the period between 2018 and 2019.

5.2 Monthly water quality data collection

This section details the method followed for the stormwater sampling and testing that was undertaken at various site locations across the Bongani River catchment. Several of these locations were the same sites studied by Harvey (2019), however samples from more locations were collected and tested to evaluate the remainder of the catchment areas for which water quality data was previously absent.

5.2.1 Sampling and testing sites

The sampling and testing across the Bongani River catchment was undertaken in collaboration with the Knysna Basin Project (KBP) – the local NGO that helped with sampling and testing and provided a laboratory for testing. The monthly sampling and testing included twelve sites along Bongani River, the Knysna WWTW's effluent, and seven sites along the Bigai Stream. This study focused on the results from the sites in the Bongani River catchment (Figure 5-7).

Initially, twelve specific site locations were selected for sampling and testing in the Bongani River catchment. After six months of data collection from these sites, however, six of the sites were replaced by new sites. The new sites were selected to acquire data from the tributaries of the Bongani River that were not covered in the first six month data collection period. The two

distinct sampling periods, which occurred between February 2019 and February 2020, were denoted as the 1st and 2nd sampling periods respectively.

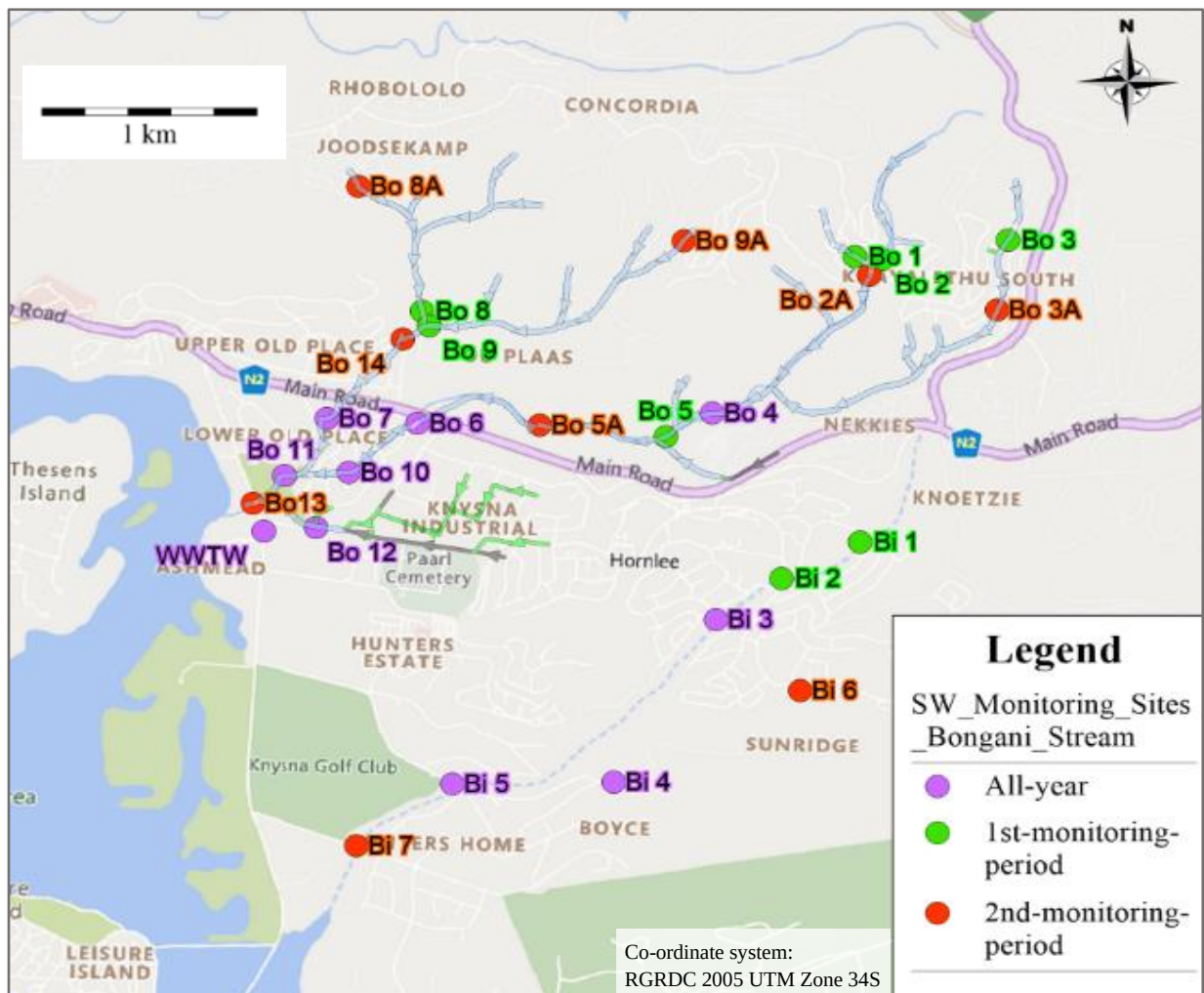


Figure 5-7: The sampling sites studied and their sampling periods (Bing map roads, n.d.)

5.2.2 Data collected

The monthly sampling and testing followed a routine where the sites were visited, samples were collected, and in-situ measurements were taken. The in-situ measurements included using OHAUS© probes for electrical conductivity (EC) and pH, both of which measured temperature.

The pollutants that were measured during the monthly sampling events included a biological indicator (*E. coli*) and four nutrients (ammonium, nitrates, nitrites, and orthophosphates). The water quality data was useful for developing a better understanding of the distribution and intensity of the water quality concerns and would later be used for the development of the water quality component of the model of the Bongani River catchment.

The testing of the *E. coli* and nutrient samples, respectively, took place in different laboratories. The testing of nutrients (ammonium, nitrates, nitrites, and orthophosphates) was carried out with the aid of a test kit. *E. coli* measurement required the use of a registered laboratory.

The first sample set of the 1st sampling period was collected in February 2019 by KBP, who managed to collect and test 15 of the 18 samples. Following this first sample set, the researcher initiated and managed the stormwater sampling and testing alongside the KBP team.

The 2nd sampling period was undertaken during the subsequent six-month period and included the following changes to the original sites:

- Bongani 8A and Bongani 9A to better understand the pollution from the low-income settlements of Joodse Kamp and Concordia
- Bongani 13 was added and is the outflow of the Bongani Wetland adjacent to where the Bongani River crosses beneath George Rex Drive.
- Sample site Bongani 3 was moved about 400 m downstream to sample site Bongani 3A to get a better understanding of the impact of the settlement of Khayaletu on the stream's water quality.
- Sample site Bongani 5 was moved about 700 m downstream to sample site Bongani 5A to investigate the impact of the sewage pipeline that runs between the sites as well as to investigate the potential impact of the Knysna Green Waste Site on the pollutant concentrations of the Bongani River as the site was considered a potential source of nutrient enrichment.

6. Flow model component

This section provides details of the process followed during the development of the hydrological model of the Bongani River catchment. The calibration, validation, and verification process is described, including the parameters of uncertainty, the data used for the calibration, the addition of the water quality component of the model, and a discussion about the Current Scenario and the Pre-development Scenario. Figure 6-1 provides a process flow diagram of the model setup.

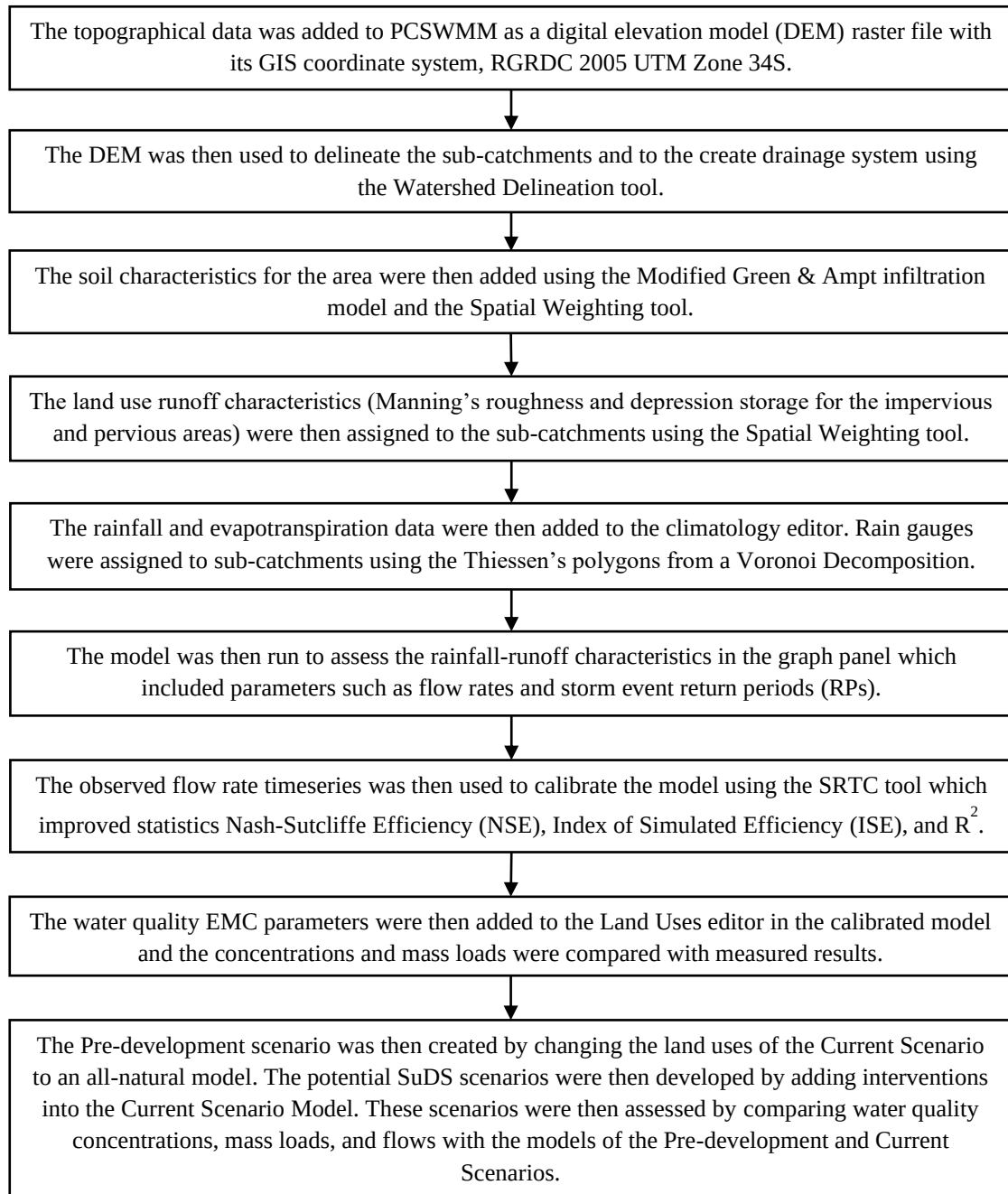


Figure 6-1: The process followed in setting up the model

Besides PCSWMM, other tools that were used in the development of the model included:

- Microsoft Excel was used to organise rainfall, evapotranspiration, flow rate, and water quality data into the correct formats for PCSWMM.
- The LEED v4.1 Rainfall Events Calculator, which is an Excel spreadsheet tool created by the Green Building Council (US) (2021), was used to calculate percentile rainfall depths from the Knysna (TNK) rainfall timeseries.
- NetStorm is a software that can be used to disaggregate rainfall data.

6.1 Hydrological modelling overview

The hydrological model that was set up in PCSWMM was developed using the following steps:

- i) The rainfall data was entered into the timeseries tab in PCSWMM by importing the three rainfall time series and assigning them to the sub-catchments that overlapped the shapes generated by the Voronoi decomposition for each rain gauge – a Voronoi decomposition involves splitting one or more polygons based on distances to a discrete set of points (for example a group of rain gauge locations).
- ii) Evapotranspiration is linked to temperature and terrestrial radiation. Therefore, it was calculated using the Hargreaves equation using timeseries data for temperature obtained from the Knysna Meer weather station and terrestrial radiation data based on the latitude of the site (Hargreaves, 1994; Hargreaves & Allen, 2003). Once an evapotranspiration timeseries was calculated for the area, it was entered into the climate editor.
- iii) The topography of the catchment was represented by the DEM, which was used to delineate the sub-catchments and to generate the conduits and junctions. The conduits were assigned cross-sections and Manning’s roughness coefficients (Rossman & Huber, 2016a) to represent the stormwater system linking the various sub-catchments. Storage components (‘Storages’) were added where ponds were located in the Bongani River catchment, and the DEM was used to estimate their depth-area relationship.
- iv) The land use runoff parameters were incorporated into the sub-catchments using the Spatial Weighting tool to aggregate the land use shapefile data.
- v) The soil types were incorporated into the sub-catchments using the Spatial Weighting tool to aggregate the soil shapefile data.
- vi) The model calibration, validation, and verification was undertaken using observed flow level data collected during storm events. This involves using the SRTC tool in PCSWMM to identify parameters of uncertainty and to optimise changes to these parameters with respect to the observed flow rate, which was calculated from the flow level data measured using the Slope-Area Method. The optimisation was based on improvements to three statistical indices to model outputs concerning the observed flow rate time series.

- vii) The final step of the development of the model was to link the water quality component to the hydrological model processed using measured water quality data from the sampling and testing completed in the Bongani River catchment (Section 7).

Once the hydrological model was developed, it was designated the ‘Current Scenario’, which was then compared to an idealised scenario designated the ‘Pre-development Scenario’. The Pre-development Scenario was developed by duplicating the Current Scenario and converting its parameters to represent ‘natural’ conditions. SuDS intervention scenarios were then incorporated into the model to assess their likely ability to address the water quality issues found in the Bongani River catchment.

6.2 Setting up the flow model

This section provides descriptions of the various components used to develop the hydrology and hydraulic network of the model. The details include rainfall and evapotranspiration data added to PCSWMMs climate editor: topographical data, land use data, and soil data for the sub-catchments in the model, and the runoff parameters and transects which were used for the conduits which convey the stormwater runoff from the sub-catchments.

Two types of GIS coordinate systems can be used to set up a hydrological model: geographic and projected. Geographic coordinate systems (GCS) are three-dimensional and are mapped on a spherical surface defined by locations represented by x, y, and z values on the Earth. Projected coordinate systems (PCS) are two-dimensional and are mapped on a flat surface in the form of a printed map or projection of a GCS. The recommendation from Fortuin (2020) was that the Réseau Geodesique de la Republique Democratique du Congo (RGRDC) 2005 UTM Zone 34S coordinate system could be used for this project, as he had worked in the area with UTM before. It is a projected coordinate system based on the GRS 1980 ellipsoid (<https://epsg.io/4062>, 2019).

6.2.1 Rainfall

Four rainfall datasets were considered for the rainfall time series in the model. The Voronoi Decomposition tool in PCSWMM, and the slope of the area was used to determine which rain gauges were to be assigned to the respective sub-catchments in the model. The tool uses nodes to divide an area into parts by approximating the equidistant boundary between the nodes, furthermore, the rain gauges were aligned with the transition between steep and flat areas.

Rainfall data from four different rain gauges on the eastern shores of the Knysna Estuary provided data for more than 20 years. The rainfall data from the gauge located on Thesen Island (Knysna Meer Weather Station) have only been collecting sub-daily rainfall since the beginning of 2017. Furthermore, the rainfall gauge was located too far from the catchment according to the Voronoi decomposition (Figure 6-2), so it was not used in the model. The rainfall data from the

gauge at the Knysna WWTW (Knysna WWTW Rainfall Gauge) spanned over 20 years and was collected at hourly intervals for that period. The Knysna WWTW Rainfall Gauge was the only long-term, sub-daily rainfall dataset within the Bongani River catchment. It was regarded as a relatively reliable data source as it was an automatic weather station. Daily rainfall data, albeit unpatched, existed for gauges in Concordia (Concordia (BOS) Rainfall Gauge) and Kruisfontein (Kruisfontein Rainfall Gauge) spanning more than 20 years. The proximity of these two gauges according to the Voronoi decomposition (Figure 6-2) and their long rainfall data collection history meant that they were helpful for representing the hydrology of the Bongani River catchment and were thus used along with the data from the Knysna WWTW Rainfall Gauge.

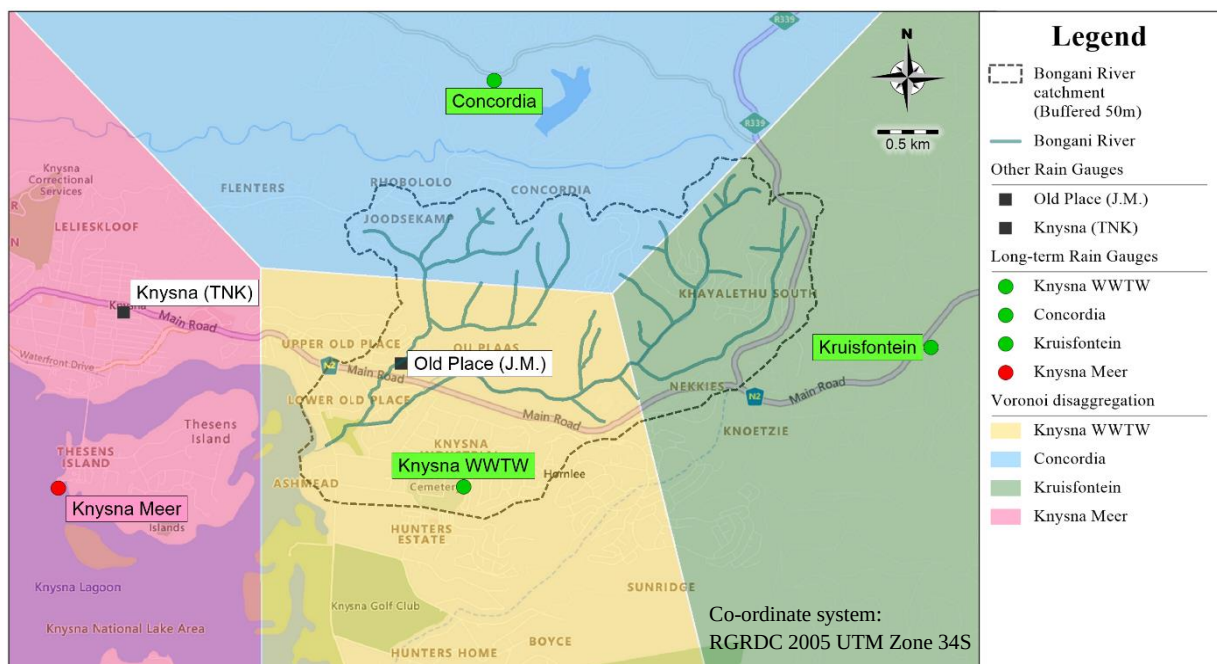


Figure 6-2: A Voronoi Decomposition of the four long-term rain gauges
(Bing Map Roads, n.d.)

The rainfall data from the three selected rainfall gauge datasets needed to be prepared before being incorporated into the PCSWMM model. A monthly rainfall factor was created for the two daily rainfall gauges to relate their data to the hourly data recorded at the Knysna WWTW Rainfall Gauge. The process that was undertaken to organise the data was as follows:

- i) A monthly rainfall factor for each month of the 20-year rainfall time series was determined for the Concordia and Kruisfontein gauges using their monthly relationship with the Knysna WWTW gauge.
- ii) Once the monthly rainfall factors were acquired for the Concordia and Kruisfontein gauges, the factors were multiplied across the hourly rainfall dataset using the Power Query tool in Microsoft Excel. The Power Query tool simplifies importing data from different source files and sorts them into a convenient and usable format.

- iii) Once the three hourly rainfall datasets were in the appropriate format, they were inputted individually into NetStorm using the Transform tab and the Short Duration Disaggregation tool (Netstorm was used to disaggregate the hourly time series to a 15-minute timeseries). The input time step (60 minutes), the desired output timestep (15 minutes), and the deterministic method (deterministic was chosen to retain desired statistics of the rainfall rather than random sampling from a stochastic model) were selected, and the desired rainfall disaggregation was complete.
- iv) The rainfall is generated as a .dat file which is ideal as this is the same file type accepted by PCSWMM, although PCSWMM can take other file types.

6.2.2 Evapotranspiration

The Hargreaves method (Equation 6-1; Hargreaves, 1994) was used to determine the time series for evapotranspiration. The daily average, minimum, and maximum temperatures were used alongside the monthly terrestrial radiation characteristic of a latitude of 34 degrees South (Hargreaves, 1994). Inconsistencies in the temperature dataset provided by SAWS were patched by replacing blank values with the average data for each month from the temperature data from the Knysna Meer weather station for Knysna to provide a complete daily time series. The Hargreaves Equation links the incoming terrestrial radiation, average temperature, and the temperature range over a given time period to estimate the evapotranspiration from a particular site (Hargreaves, 1994; Hargreaves & Allen, 2003).

$$E_{t0} = 0.0023 \times R_a \times (Tc + 17.8) \times T_R^{0.5} \quad \text{Equation 6-1}$$

Where E_{t0} = Evapotranspiration in mm/day; R_a = total incoming terrestrial radiation in mm/day; Tc = average temperature in °C; and T_R = temperature range in °C.

6.2.3 Topography

Topography was the first component addressed in the development of the landscape characteristics. A digital elevation model provides a detailed grid of elevations across the catchment area being modelled and provides the basis for the rest of the hydrological and water quality model. The DEM illustrated in Figure 6-3 was developed using the following steps:

- i) The w001001.adf raster DEM for Knysna was projected into the RGRDC 2005 UTM Zone 34S coordinate system, which was used for the PCSWMM model.
- ii) A polygon shapefile of the Bongani River catchment was acquired from the Knysna Catchments shapefile. The polygon was then given a 50 m offset buffer using the Spatial Detail Buffer tool in PCSWMM to ensure that any inconsistencies along the boundary of the catchment were considered. This shapefile was then used as the outline to clip the DEM.

- iii) The buffered Bongani River catchment shapefile was then used as the outline for clipping the projected raster using the Clipping tool. This clipped raster was to be used to delineate the drainage system of the Bongani River catchment.
- iv) The clipped raster was then converted into a points shapefile using the Raster to Points tool to create a more refined DEM for delineating sub-catchments and transects. The generated points shapefile could then be used to create the final DEM raster.
- v) The final 1 m DEM raster was created using the Points to DEM tool. This raster was then ready to be used to delineate the drainage system.

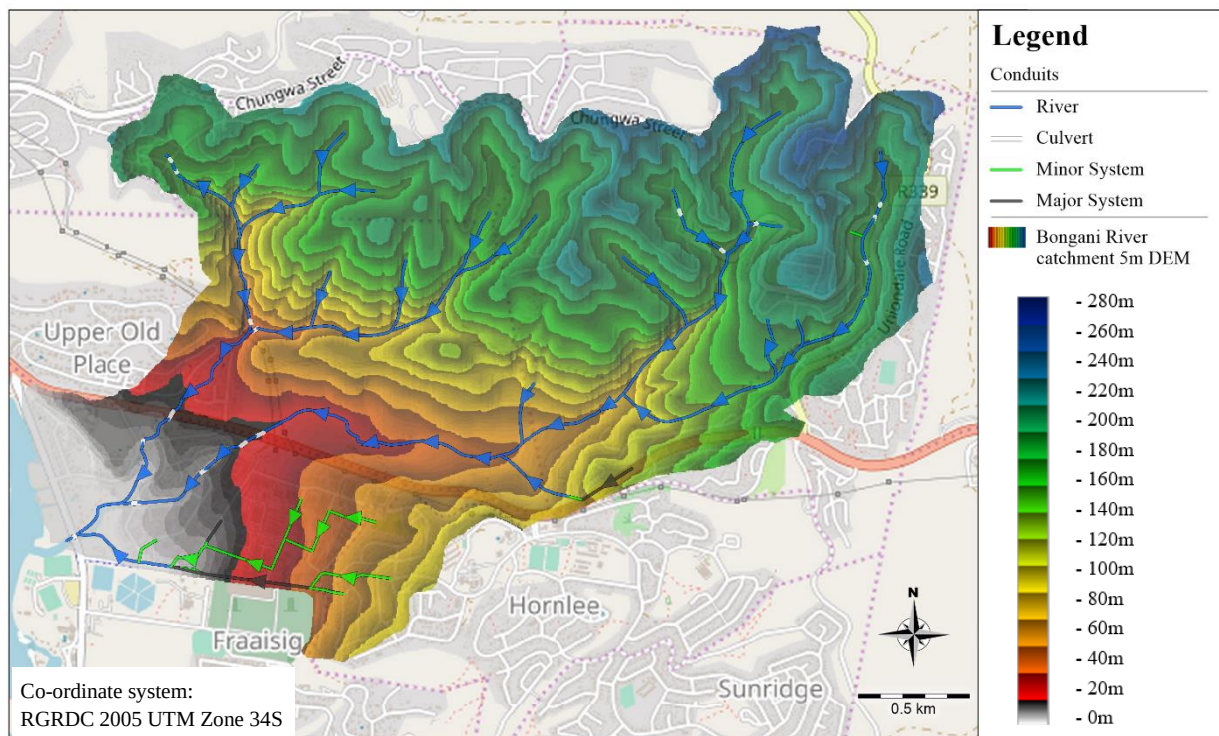


Figure 6-3: A DEM representing Bongani River catchment's topography
(Bing Map roads, n.d.; Knysna Municipality, n.d. d)

6.2.4 Delineating the stormwater drainage system

Once the topography was set up, a sub-catchment delineation was undertaken. The delineation involved using the PCSWMM Watershed Delineation tool – which delineates sub-catchments and creates drainage systems from a DEM – to create sub-catchments from the DEM. The sub-catchments drain to junctions located at their lowest point or to other sub-catchments if there are no defined flow paths at the downstream end of the sub-catchment.

The conduits in the model are linked by junctions connecting model's stormwater drainage network. A part of the Watershed Delineation tool is that PCSWMM assigns a standard cross-

section to the conduits generated. The generated conduits were then manually converted into one of four types: irregular, trapezoidal channel, rectangular culvert, or circular pipe. The cross-sections of each conduit were inputted manually based on the stormwater network provided by the Knysna Municipality (n.d.e). Field measurements were used for the stormwater infrastructure that were not included in the shapefile. The remainder of the conduits were assigned an irregular cross-section and were first drafted using the Transect Creator tool – which creates transects from a DEM layer – to estimate the topography in the natural drainage areas. After that, the transects were manually adjusted to ensure that they resembled cross-sections observed in the field, to eliminate any discrepancies from the transect delineation. The two flow sensor sites' cross-sections – Bongani 7 and 10 – were also inputted as irregular and resembled the surveyed cross-sections. Manning's roughness coefficients were then assigned to the conduits (Table 6-1).

Table 6-1: The Manning's roughness coefficients used for the conduits

Conduit description	Manning's roughness coefficient (n)
Minor system	0.012
Major system	0.014
Culverts	0.013
Concrete channels	0.015
Grass-lined channels	0.025
Streams in the suburban and peri-urban areas	0.03 – 0.045
Streams in Afromontane Forest areas	0.06 – 0.08

Once the cross-sections for the various conduits were assigned, the rainfall-runoff relationship for the sub-catchments was considered. The Manning's roughness coefficients for the conduits were not considered for calibration. The rainfall-runoff relationship comprised two distinct parts: the soil types and their infiltration parameters and the land use and their runoff parameters.

6.2.5 Soil data

Soil types affect the parameters related to rainfall infiltration into the sub-catchments. Three soil types overlapped the Bongani River catchment (Figure 6-4). Therefore, there were three soil-type parameter estimates included in the model.

The Modified Green and Ampt parameters were estimated using the soil percentage make-up, and a table of the parameters for the soil make-up from Rawls *et al.* (1983) (Appendix D – Modelling the Bongani River). The suction head (mm), hydraulic conductivity (mm/hour) and initial deficit (fraction) were the parameters estimated using percentage weightings of different soil texture classes provided by Land Use Survey Staff (2006) and the texture class parameters from Rawls *et al.* (1983). Table 6-2 shows the values from the Modified Green and Ampt parameter estimation process.

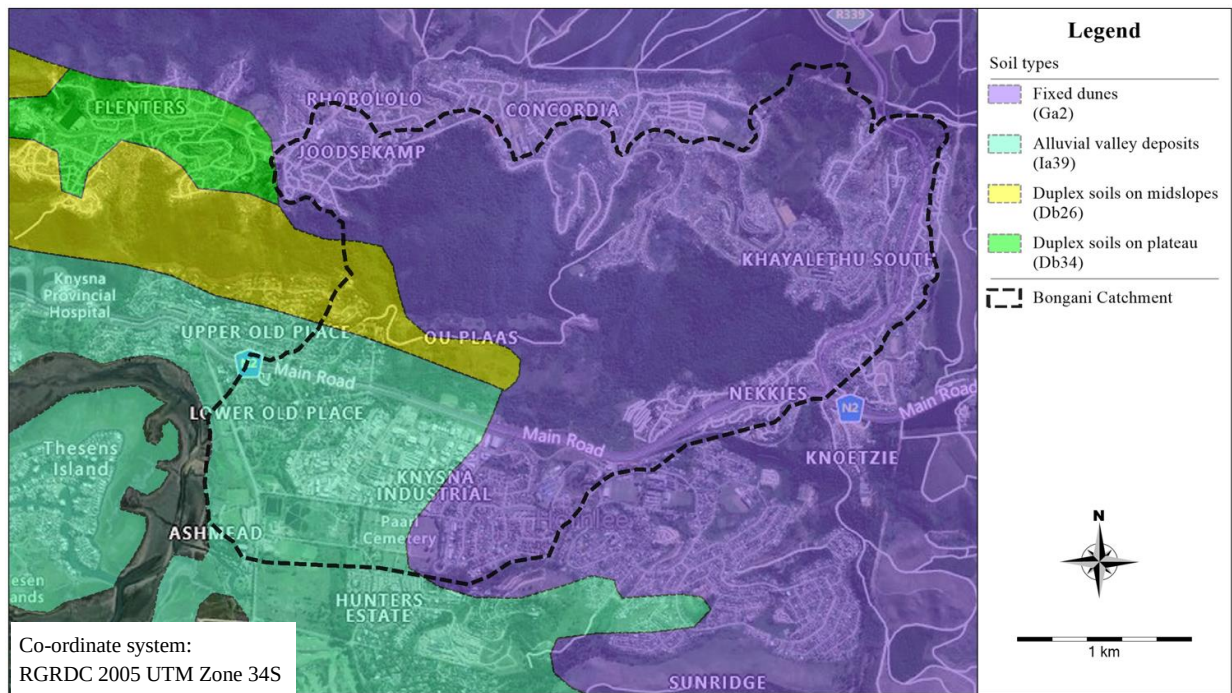


Figure 6-4: Soil types (Bing map hybrid, n.d.)

Table 6-2: The Modified Green and Ampt parameter estimations

(Rawls *et al.*, 1983; Land Use Survey Staff, 2006)

Soil code	Soil type	Suction head (mm)	Hydraulic conductivity (mm/hour)	Initial deficit (fraction)
IA39	Alluvial Valley Deposits	142	37.7	0.33
DB26	Duplex soils on Midslopes	150	11.5	0.30
GA2	Fixed Dunes	65	85.3	0.40

PCSWMM's Spatial Weighting tool was used to assign the soil parameters from the soil shapefile to the sub-catchments overlapping each soil type as follows:

- The shapefile was restructured, and attribute columns were added for the respective soil types and the soil infiltration parameters associated with each soil type.
- In the table tab, a value of 100% was added to the soil type shapefile area in its related attribute column, and a value of 0% was added to the other soil type columns.
- The soil infiltration parameters were then added to their soil type shapefile area in the parameter attribute columns for suction head, hydraulic conductivity, and initial deficit.
- Once the Green and Ampt soil parameters were assigned to the shapefile, the Spatial Weighting tool was used. The tool used the soil shapefile to assign the soil parameters to the respective sub-catchment areas. The same shapefile preparation and spatial weighting process was followed for assigning the land use parameters to the sub-catchments.

6.2.6 Land use and runoff parameters

The land use map presented in Figure 6-5 shows the different land use types across the catchment area. It was created as a shapefile in PCSWMM (2020) and informed by Google Earth Pro (Google, 2020) and Bing map satellite (n.d.) with a degree of verification from site visits. The parameter coefficients for each land use were then spatially weighted for the impervious, zero-impervious, and pervious sections of the sub-catchments in the model. The runoff coefficients assigned to each land use parameter included the following runoff characteristics:

- Percentage impervious area.
- Depression storage for both the pervious and impervious areas.
- Areas where there was no depression storage (zero-impervious area).
- Manning's runoff coefficients for each land use's impervious and pervious portions.

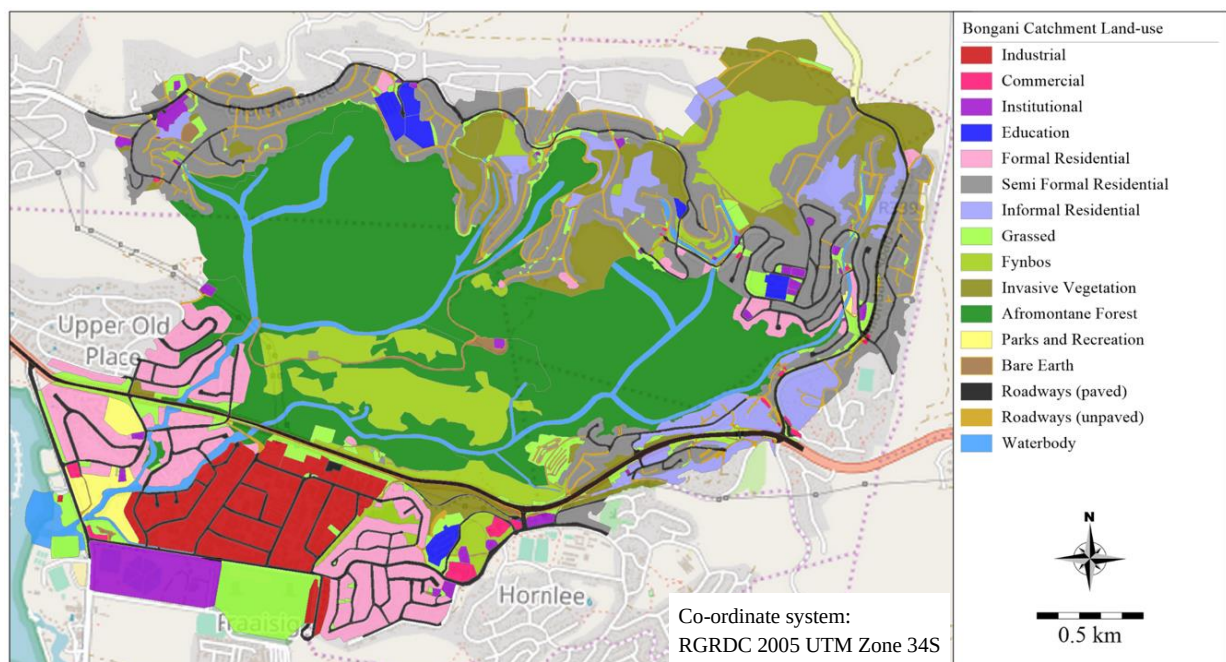


Figure 6-5: A comprehensive land use map of the Bongani Catchment
(Google, 2020; PCSWMM, 2020; Bing Map roads, n.d.)

Once the land use map was completed, input data for each runoff parameter coefficient needed to be chosen and included in the attribute columns of the land use shapefile. The high-level land use map described in Section 4.2.3 was structured in the table tab within PCSWMM. Attribute columns for percentage pervious, impervious, and impervious with no depression storage areas and depression storage and Manning's roughness coefficients for the pervious and impervious areas were added. Using the Spatial Weighting tool, the land use parameters were then ready to be spatially weighted into the sub-catchments.

The step that followed the development of the land use map involved the estimation of runoff parameter coefficients for each land use. The runoff parameter coefficients that needed to be estimated included the impervious percentage area, impervious and pervious Manning's runoff coefficients, impervious and pervious depression storage, and zero imperviousness percentage area. Once the land use runoff coefficients were assigned to the land uses, the estimated runoff parameter coefficients for the land uses were assigned to each sub-catchment in PCSWMM using the Spatial Weighting tool. Table 6-3 presents the runoff coefficients estimated from published values.

Table 6-3: A table showing the land use's runoff coefficient parameter estimations

Land use	Imperv. %	Imperv. n	Pervious n	Imperv. DS (mm)	Pervious DS (mm)	Zero Imperv. %
Industrial	90	0.013	0.05	1	4	75
Commercial	80	0.013	0.05	1	4	75
Institutional	50	0.015	0.1	1	5	50
Education	40	0.015	0.1	1	5	50
Formal Residential	40	0.02	0.2	2	5	50
Semi-formal Residential	60	0.025	0.2	2	5	50
Informal Residential	20	0.04	0.3	2	7	50
Parks and Recreation	5	0.03	0.3	3	7	25
Roadways (paved)	90	0.012	0.05	1	4	75
Roadways (unpaved)	60	0.03	0.15	2	4	25
Bare Earth	50	0.03	0.15	2	6	25
Grassed	5	0.03	0.2	3	7	10
Alien Vegetation Sparse	2	0.04	0.4	4	7	10
Alien Vegetation Dense	0	0	0.6	0	15	0
Sand Fynbos	0	0	0.25	0	10	0
Afromontane Forest Sparse	2	0.06	0.4	4	10	10
Afromontane Forest Dense	0	0	0.6	0	15	0
Shale Fynbos	5	0.04	0.25	4	7	10
Stream (Sand)	10	0.06	0.4	5	8	10
Stream (Forest)	10	0.06	0.6	5	8	10
Stream (Shale)	25	0.05	0.1	4	8	10
Stream (Channel)	75	0.025	0.05	1	5	10
Wetland	50	0.05	0.5	4	15	10
Saltmarsh	25	0.05	0.1	4	8	10

6.3 Calibration, validation, and verification

The calibration, validation, and verification process involved using the Sensitivity-based Radio Tuning Calibration (SRTC) tool provided in PCSWMM. The calibration process was made up of several components:

- i) The calibration required sufficient storm event flow data; it was determined that the storm events measured were sufficient as they captured a range of storm event sizes.
- ii) The flow data, or flow rate timeseries, were assigned to the respective conduits that represent the flow measurement site from the Bongani River in the model to calibrate the modelled flows with the measured flows.
- iii) Parameter uncertainties were then inserted into the table tab in PCSWMM for sub-catchments and conduits concerning recommended uncertainties from CHI (2020). A parameter uncertainty is a percentage of variability of a parameter and represents the range that the parameter value could fall within. Therefore, if a parameter is assigned an uncertainty of 50%, the value for the parameter could either be 50% above or below the value assigned to it in the uncalibrated model (See Table 6-5).
- iv) The SRTC tool was then run for the uncertain parameters in the model using four sensitivity points. The number of sensitivity points represents the number of runs the tool will use within the assigned uncertainty ranges. Thus, the model was run at both the maximum uncertainties assigned, and at 50% of those uncertainties. Four sensitivity points were selected and provided an output of the variation of the parameters assigned an uncertainty.
- v) The data from each of the observed time series locations at each respective conduit was then loaded into the model for each calibration location in the SRTC tool.
- vi) Once loaded, the relative sensitivity was assessed for maximum and mean flow to determine which parameter variations had the most significant impact on the flows in the model, hence identifying which parameters the model was most sensitive to.
- vii) The most sensitive model parameter was varied first, followed by the next most sensitive parameter, and so forth, using the SRTC tool, which optimises a parameter's statistics using a statistically weighted average.
- viii) The calibration statistics, namely the Index of Simulated Efficiency (ISE), Nash-Sutcliffe Efficiency (NSE), and the coefficient of determination (R^2), were then optimised by improving the model for both the calibration group of events at Bongani 10 and the individual validation events from Bongani 10, 7, and 12.
- ix) The validation events were then checked after the verification run to assess how the calibration affected their statistics.
- x) The graphs were then saved such that they were available at a later stage.
- xi) The statistics for each location, before and after the calibration, were then assessed.

6.3.1 Flow rate data

The calibration of the hydrological model required a reliable flow rate or flow depth dataset at a significant point in the stream network. Long-term time series data are generally preferred for continuous calibration; however, only storm event periods were available. Thus, the model was calibrated using the measured flow rates for these storm events. The observed flow rate time series were assigned to conduits in the model (for reference to the sites, see Figure 5-7). The calibration, validation, and verification process required that some storm events were used for calibration and some for validation and verification. Mancipe-Munoz *et al.* (2014) recommend a ratio of 2:1 of calibration to verification, which was used as a baseline.

The model was calibrated using a group of five storm event periods of observed data from the Bongani River Sensor at Bongani 10 from 2019. The model was subsequently validated and verified by the flow data from individual storm event periods at the Bongani River Sensor from 2018, from the Old Place Stream Sensor at Bongani 7, and from the Vigilance Canal Sensor at Bongani 12 from 2019, for which insufficient data were available for calibration. The storms used for calibration and validation of the model are given in Table 6-4.

Table 6-4: Storm events used for the calibration and validation process

Location	Researcher	Calibration / validation #	Storm event period (hh:mm dd/mm/yyyy)	Peak rainfall intensity (mm/hour)	Total rainfall (mm)	Event duration (hours)	
Bongani 10	Alice Harvey	V1	11:58 21/05/2018 – 12:00 15/06/2018	4.0	45	600	
		V2	19:00 21/06/2018 – 19:01 03/07/2018	2.8	19	264	
	Calvin van der Merwe	C1	19:27 30/06/2019 – 07:29 08/07/2019	4.2	19	180	
		C2	03:17 19/07/2019 – 03:29 25/07/2019	8.8	90	144	
		C3	15:01 08/10/2019 – 15:13 13/10/2019	4.4	21	120	
		C4	00:55 26/10/2019 – 00:58 27/10/2019	5.6	11	24.1	
		C5	13:07 12/11/2019 – 07:16 16/11/2019	5.4	64	90.2	
		Bongani 7	V3	20:30 03/07/2019 – 12:30 06/07/2019	4.2	12	64
			V4	15:24 18/07/2019 – 22:30 21/07/2019	8.8	64	79.1
V5	09:43 23/07/2019 – 12:49 26/07/2019		3.2	5.6	75.1		
Bongani 12		V6	05:04 19/07/2019 – 08:11 25/07/2019	8.8	90	147	

The Bongani 10 Sensor flow measurement site had the longest and straightest reach, which meant it was the most likely to display uniform flow. The flow data spanned over 1.5 years, the longest available flow timeseries, and included seven critical storm events used to calibrate, validate, and verify the model. The observed flow time series at the Old Place Stream Sensor site comprised three storm event periods, whereas there was only flow data for one storm event at the Vigilance Canal Sensor site. The timeseries were then assigned to the conduits they represented via the graph tab in PCSWMM, where they were given the same name as their representative conduit.

6.3.2 Parameter uncertainties

Sub-catchment parameter uncertainty estimations were made using recommended uncertainty ranges provided by PCSWMM Support (CHI, 2020). The recommended sub-catchment uncertainty ranges, as well as the assigned uncertainties in the model of the Bongani River catchment, are provided in Table 6-5. The upper bound was used for the calibration to ensure that the maximum possible envelope was considered. These parameters were assigned in PCSWMM using the render uncertainties option in the table tab.

Table 6-5: Uncertainty assigned to sub-catchment and conduit model parameters

Sub-catchment parameter	Uncertainty assigned (%)	Category	Recommended range (%)
Area	10	1	5-10
Width	100	4	50-100
Slope	100	2-4	10-100
Impervious %	50	3	25-50
Impervious n	25	2	10-25
Pervious n	100	4	50-100
Impervious DS	50	3	25-50
Pervious DS	100	4	50-100
Zero DS Impervious	100	4	50-100
Suction Head	50	3	25-50
Hydraulic Conductivity	50	3	25-50
Initial Deficit	100	4	50-100
Conduit parameter	Uncertainty assigned (%)	Reason for use	
Length	5	Uncertainty of the measurement of meanders	

Once the uncertainty was assigned to the parameters considered for the calibration of the model, the calibration run was set up with four sensitivity points assigned. The first SRTC run included all the uncertain parameters mentioned in Table 6-5. The first calibration run was done to determine which model parameters were the most sensitive, after which only the most sensitive

parameters were to be included for the calibration, validation, and verification. The reason for choosing fewer sensitive parameters was to speed up model run times, as fewer parameters would need to be used for the final calibration, validation, and verification process.

6.3.3 Calibration, validation, and verification process

A reliable calibration includes observed time series for small, medium, and large storm events. For this study, there was no long-term data available for the stream; however, the storm events for which there was flow data available for at least small and medium-sized storm events were used. An initial step in the calibration was determining the parameter variations the model was most sensitive to by increasing or decreasing the input values of a parameter within a specified uncertainty range, which was deduced from a sensitivity graph. A sensitivity graph presents the model sensitivity for the different uncertain parameters. The model's sensitivity was assessed for the maximum and mean flow rates.

The sensitivity graph was used to determine the parameters which caused the most variation in the model outputs. The sensitivity gradients for all of the parameters assigned uncertainty were assessed for the flows in the model at the Bongani 10 Sensor site where the calibration took place. Figure 6-6 illustrates the sensitivity gradients for uncertainty for maximum flow in the model.

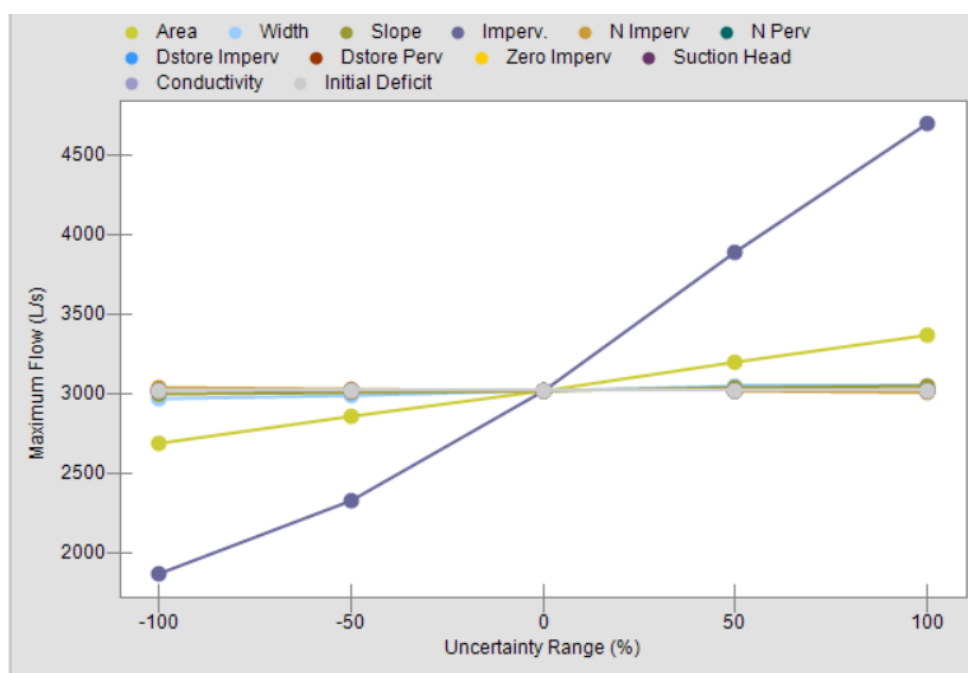


Figure 6-6: Maximum flow sensitivity gradients at Bongani River Sensor

Seven of the most sensitive parameters were selected for the calibration once the calibration had been run. These model parameters included: percentage impervious area, zero impervious area, impervious depression storage, conduit width and length, a sub-catchment slope and impervious Manning's runoff coefficients. This implies that incrementally changing these parameters varies

the outputs of the model more than any other parameters. The mean normalised sensitivity for the parameters chosen for calibration are provided in Figure 6-7.

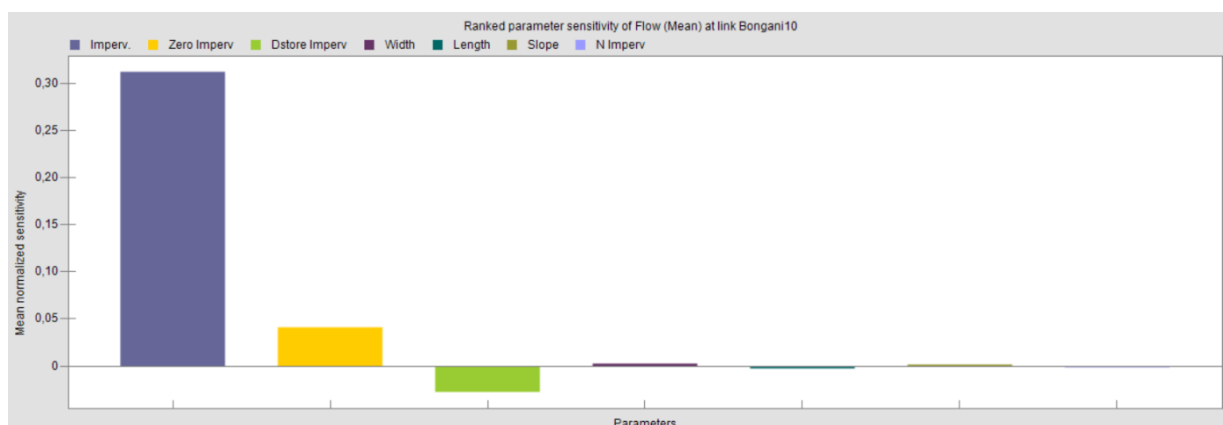


Figure 6-7: Mean normalised sensitivity for mean flow at Bongani Flow Sensor

An initial step in the calibration process involved identifying which parameter variations the model was most sensitive to. The model's sensitivity was determined by changing the input values of each parameter by a specified uncertainty range and plotting the results on a sensitivity graph. The most uncertain parameter (percentage impervious area) was excluded from the graph to improve the interpretation of which parameters the model was sensitive to, allowing for a clearer understanding of the model's sensitivity to the remaining uncertain parameters. The sensitivity gradients of the remaining parameters concerning maximum (max) flow are shown in Figure 6-8.

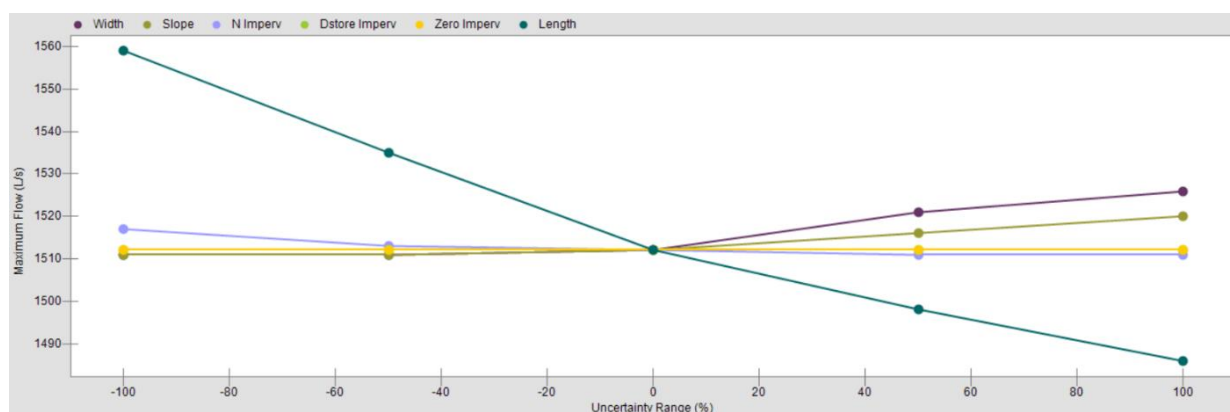


Figure 6-8: Max flow sensitivity gradients at Bongani River Sensor without Imperv %

The relevant observed storm event periods were then selected within the SRTC tool. Thus, the observed storm event flow timeseries that were assigned to their respective conduits in the model were defined as the storm events for calibration. After that, the various storm events could be used either individually or as a group to calibrate the uncertain parameters.

The calibration of the hydrological model was viewed in two ways:

- The first was graphical, where the flow rate plots of the various storm events were compared for the observed flows, the flows from the model prior to calibration, and the flows from the model after calibration.
- The second method was using individual storm event statistics.

Three statistical indices were selected from the PCSWMM SRTC tool's interface to conduct the calibration. They were chosen because of their use in practice and data availability for their evaluation (CHI, 2020; Moriasi *et al.*, 2007). They included the Index of Simulated Efficiency (ISE), Nash-Sutcliffe Efficiency (NSE), and the coefficient of determination (R^2), which are widely used indices for evaluating the accuracy of hydrological models. Table 6-6 provides ranges for ISE and NSE (See Glossary for their definitions) and describes their calibration ratings and model applications, whereas a description of the use of R^2 is provided after that.

Table 6-6: Ranges for ISE and NSE for model calibration and application (CHI, 2020)

ISE range	Calibration rating	Model application
0 to 3	Excellent	Planning, Preliminary Design, Final Design
3.1 to 6	Very good	Planning, Preliminary Design, Final Design
6.1 to 10	Good	Planning, Preliminary Design
10.1 to 25	Fair	Planning
More than 25	Poor	Screening
NSE range	Calibration rating	Model application
0.5 to 1.0	Excellent	Planning, Preliminary Design, Final Design
0.4 to 0.49	Very good	Planning, Preliminary Design, Final Design
0.3 to 0.39	Good	Planning, Preliminary Design
0.2 to 0.29	Fair	Planning
Less than 0.2	Poor	Screening

R^2 describes the proportion of the variance in measured data explained by the model. R^2 ranges from 0 to 1, with higher values indicating less error variance, with values greater than 0.5 considered acceptable (Moriasi *et al.*, 2006; Santhi *et al.*, 2001; Van Liew *et al.*, 2003).

The option for optimising the calibration using either the statistic of NSE or ISE is provided within PCSWMMs SRTC tool. Both options were investigated, and their results were checked across all three relevant statistics for individual storm event periods and for groups of storm event periods.

There were several iterations undertaken for the calibration, validation, and verification. The iterations process involved the following:

- i) The first three uncertainty parameters calibrated were those of the sub-catchments. The parameter of most uncertainty in the calibration – percentage impervious – was optimised first, and the following uncertain parameters were subsequently optimised to improve the three statistics. The second parameter calibrated was the zero-impervious percentage area, and the third was the impervious area depression storage. The maximum, total, and mean objective calibration graphs were used for the five storm events selected for calibration at the Bongani 10 site/conduit. The final calibration parameter was conduit length, which in the case of irregular cross-sections, can vary based on the path it takes through the landscape.
- ii) The four optimum percentages were then accepted based on their effect on the statistics of the model. The validation storm events were assessed to check that the calibration was appropriate. The assessment aimed to determine whether the parameter variations identified in the first step of the calibration process had also improved their statistics. This process was undertaken several times until an appropriate statistic was achieved for both the calibration and validation events.
- iii) Once the calibration and validation process was complete and the variations of the uncertain parameters provided the best statistics for ISE, NSE, and R^2 , the model needed to run again for final verification.

6.3.4 Results of the calibration

The statistics were assessed for the calibration, validation and verification runs in the SRTC tool. An example of the flow hydrographs at the Bongani River Sensor that were used for calibration is provided in Figure 6-9.

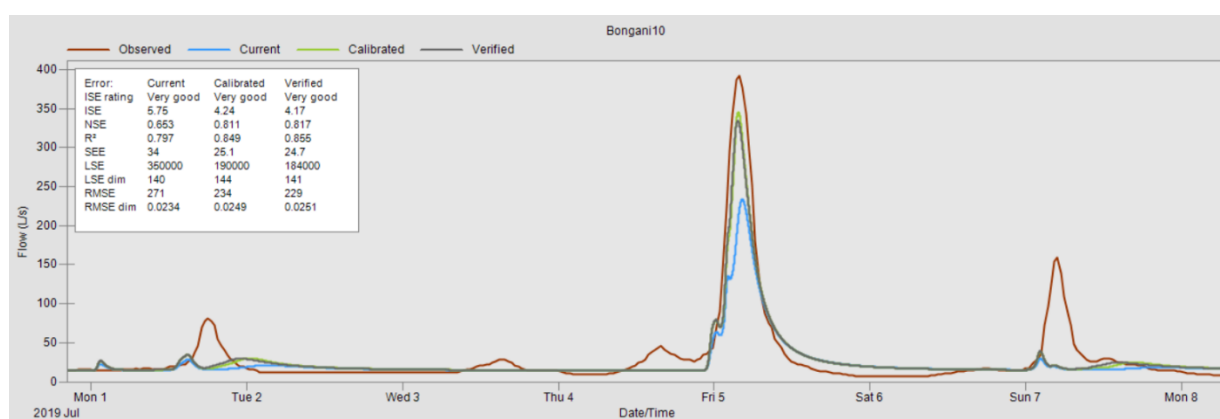


Figure 6-9: Calibration event 1 in early July 2019 at the Bongani River Sensor

In Figure 6-9, it is evident that the smaller storm events measured on 1 July and 7 August 2019 were not reflected well in the model. The observed flow rate increased in these periods, whereas the models flow rate only had minor fluctuations. These kinds of anomalies could either occur because of the rainfall depth at the rainfall gauge used did not describe the precipitation event across the catchment effectively, or because the model has a high infiltration rate or depression storage during small events which could skew their results.

The calibration was undertaken using maximum and mean flow rates. The calibration entailed optimising the parameters of uncertainty using the SRTC tool to achieve the best results for the three statistical objectives chosen. The statistical objectives that were chosen included ISE, NSE, and R^2 . The parameters of uncertainty were optimised for a group of five storm events simultaneously as shown in Figure 6-10.

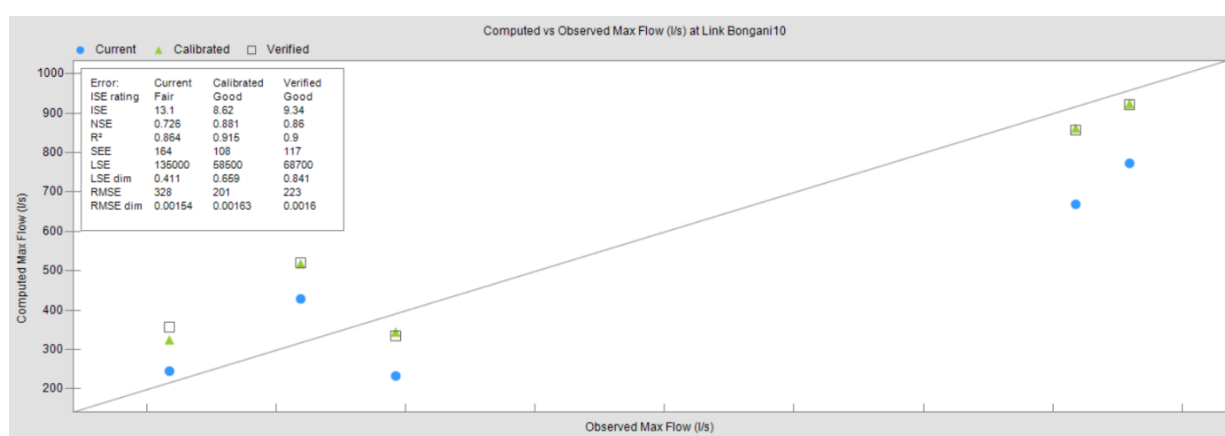


Figure 6-10: Maximum flow objective calibration graph at the Bongani River Sensor

Storm event periods measured by Harvey (2019) from 2018 at the Bongani River Sensor were used to validate the hydrological model, an example of which is provided in Figure 6-11.

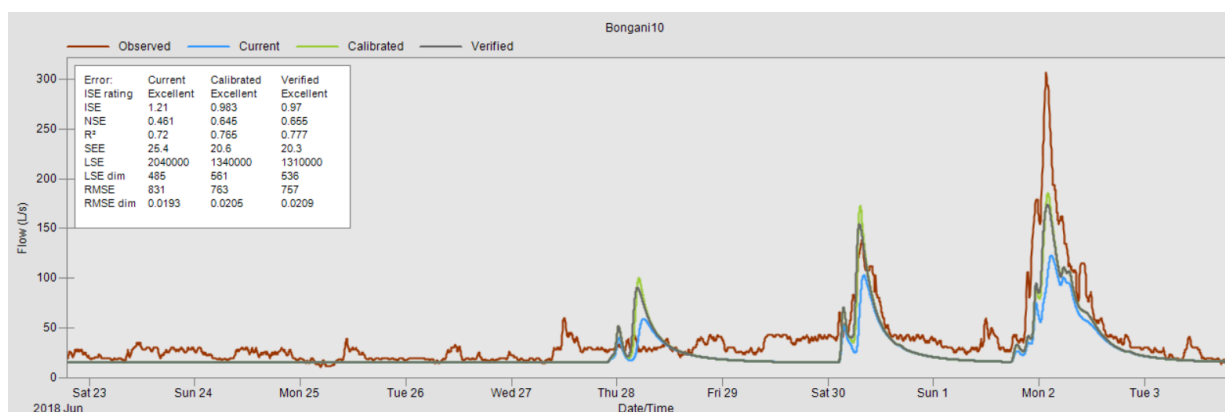


Figure 6-11: Validation event 2 from June and July 2018 at the Bongani River Sensor

Verification storm events hydrographs and statistics are provided for the Old Place Stream Sensor (Figure 6-12) and Vigilance Canal Sensor (Figure 6-13).

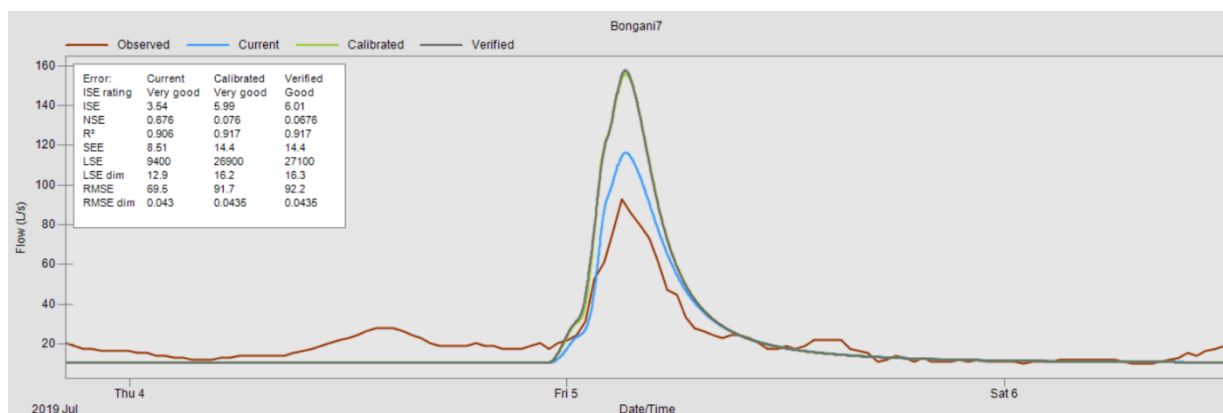


Figure 6-12: Verification event 3 in early July 2019 at the Old Place Stream Sensor

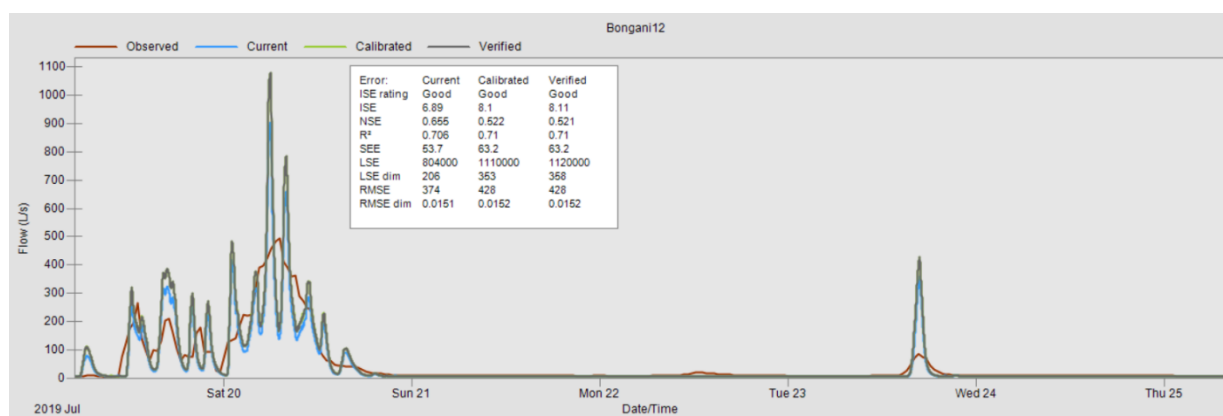


Figure 6-13: Verification event 4 in late July 2019 at the Vigilance Canal Sensor

The current and verified (after the verification run) statistics are presented in Table 6-7 for Bongani Sensor Site concerning the objective storm event statistics for the five storm events calibrated for in the SRTC tool.

Table 6-7: Final statistics for the calibration of the hydrological model

Calibration result		Maximum flow (L/s)		Mean flow (L/s)		Total Flow (L/s)	
Location	Statistic	Current	Verified	Current	Verified	Current	Verified
Bongani 10	ISE	13.1	9.34	21.2	16.3	23	17.3
	NSE	0.726	0.86	0.609	0.768	0.586	0.765
	R²	0.864	0.9	0.893	0.879	0.961	0.964

The final statistics of the calibration for the Bongani River tributary upstream of its confluence with the Old Place Stream tributary were considered excellent according to the criteria from CHI (2020) for the NSE statistic for all three calibration results meaning that it could be used for, planning, and final design according to this statistic. Furthermore, the R^2 statistic was above 0.9 for Maximum and Total Flow, while Mean Flow was very close to 0.9, representing a good fit (CHI, 2020). However, all three ISE statistics in the model were only in the fair category which lies between 10 and 25. Thus, the model would only be appropriate for the screening and planning phase according to this statistic (CHI, 2020).

The soil parameters in the model that represented infiltration were not calibrated. The main reason is that the model was not sufficiently sensitive to infiltration rates to warrant their calibration.

The validation and verification were carried out using the data from the other two sites to evaluate the impact of the calibration on datasets that were independent of those used in the calibration. The last parameter changes from the model calibration are provided in Table 6-8.

Table 6-8: Final calibration summary indicating the accepted percentage variations of the parameters of uncertainty

Parameter	Percentage change (%)	Uncertainty (%)	Parameter variation (%)
Sub-catchments			
Imperviousness	+40	50	+20
Depression Storage Impervious	-50	50	-25
Zero Impervious Area	+25	100	+25
Conduits			
Length	-50	5	-2.5

Once the calibration, validation, and verification process were complete and the statistics accepted, the development water quality component of the hydrological model could be investigated and completed. The remainder of the statistics for storm events, individually and as a group, can be found in Appendix D. The following chapter discusses the inclusion of the water quality component of the hydrological model.

7. Water quality model component

Once the hydrology and hydraulic components of the hydrological model had been set up and calibrated, validated, and verified, the water quality component of the model was developed. The development of the water quality model incorporated the data collected from the Bongani River and published water quality modelling data (Table 4-3).

The water quality sampling and testing provided information about where the major concerns were in the drainage system. This chapter analyses the sampling and testing that took place during the study. The sites for which water quality data were collected are displayed in Figure 7-1.

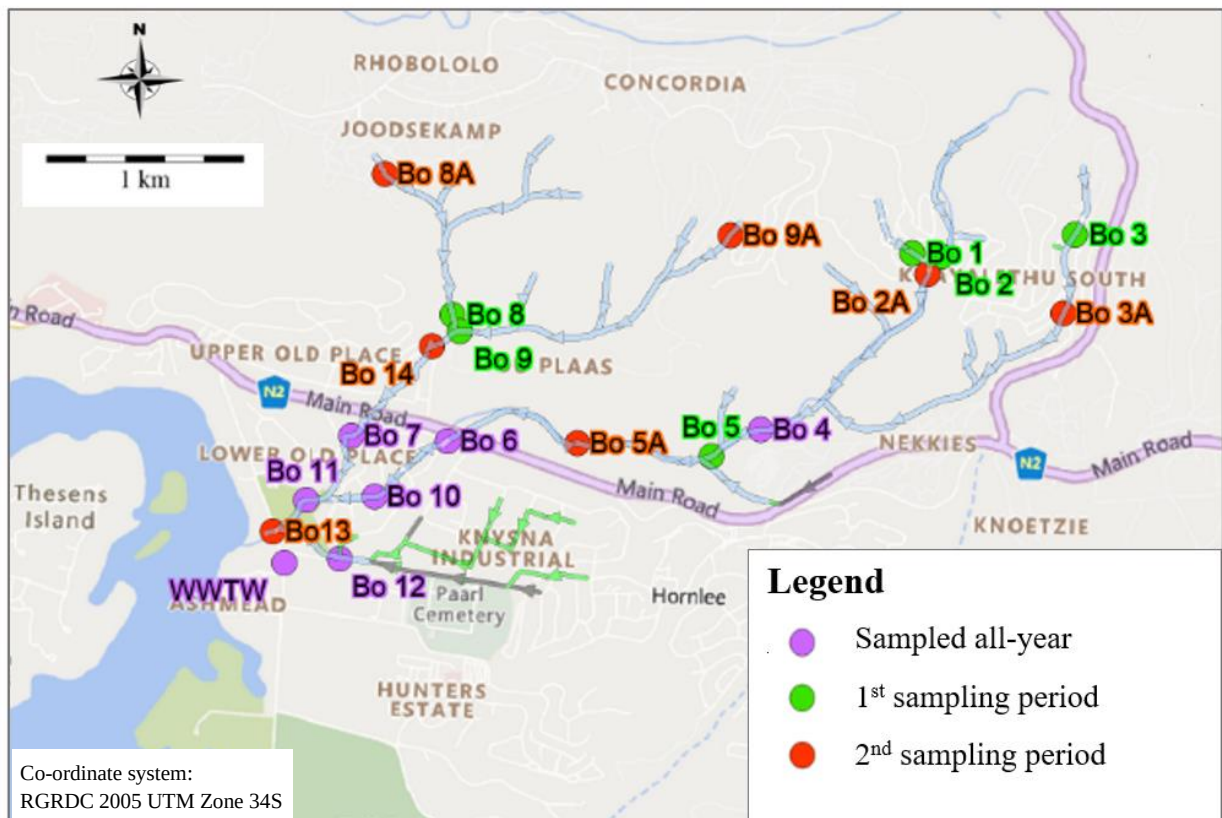


Figure 7-1: The sample sites in the Bongani River catchment and their sampling periods
(Bing Map Roads, n.d.)

The following sections provide the analysis of the water quality data used to help identify which parts of the stormwater drainage system were problematic in terms of water quality. Furthermore, a summary of a storm event assessed for flow rate and water quality is provided. After that, a description of the development of the water quality component of the model of the Bongani River catchment is provided.

7.1 Water quality data

The water quality data presented in this section comprise three distinct water quality parameters:

- Inorganic nitrogen in the form of TIN.
- Inorganic phosphorus in the form of SRP.
- Biological contamination in the form of *E. coli*.

Several sources have proposed limits (Table 2-4) for the pollutant categories (TIN, SRP, and *E. coli*). The various limits for the three water quality parameters are used in this section to show the extent of the pollution problem in the Bongani River catchment. The water quality data that are presented in this section are thus displayed with the water quality limits and are shown in three different formats for each of the three water quality parameters:

- A table providing the minimum, maximum, and mean values for each site.
- A map of the sites showing the mean values for each site.
- Box and whisker plots were developed to illustrate the variation of the measurements of the pollutants at the various sites. The box and whisker plots show the data's first quartile, median, third quartile, and outliers.

The results for the measured data for TIN and SRP for the various site locations are displayed in this section with the limits provided by DWAF (1996a), which focused on aquatic ecosystems and their respective eutrophic categories. In addition, the analyses of biological pollution, as colony forming units (CFU) of *E. coli*, are shown in this section so that the measured data could be compared with guidelines from several local and international sources.

As highlighted in Section 5.2.1, there were two distinct water quality data collection periods: the 1st sampling period and the 2nd sampling period. However, some of the sites had data collected during both sampling periods. The data collected in both the 1st and 2nd sampling periods included the water quality sampling and testing data for the following sites for the three distinct tributaries of the Bongani River catchment as follows:

- Concordia Stream was represented by Bongani 7.
- Vigilance Canal was represented by Bongani 12
- The Bongani River's main tributary was represented by Bongani 10; however, samples from Bongani 4 and 6 were collected and tested for the whole year of data collection and were located on this tributary too.
- Bongani 11 represented the point below the confluence of the Concordia Stream with the Bongani River.

The collection of data from these sites was done on a month-by-month basis to provide a general understanding of the water quality of each of the streams entering the Bongani Wetland. It provided information about the levels of contamination of each of those sites throughout the study period.

7.1.1 TIN results

The total inorganic Nitrogen results are the sum of measurements of ammonia, nitrites, and nitrates from the sample sites in the Bongani River catchment and are shown in Table 7-1.

Table 7-1: TIN minimum, maximum, and mean results

Legend (DWAF, 1996a)	Oligotrophic (< 0.5 mg/L)	Mesotrophic ($0.5 - 2.5$ mg/L)	Eutrophic ($2.5 - 10$ mg/L)	Hypertrophic (> 10 mg/L)
Sampling site	Min TIN (mg/L)	Max TIN (mg/L)	Mean TIN (mg/L)	
Bongani 1	0.7	5.1	3.6	
Bongani 1A	0.4	15.1	6.2	
Bongani 2	0.7	5.5	3.5	
Bongani 2A	0.5	56.3	10.9	
Bongani 3	2.7	4.8	3.6	
Bongani 3A	2.0	8.2	4.1	
Bongani 4	1.9	19.4	7.4	
Bongani 5	2.1	16.2	7.1	
Bongani 5A	8.5	120	33.5	
Bongani 6	3.7	107	26.8	
Bongani 7	0.6	48.5	7.5	
Bongani 8	1.6	9.2	4.5	
Bongani 8A	0.6	185	36.6	
Bongani 9	1.9	5.6	4.1	
Bongani 9A	0.5	85.4	20.2	
Bongani 10	3.4	81.7	15.0	
Bongani 11	2.3	53.6	20.3	
Bongani 12	0.6	16.3	5.7	
Bongani 13	2.0	50.5	12.8	

A map of the sample sites with the mean TIN results across the Bongani River catchment is given in Figure 7-2.

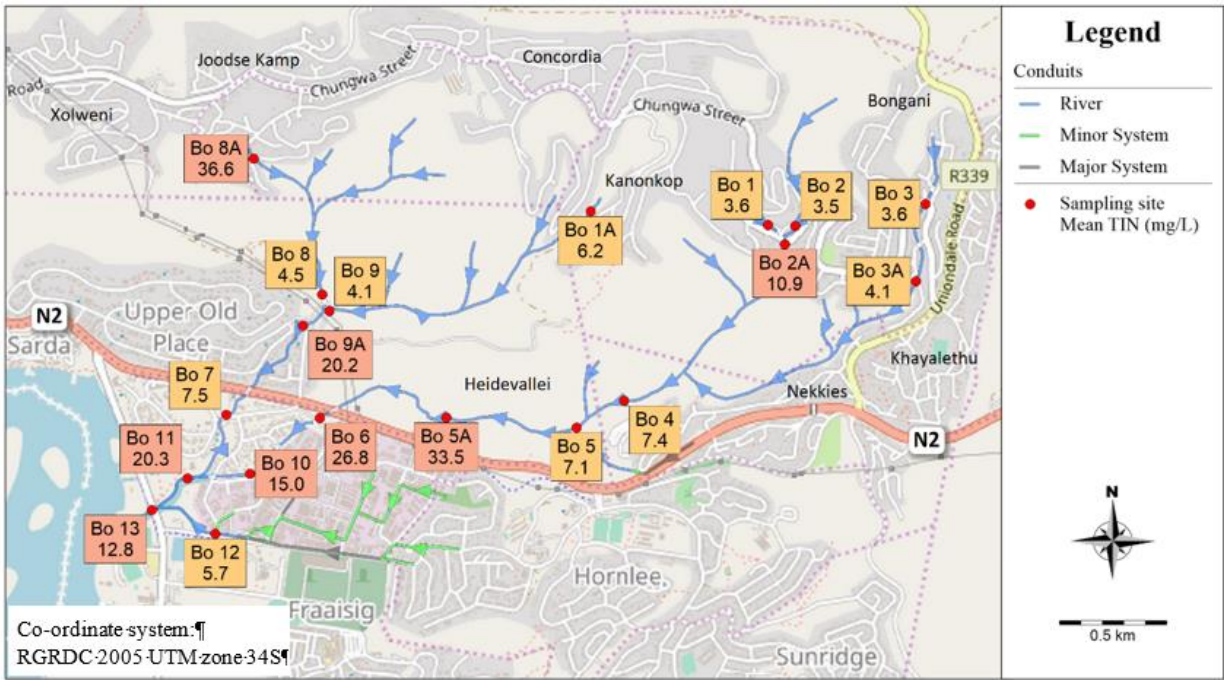


Figure 7-2: Mean TIN results across the Bongani Catchment (Open Street Map, n.d.)

Figure 7-2: Mean TIN results across the Bongani Catchment (Open Street Map, n.d.)

Figure 7-3 presents a box and whisker plot for the TIN concentrations over the 1st sampling period at selected sites in relation to the four aquatic ecosystem trophic states.

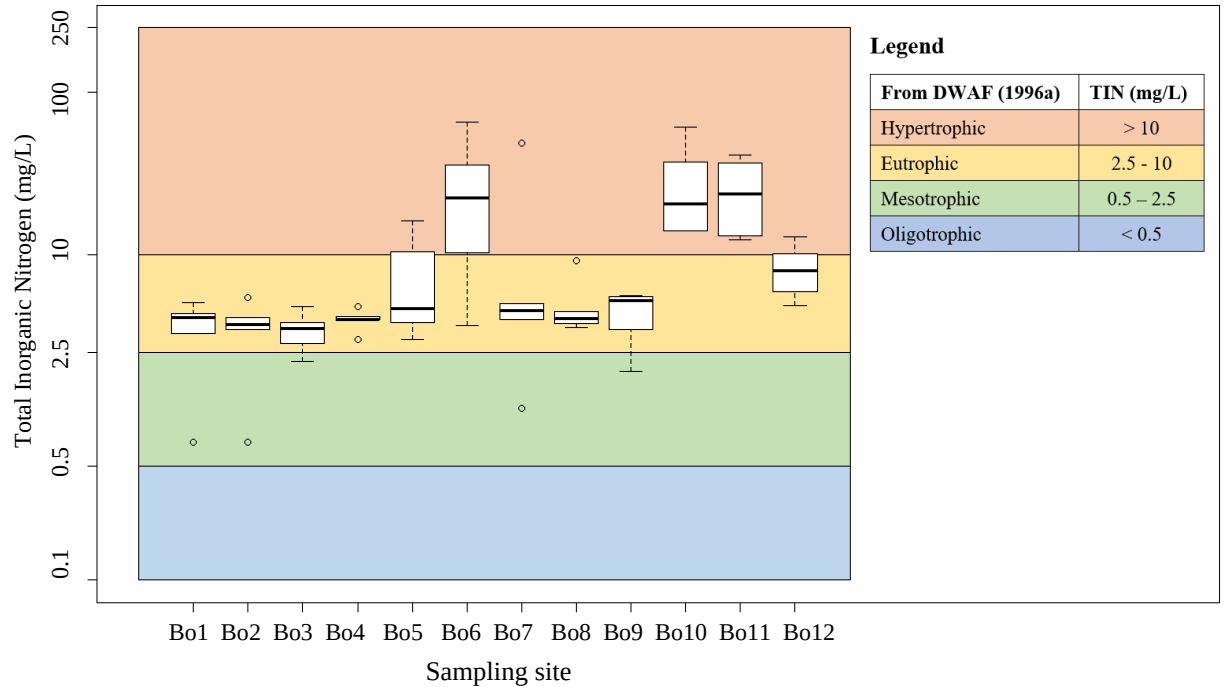


Figure 7-3: Box and whisker plots of the TIN concentrations over the 1st sampling period

As shown in Figure 7-3, most samples taken in the 1st sampling period were eutrophic or worse, with only a few outliers being mesotrophic or (relatively) uncontaminated. Samples from sites Bo 6, Bo 10, and Bo 11 all had median TIN concentrations above the limit for hypertrophism. These sites were located along the Bongani River's major tributary, beginning beneath the N2 highway at Bo 6, through the Knysna Industrial area at Bo 10, and extending downstream of the confluence of the Bongani River's major tributary and the Old Place Stream. The remainder of the sites were also polluted, falling into the eutrophic category according to DWAF (1996a). There were, however, a few samples measured that were in the lower mesotrophic range.

The sampling and testing then shifted its focus to incorporate other sites in the 2nd sampling period. Figure 7-4 presents the TIN data in a box and whisker plot, which displays the TIN results for the sites that were included in the 2nd sampling period.

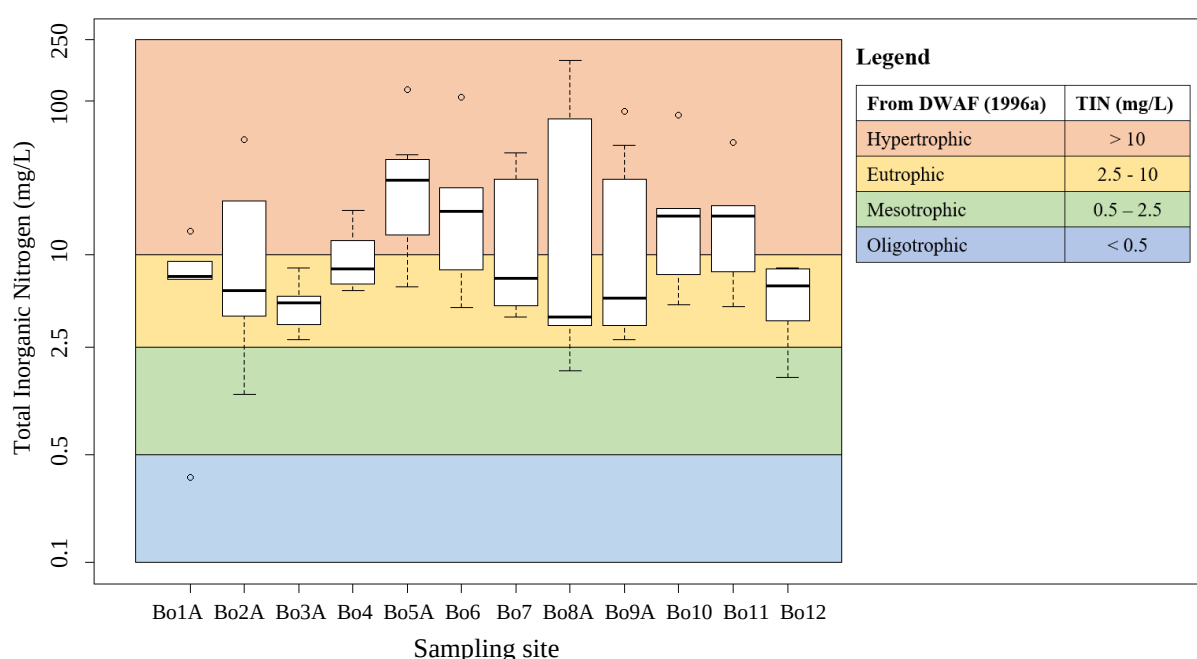


Figure 7-4: Box and whisker plot of the TIN results from the 2nd sampling period

High concentrations of TIN were observed from Bo 5A, Bo 6, Bo 10, and Bo 11, with median values in the hypertrophic range for both sampling periods. These sites are all located along the main stream of the Bongani River, with Bo 11 located downstream of the confluence of the Bongani River and the Old Place Stream. This trend highlights that the main stream of the Bongani River becomes hypertrophic in the Heidevallei between sample sitea Bo 4 and Bo5a. Besides those sites, the other sample locations remained eutrophic besides intermittent spikes at Bo 2A, Bo 7, Bo 8A and Bo 9A – for all these spikes, it is noted that there were several cases in which a sewage pump station was found to be leaking at the Bo 9A and Bo 2A sampling sites. Only a handful of sites had samples were within the mesotrophic range which is a concern for the tributaries of the Bongani River which flow through an Afromontane Forest.

7.1.2 SRP results

This section details the results of the inorganic Phosphorus samples and test data gathered from the Bongani River catchment. It provides a comparison between the results and three of the trophic states of aquatic ecosystems according to DWAF (1996a). Table 7-2 provides the results of SRP sampling across the Bongani River catchment.

Table 7-2: SRP minimum, maximum, and mean results

Legend (DWAF, 1996a)	Mesotrophic (0.005 – 0.025 mg/L)	Eutrophic (0.025 – 0.25 mg/L)	Hypertrophic (> 0.25 mg/L)
Sample site	Min SRP (mg/L)	Max SRP (mg/L)	Mean SRP (mg/L)
Bongani 1	0.18	0.84	0.34
Bongani 1A	0.05	1.5	0.38
Bongani 2	0.12	0.39	0.22
Bongani 2A	0.03	5.0	0.91
Bongani 3	0.13	1.5	0.49
Bongani 3A	0.05	0.59	0.25
Bongani 4	0.04	1.8	0.70
Bongani 5	0.07	0.45	0.29
Bongani 5A	0.61	5.0	2.7
Bongani 6	0.20	4.3	2.0
Bongani 7	0.03	2.6	0.39
Bongani 8	0.10	2.0	0.52
Bongani 8A	0.10	8.0	2.0
Bongani 9	0.02	0.62	0.35
Bongani 9A	0.04	5.0	0.97
Bongani 10	0.13	4.2	0.94
Bongani 11	0.10	4.2	1.6
Bongani 12	0.02	1.1	0.31
Bongani 13	0.05	4.7	1.1

From Table 7-2, it can be seen that SRP contamination of the Bongani River catchment is a widespread issue, with only one of the mean results being below the hypertrophic level. A map of the sample sites with the mean SRP concentration for each site is provided in Figure 7-5.

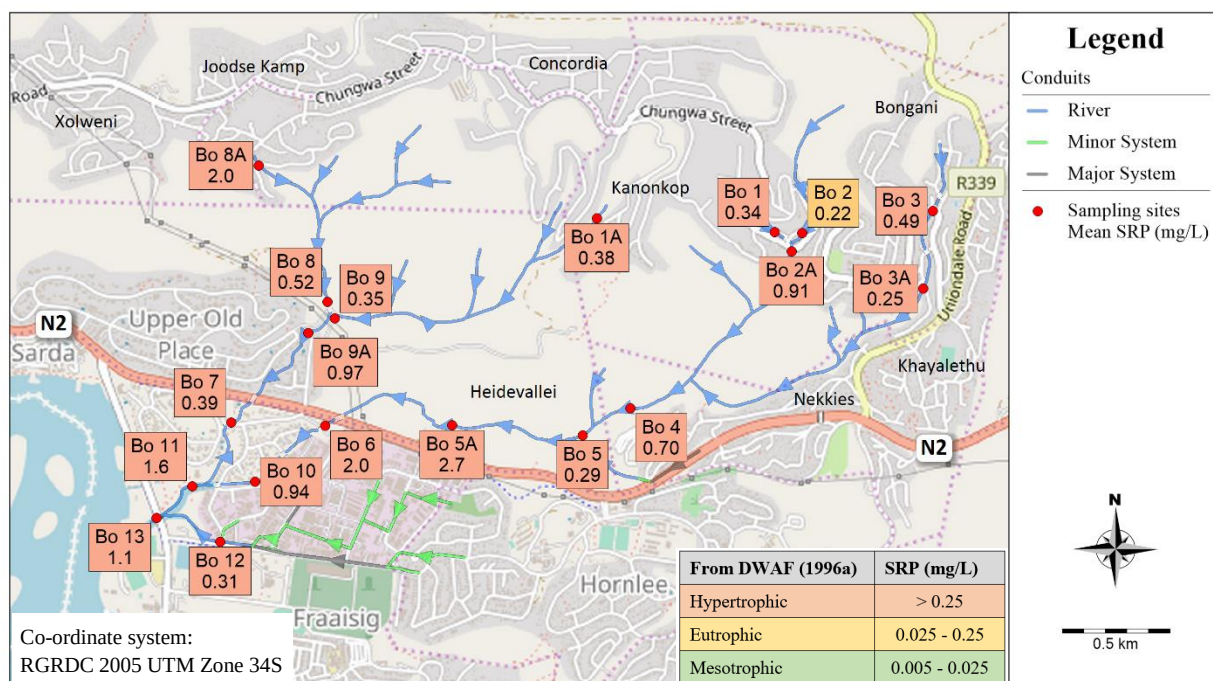


Figure 7-5: Mean SRP results across the Bongani Catchment (Open Street Map, n.d.)

Figure 7-6 presents a box and whisker plot for the SRP concentrations over the 1st sampling period at selected sites in relation to three of the aquatic ecosystem trophic states.

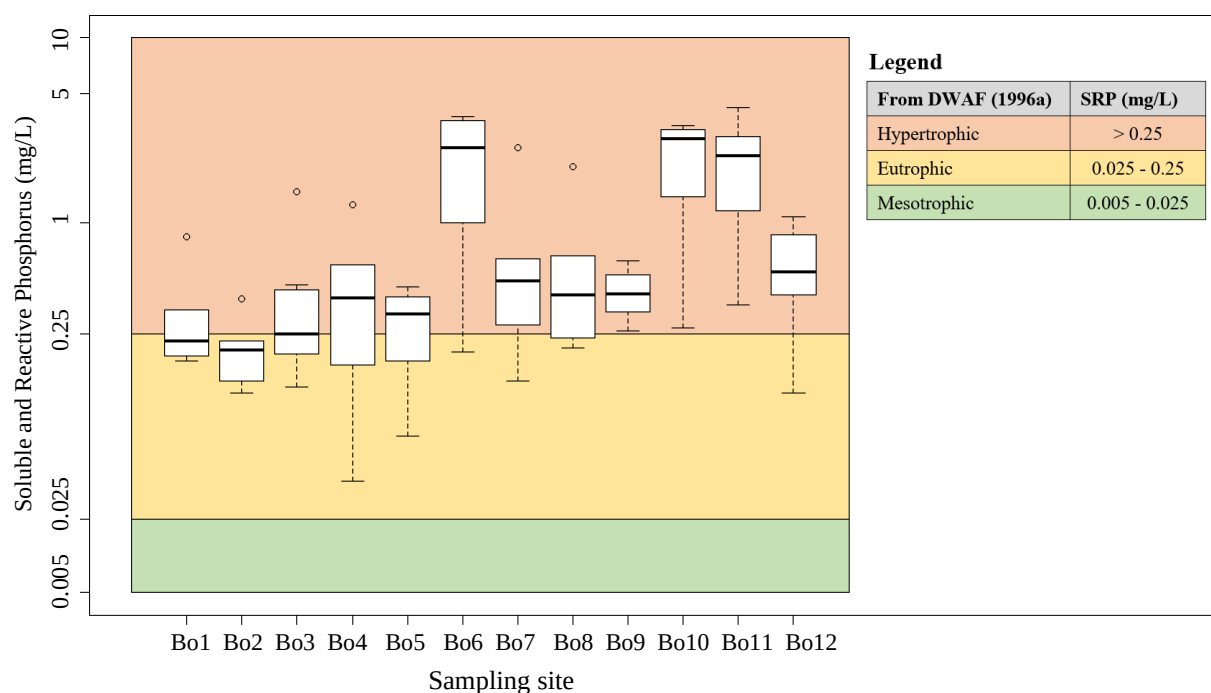


Figure 7-6: Box and whisker plot of the SRP results from the 1st sampling period

Sample sites Bo 4, Bo 5, Bo 6, Bo 7, Bo 8, Bo 9, Bo 10, Bo 11, and Bo 12 were all hypertrophic. Bo 1 and Bo 2 were both in a eutrophic state, and Bo 3 was between hypertrophic and eutrophic. The eutrophic and hypertrophic states of the sample sites were evidence of excess SRP throughout the stormwater network, with none presenting a sample within the mesotrophic range.

The SRP median results from the sample sites on the main stream of the Bongani River downstream of where it crosses the N2, sample sites Bo 6, Bo 10, and Bo 11, were notably worse than the other sample site locations. The trend of poor water quality along the main stream of the Bongani River aligns with the data from TIN sampling and testing, which also demonstrated that those three sites had the results during both the 1st and 2nd sampling periods.

In comparison to the TIN concentrations, the SRP concentrations were more elevated relative to the limits for trophic states from DWAF (1996a), highlighting a concern for SRP contamination of the Bongani River's major tributary. Figure 7-7 presents the data for the 2nd sampling period for SRP.

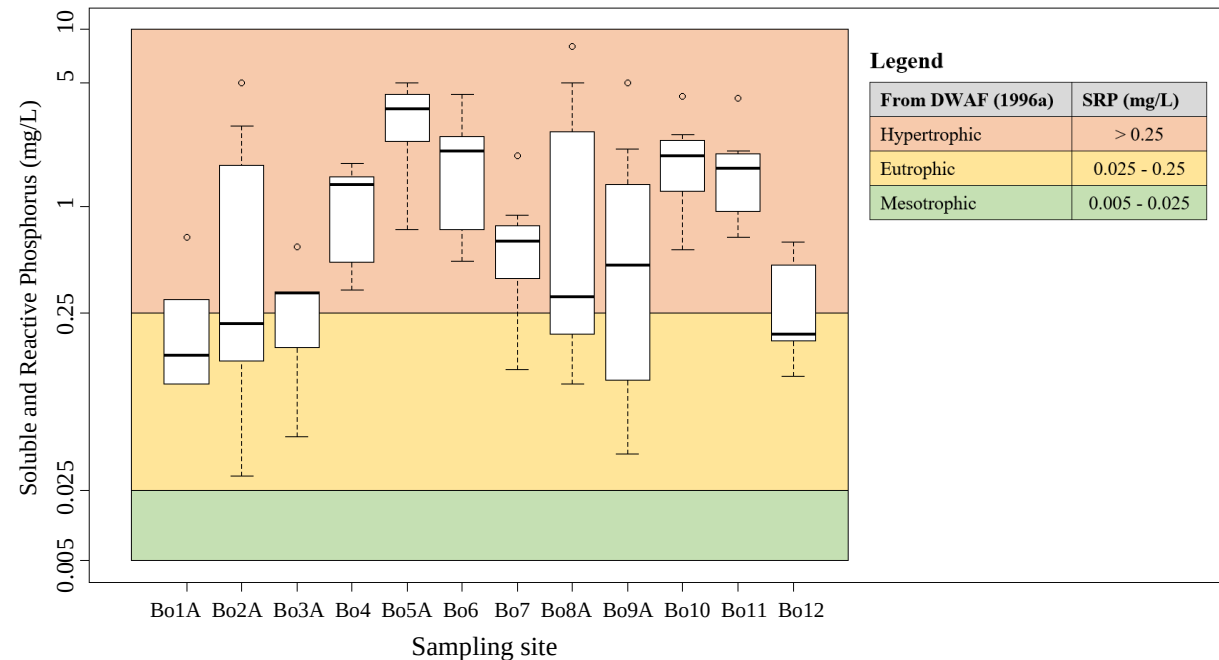


Figure 7-7: Box and whisker plot of the SRP results from the 2nd sampling period

It can be seen in Figure 7-7 that all of the SRP samples collected were above the upper limit for the mesotrophic category, highlighting the widespread issue of SRP contamination. The sample sites in Kanonkop (Bo 1A), Bongani (Bo 2A), and Vigilance Canal (Bo 12) all had their median values in the eutrophic category. However, their upper quartiles were situated in the hypertrophic category. The remainder of the sample site locations had their median values in the hypertrophic category highlighting the SRP enrichment across the catchment. The water quality of the main stream of the Bongani River was also concerning in terms of SRP enrichment in the Heidevallei, with sample sites Bo 4, Bo 5A, Bo 6, Bo 10, and Bo 11 having median SRP values above 1 mg/L.

The key outcome of the analysis of inorganic constituents of nutrients N and P was a concern for the Bongani River's major tributary. It was also noticeable that spikes in the data were not observed in the headwaters at Bo 1, Bo 2, Bo 3, Bo 1A, and Bo 2A, where the tributaries begin. Instead, the concentrations were seen at their maximum between Bo 4 and 5A in the Heidevallei. The trend of nutrient enrichment in the Heidevallei is likely from sewage spills at locations where the sewerage network has gradient changes from steep to gradual.

7.1.3 *Escherichia coli* results

Biological contamination was studied by collecting samples and providing them to a certified laboratory for testing *Escherichia coli* (*E. coli*). This section presents the *E. coli* results concerning recommended limits both locally (WHO, 1989; DWAF, 1996b.; DWAF, 1996c; DEA, 2012) and from Europe (Kavka *et al.*, 2006) as presented in Section 2.2.1. Table 7-3 shows the minimum, maximum, and mean *E. coli* results with reference to the South African limits.

Table 7-3: *E. coli* results summary

Legend	Fine for recreation (< 500 CFU/100mL)	Fine for irrigation (< 1000 CFU/100mL)	Unacceptable (> 1000 CFU/100mL)
Sample site	Min <i>E. coli</i> (CFU/100mL)	Max <i>E. coli</i> (CFU/100mL)	Mean <i>E. coli</i> (CFU/100mL)
Bongani 1	22	6500	1566
Bongani 1A	5	2419	731
Bongani 2	270	6300	1711
Bongani 2A	510	980 000	171 141
Bongani 3	460	4500	1954
Bongani 3A	150	39 720	8933
Bongani 4	310	34 600	6078
Bongani 5	340	8000	2920
Bongani 5A	2419	242 000	65 681
Bongani 6	690	48 380	11 300
Bongani 7	170	30 000	6266
Bongani 8	24	5750	1899
Bongani 8A	225	30 000	10 969
Bongani 9	160	225	196
Bongani 9A	22	30 000	6013
Bongani 10	420	91 000	20 634
Bongani 11	430	150 000	24 369
Bongani 12	1350	55 000	21 567
Bongani 13	300	99 300	36 583

A map of the sample sites with the mean *E. coli* results for each site is provided in Figure 7-8. The colour legends are presented with respect to both local and European recommended limits.

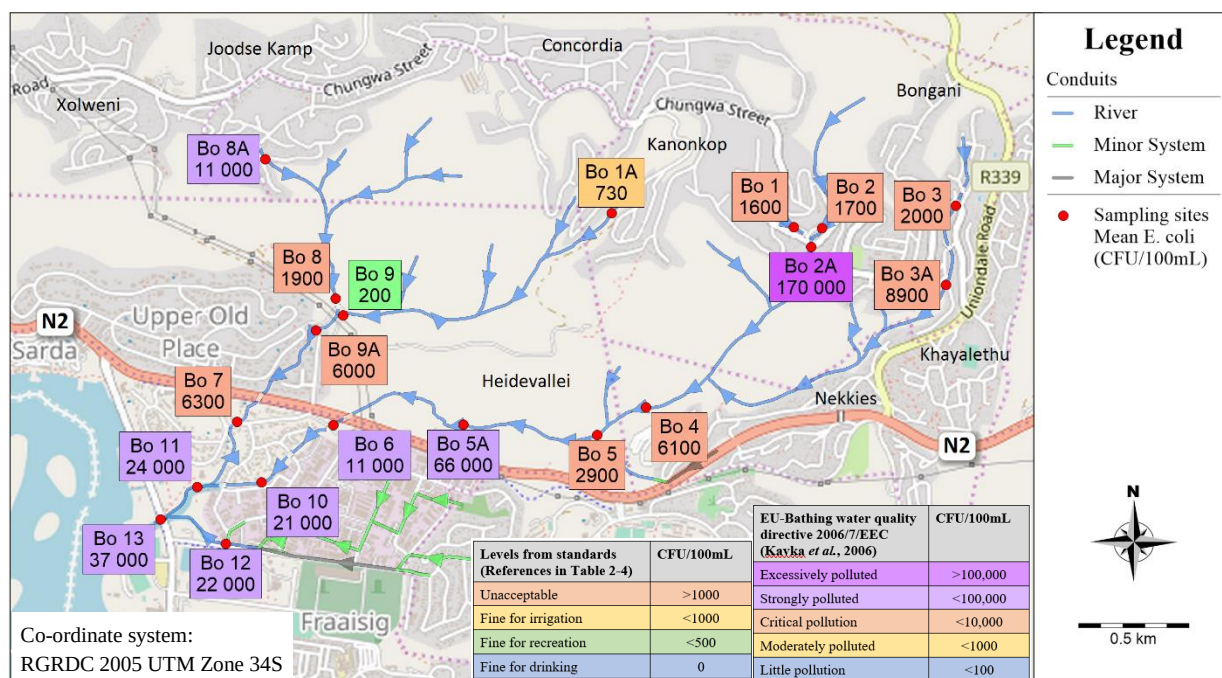


Figure 7-8: Mean *E. coli* results across the Bongani Catchment (Open Street Map, n.d.)

Figure 7-9 presents a box and whisker plot of the *E. coli* results from the 1st sampling period with respect to both the local and European recommended limits.

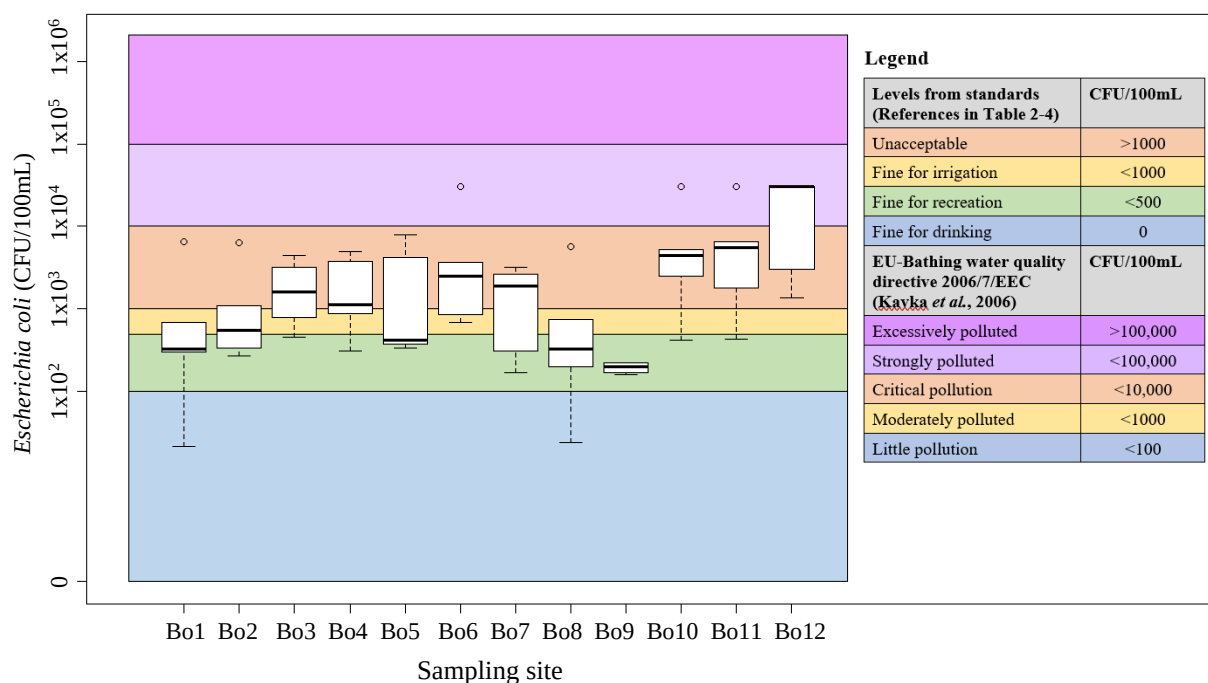


Figure 7-9: Box and whisker plot of the *E. coli* results for the 1st sampling period

From Figure 7-8 and Figure 7-9, it can be seen that the outflow of the wetland downstream of Concordia and Kanonkop (Bo 9) was the only site which had all its sample results beneath the target level for recreation at 500 CFU/100mL (DWAF, 1996c; DEA, 2012). The Bongani Rivers main stream was the most concerning part of the catchment, highlighting the same issue as the nutrient enrichment concern (Section 7.1.1 and 7.1.2). Unacceptable *E. coli* counts were found from Khayaalethu (Bo 3) and in the Heidevallei (Bo 4). Moreover, the mean *E. coli* counts from Figure 7-8 showed that the Bongani River from the Heidevallei (Bo 5A) through Lower Old Place (Bo 6, Bo 7, Bo10, Bo 11, and Bo 13), as well as the Vigilance Canal (Bo 12), were all highly polluted according to the limits provided by Kavka *et al.* (2006).

After a few months of data collection, the most extreme values were all reported by the registered laboratory to be 30,000 CFU/100mL or less because 30,000 CFU/100mL was the maximum limit the registered laboratory was reporting at the time. Therefore, for the second sampling period, total *E. coli* counts were measured by the registered laboratory to acquire more realistic estimates of the level of biological pollution in the Bongani River's catchment. This was relevant as it was later seen that the maximum *E. coli* value was 980,000 CFU/mL, more than an order of magnitude larger than the initial limit. Figure 7-10 summarises the 2nd sampling period for *E. coli* with reference to the local and European recommended limits.

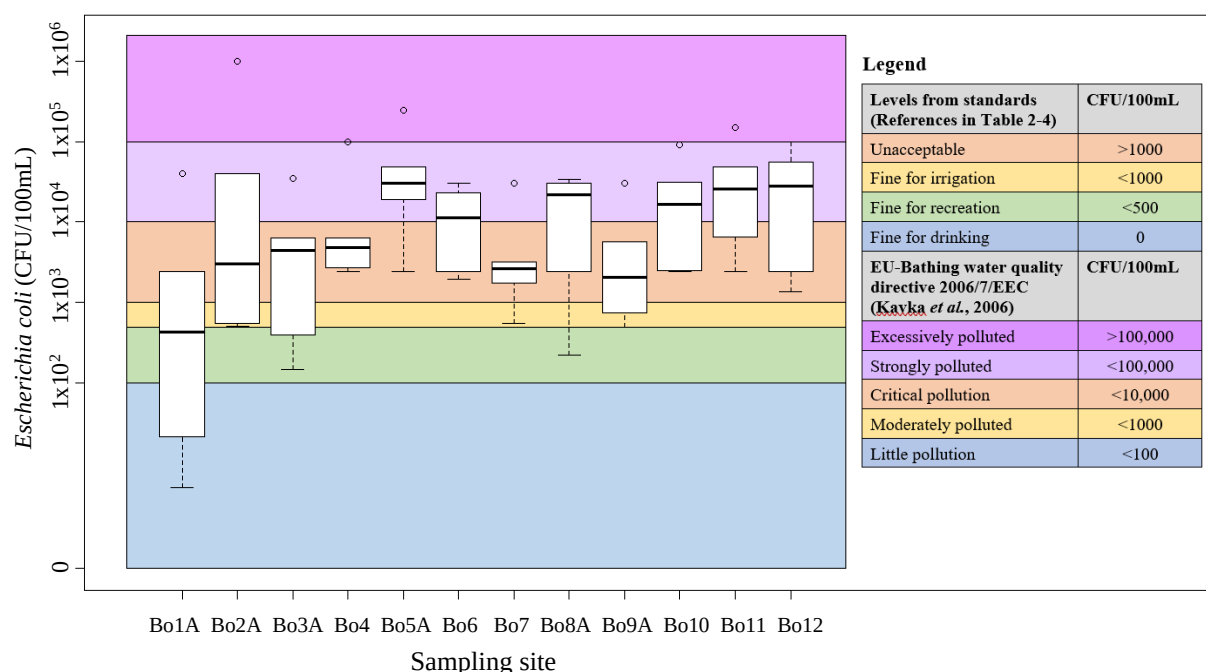


Figure 7-10: Box and whisker plot of *E. coli* results for the 2nd sampling period

The results of the 2nd sampling period showed that biological pollution was a concern, with the median *E. coli* counts along the main stream of the Bongani River (Bo 5A, Bo 6, Bo 10, and Bo 11) all being in the strongly polluted category, along with the tributary arising in Joodse Kamp (Bo 8A) and Vigilance Canal in the industrial area (Bo 12). The only median value from the 2nd

sampling period that was below the limit of the range for ‘moderately polluted’ and slightly beneath the limit for recreational use, according to DWAF (1996c), was in the headwaters of the Bongani River’s main tributary in Bongani (Bo 1A).

There were three extreme values within the ‘excessively polluted’ range from the EU-Bathing water quality directive (Kavka *et al.*, 2006), and one or two on the boundary between that and the limit for ‘strongly polluted’, with each being located at a different sample site (Bo 2A, Bo 4, Bo 5A, Bo 10, and Bo 11). The maximum *E. coli* value was 980,000 CFU/100mL at Bo 2A, measured downstream of a broken sewage pump station (Figure 7-11). The issue was reported to the Knysna Municipality and was attended to at the time.



Figure 7-11: Bongani 2A sample site showing the sewage overflow into the stream

Storm event data provides insight into how nutrient and solid pollutants are flushed through the system during storm flows. Both datasets showed the pollution levels across the system and provided data for the water quality component of the hydrological model. The following section focuses on the rainfall, flow rate, and water quality data measured during a storm event.

7.2 Storm event data summary

This section summarises the data collected during a storm event in late July 2019. The sampling and testing data collected during the storm event provided insights into the variation of dissolved and solid pollutant concentrations in the Bongani River.

The results provided in this section are based on a storm event studied in late July 2019. This storm event was chosen for reporting in this section as there was comprehensive data collected for rainfall, flow level, and water quality parameters TSS, TN, and TP during the beginning of the event. Collecting data from the beginning of the event was essential to ensure that the first flush was measured. Measuring the first flush was necessary because the initial runoff washed off the pollutants that had built up on surfaces in the catchment during the dry period prior to the storm event. Thus, the highest pollutant concentrations can be accounted for by collecting samples representing the first flush. Figure 7-12 is a combination of the rainfall hyetograph and the flow hydrograph for the main stream of the Bongani River at the Bongani River Sensor (Bongani 10) during the storm event of the 19th of July 2019.

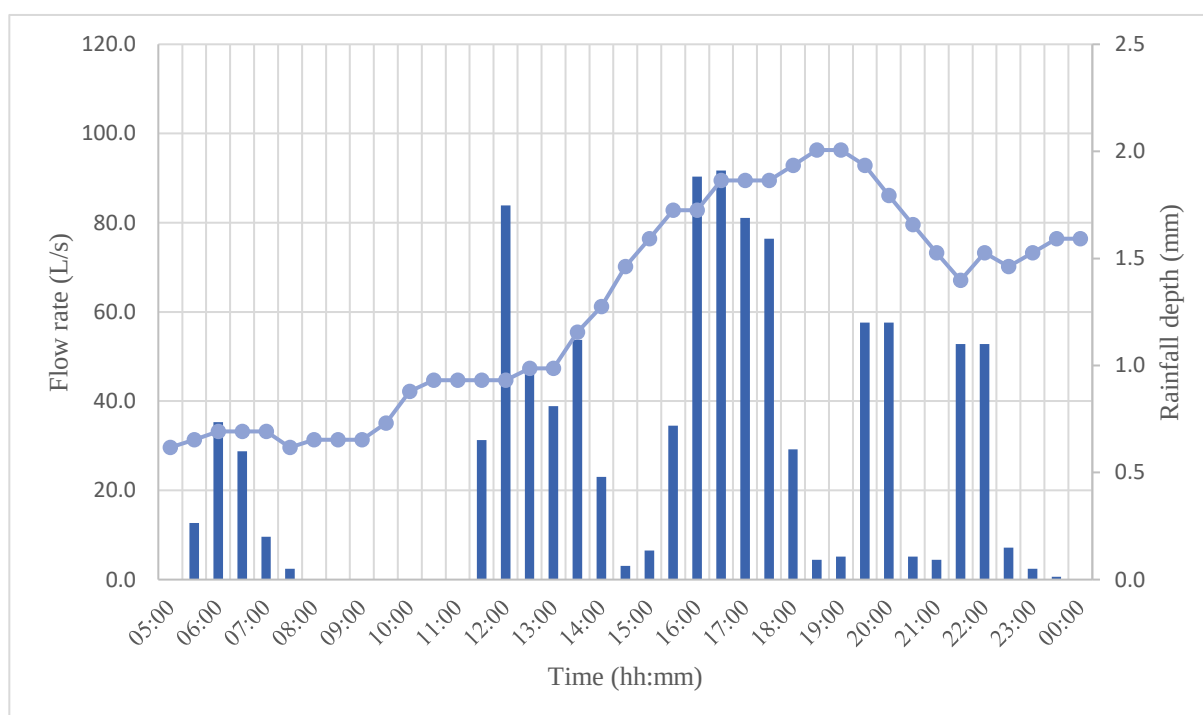


Figure 7-12: Flow rate (line graph) and rainfall depth (bar graph) measured during the storm on the 19th of July 2019 at Bongani 10 flow sensor site

The first increase in flow rate occurred at about 09:25 on the 19th of July 2019, and the peak flow rate for the day was at about 18:26 at a value of 96 L/s. Figure 7-13 presents the hourly variation of TIN, Figure 7-14 the variation of SRP, and Figure 7-15 the variation of TSS concentrations – all with respect to time during a storm event. The concentrations were already relatively high before the storm event began.

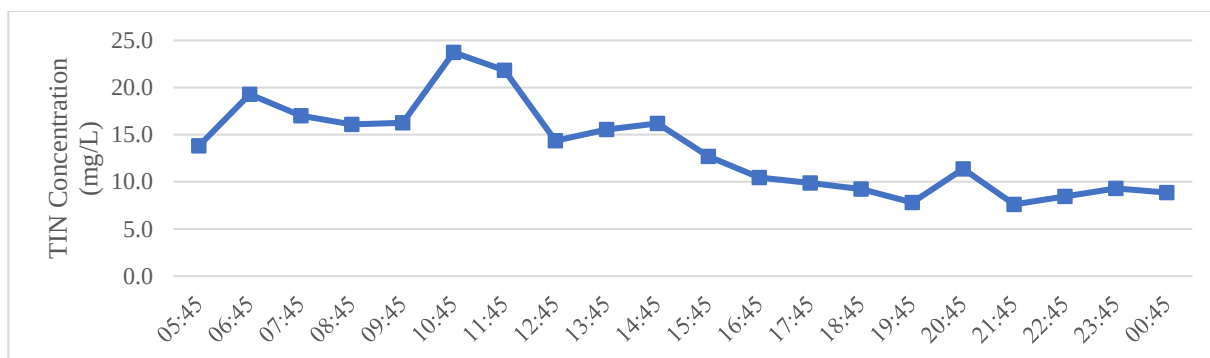


Figure 7-13: Variation of TIN concentration at Bo 10 during the 19 July 2019 storm

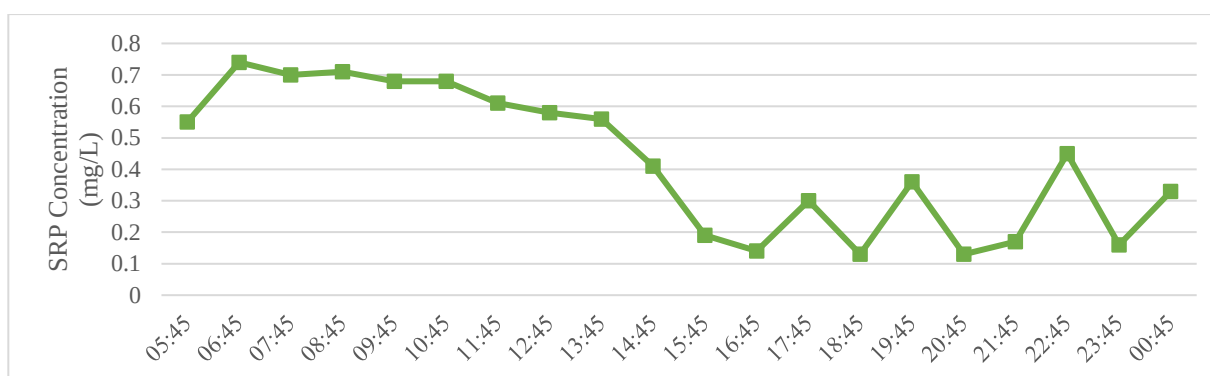


Figure 7-14: Variation of SRP concentration at Bo 10 during the 19 July 2019 storm

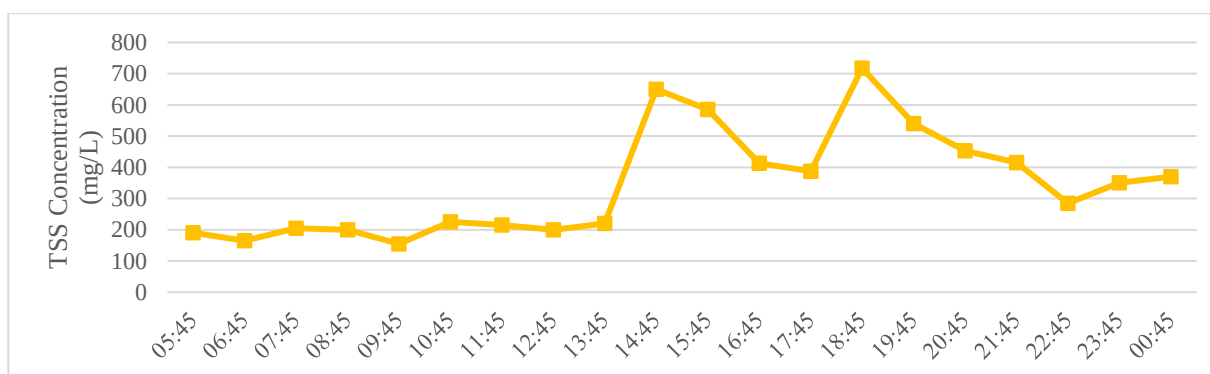


Figure 7-15: Variation of TSS concentration at Bo 10 during the 19 July 2019 storm

The most apparent trend with the nutrients TIN and SRP was the continuous decline in concentration during the storm suggesting dilution. A comparison that was drawn between the nutrient graphs and the TSS graph is the time of the increase in their concentrations. The TIN and SRP concentrations increased first as these pollutants were dissolved and thus in the water column. Alternatively, suspended particles in the stream increased in concentration with an increase in flow rate in the stream, explaining the later increase in concentration compared to the other two. It can also be seen that the pollutant concentrations varied throughout the storm, showing the heterogeneity of the measurements and wash off in the catchment (Figure 7-14).

7.3 Water quality model

EMC wash-off modelling was chosen to represent the water quality component in the model. The EMC wash-off parameters were estimated using measured water quality data from the Bongani River. These EMC estimates were compared with values from the literature to ensure they were comparable and not excessively different.

The pollutants selected for the water quality model were TN and TP. These pollutants were selected because of the Ashmead Channel's nutrient enrichment problem. Furthermore, published pollutant EMCs were available for these two nutrients enabling the comparison between the estimated and existing parameter estimates. The water quality data were measured as concentrations of different pollutants at various locations in the Bongani River catchment. Each site location where samples were collected and tested comprised a unique combination of upstream land uses, which was helpful when estimating the water quality modelling parameters.

The EMC parameter estimates for TN and TP were calculated by dividing some sample sites into particular land use groups and associating at least one sample site with each group. This allowed the water quality data from these sites to reflect the characteristics of their respective land use groups. The global-scale or general land use map was based on the high-level land use map used for the runoff characteristics (Section 6.2.6) and entailed joining land uses that were presumed to have similar water quality. The general land use map was also used to model fewer water quality parameters, thus reducing the model's complexity. The water quality data from the selected sample sites were then organised so that their data could resemble an EMC of one of the land uses from the generalised land use map (Figure 7-16).

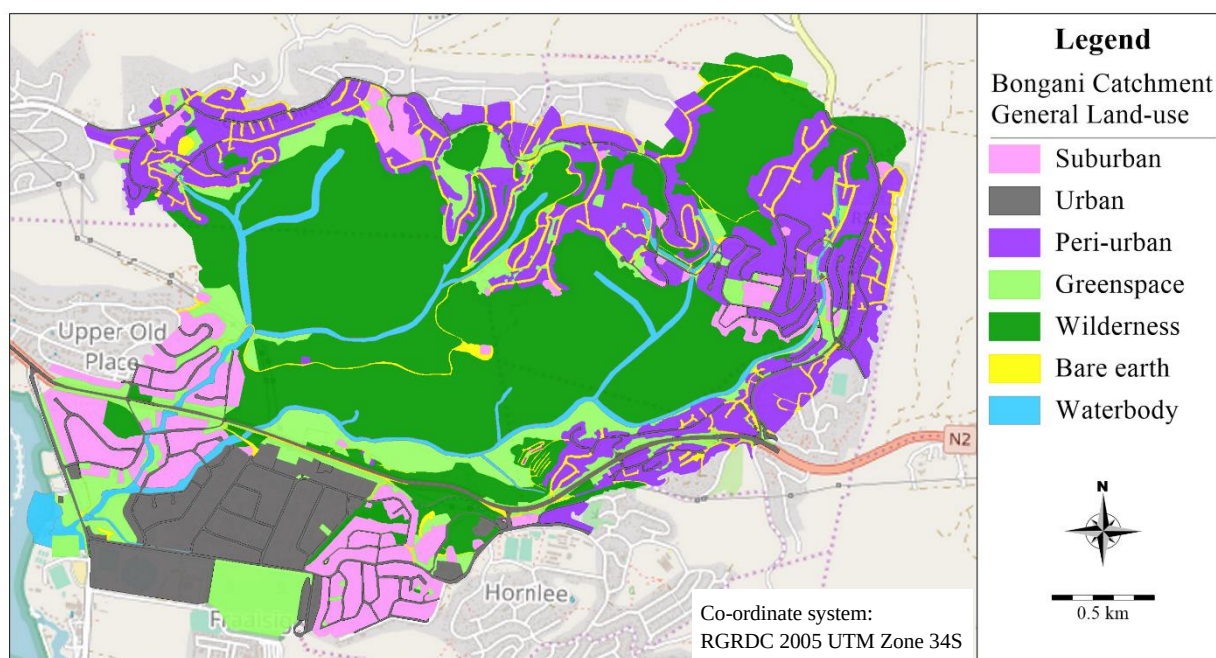


Figure 7-16: General land uses of the Bongani River
(Google, 2020; PCSWMM, 2020; Bing Map roads, n.d.)

The EMC parameter estimates for TN and TP were compared with the published EMCs, and the EMC parameters estimated for the Bongani River were slightly higher than most published figures. The estimated parameters were, however, within the parameter ranges provided by Coleman (2001), who published wash-off data for the South African context. Four critical steps followed in the development of the water quality model:

- i) A Bongani River water quality database was tabulated in Microsoft Excel for each of the sample sites that were determined to be representative of a particular land use based on the land use upstream of the respective sample site. It was made up of data collected with KBP and data collected during storm events.
- ii) A summary of the water quality database, which was made up of the data for the respective sample sites selected for each land use group, as shown in Table 7-4 for the Bongani River, was created for the Total Nitrogen (TN), Total Phosphorus (TP), Ammonium, Nitrites, Nitrates, and Soluble and Reactive Phosphorus (SRP) as well as TSS values. The extreme water quality measurements were omitted. These extreme values were removed to remove the known sewage overflow events from water quality parameter estimates for the various land uses, preventing such data from being represented in the EMC parameters.

Table 7-4: Land use group composition and the sites used to represent them

Land use group	Land uses in the group	Representative sites
Urban	Roadways (paved), Commercial, and Industrial	Bongani 12 – Vigilance Canal
Suburban	Education, Institutional, and Formal Residential	Bongani 7 – Concordia Stream
Peri-urban	Semi-formal Residential and Informal Residential	Bongani 10 – Bongani River
Bare earth	Roadways (unpaved) and Bare earth	Bongani 8A – Joodse Stream Bongani 9A – Kanonkop Seep
Green space	Parks and Recreation Open, Alien, and Shale Fynbos	Bongani 2 – Bongani Settlement Bongani 4 – Heidevallei
Pervious	Sand/Sandstone Fynbos, Afromontane Forest, and Dense Alien vegetation	Natural TN, TP, and TSS estimates from literature
Stream areas	Streams, wetlands, and other water bodies	No build-up and wash-off assumed

- iii) The parameters from water quality modelling literature were then summarised by grouping the EMC estimates, allowing for measured EMCs from the water quality database summary to be compared with the mean of the EMCs from the literature; in the case of TSS, the literature EMCs were used for scaling.
- iv) The summary of the water quality database provided the factors used to convert inorganic nutrients to total nutrients. Each of the nutrient's water quality parameter's EMC wash-off coefficients was estimated differently:

- Only eight samples were collected for TN, primarily due to the time and budget required for measuring it. Therefore, because of the small amount of data available, a single conversion factor was used to convert Total Inorganic Nitrogen (TIN) data to TN EMCs. This factor was calculated as a ratio of TN to TIN with a value of 1.4.
- 62 samples were collected and tested for TP. Therefore, because more data was available compared to the number of TN samples collected and tested, unique factors were used to convert SRP measurements to TP EMCs for the different land use groups. The factors used were the ratio between SRP and TP at the respective sample sites and were based on the ratios between the measured SRP and TP values. These factors were then used to scale the SRP measurements taken at all the sample locations up to a representative TP EMC for each land use group (Table 7-5).

Table 7-5: The factors used to scale TIN and SRP to TN and TP EMCs for the model

Pollutants	Urban	Suburban	Peri-urban	Bare earth	Natural
TIN	4.0	4.7	12.4	4.8	2.5
Factor	1.4	1.4	1.4	1.4	1.4
TN	5.6	6.6	17.4	6.7	3.5
SRP	0.26	0.50	1.18	0.26	0.22
Factor	8.3	5.6	4.6	5.0	4.2
TP	2.1	2.8	5.5	1.3	0.9

- v) For TSS, data was only collected from the three flow sensor sites and were measured *ad hoc*. Because of the lack of data available for the whole catchment, the measured TSS data from the four sites were scaled using a fraction (each land use's mean published TSS EMCs divided by the sum of the published TSS EMCs) that was multiplied by the number of land uses to get a factor. The factor was then multiplied across the measured TSS data to get TSS EMCs for the different land use groups.

Of the three pollutants modelled, TN and TP were seen as the most critical indicators affecting Ashmead Channel's nutrient enrichment. These two nutrients, for which at least twelve months of reliable nutrient data were collected, were thus prioritised in the water quality model. The final estimations for EMCs for the model used the method described above using the water quality data that was collected from across the Bongani River catchment. Furthermore, the estimated EMCs were compared with published values, and it can be seen in Table 7-6 that the EMC estimates from the Bongani River catchment, besides for the pervious land use group, were elevated in contrast with mean EMCs from the literature.

Table 7-6: Estimated wash-off EMCs compared to mean literature values

Land use group	Literature mean TN (mg/L)	EMC -TN (mg/L)	Literature mean TP (mg/L)	EMC -TP (mg/L)	Literature mean TSS (mg/L)	EMC -TSS (mg/L)
Urban	2.84	5.6	0.47	2.1	266	470
Suburban	2.92	6.6	0.49	2.8	273	571
Peri-urban	4.33	17.4	0.54	5.5	662	1470
Bare earth	3.14	6.7	0.41	1.3	396	761
Green space	1.89	3.5	0.22	0.90	134	176
Pervious	0.50	0.5	0.13	0.13	21	21.3

The TN and TP EMCs were then inserted into the calibrated hydrological model of the Bongani River catchment. The following step incorporated modelling a scenario representing, as best as possible, the conditions in the catchment that existed before its development and involved using the Green Space and Pervious EMCs given in Table 7-6. Finally, scenarios incorporating SuDS strategies that could be implemented in the catchment to improve the water quality in the model of the Bongani River were investigated. Details of these various stormwater management scenarios, including the Current Scenario, are elaborated on in the following chapter.

8. Stormwater management scenarios

This section is about the SuDS intervention scenarios developed for the hydrological model of the Bongani River. The method followed in this component of the research is presented in Figure 8-1 was adapted from the method provided by Armitage *et al.* (2013), Woods-Ballard *et al.* (2007), and Wilson *et al.* (2004).

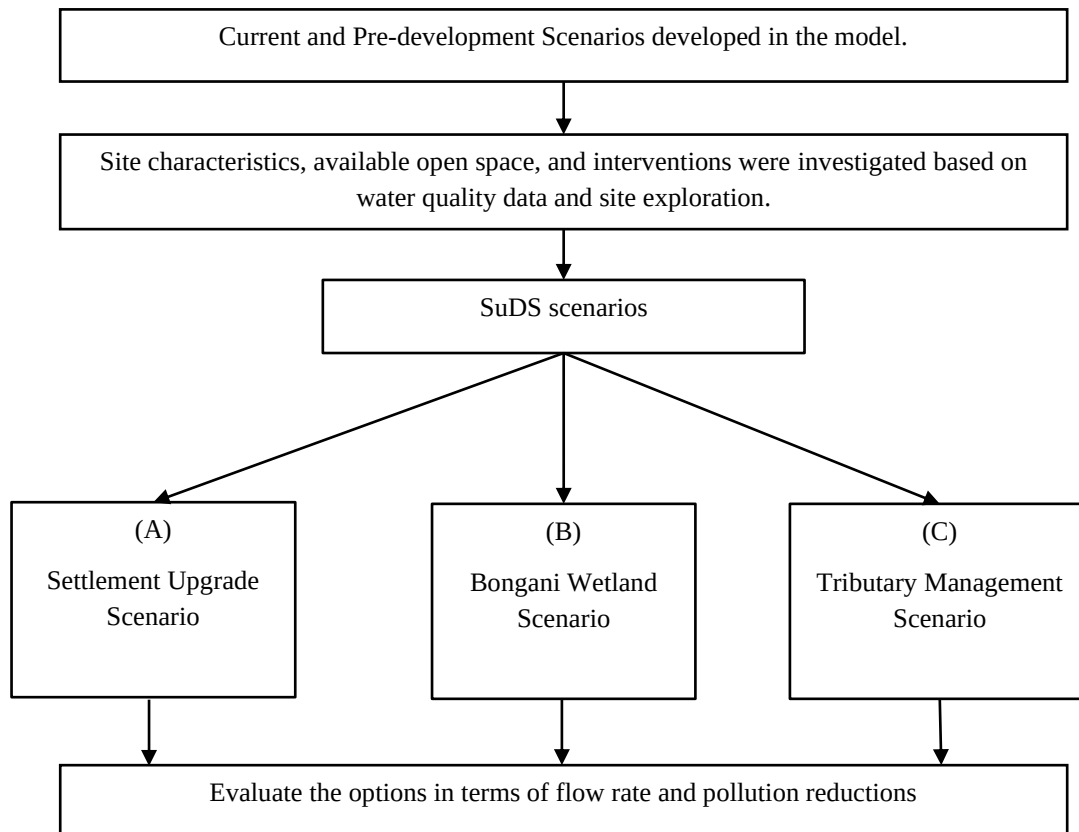


Figure 8-1: Method followed in the development of the SuDS intervention scenarios

Several of the SuDS interventions considered were recommended for improving the Bongani River's water quality. However, not all of the recommended SuDS interventions were modelled due to their complexity. The key water quality problems that were identified during the research project included the following:

- Point pollution sources such as sewage overflows at points where the sewer goes from being at a steep gradient to a flatter gradient at a manhole which causes the overflow, as well as sewage overflows at pump stations when they are occasionally non-functional, as shown in Figure 8-10.
- Diffuse pollution sources such as the litter, particulates, and nutrients accumulating in stormwater (Figure 8-3); wash-off from impervious surfaces such as the N2 and the Knysna Industrial area; and as faecal pollution from sub-serviced settlements and livestock.



Figure 8-2: A manhole sewage overflow problem at a gradient transition



Figure 8-3: Diffuse source pollution visible by the foam formed due to excessive nutrients and detergents/ soap in the water

The following sections describe the various scenarios developed in the model, beginning with a section about the Current Scenario of the Bongani River Catchment.

8.1 Current Scenario

The Current Scenario is based on the hydrological conditions with a 20-year timeseries, hydraulic network as of 2020, and water quality components that were incorporated in the base model of the Bongani River catchment from measurements taken between 2019 and 2020 (Figure 8-4). The final model included 78 sub-catchments, connected by a dendritic network of 110 junctions, three storages, and 116 conduits that interlinked and merged to the outfall which drained freely into the Ashmead Channel.

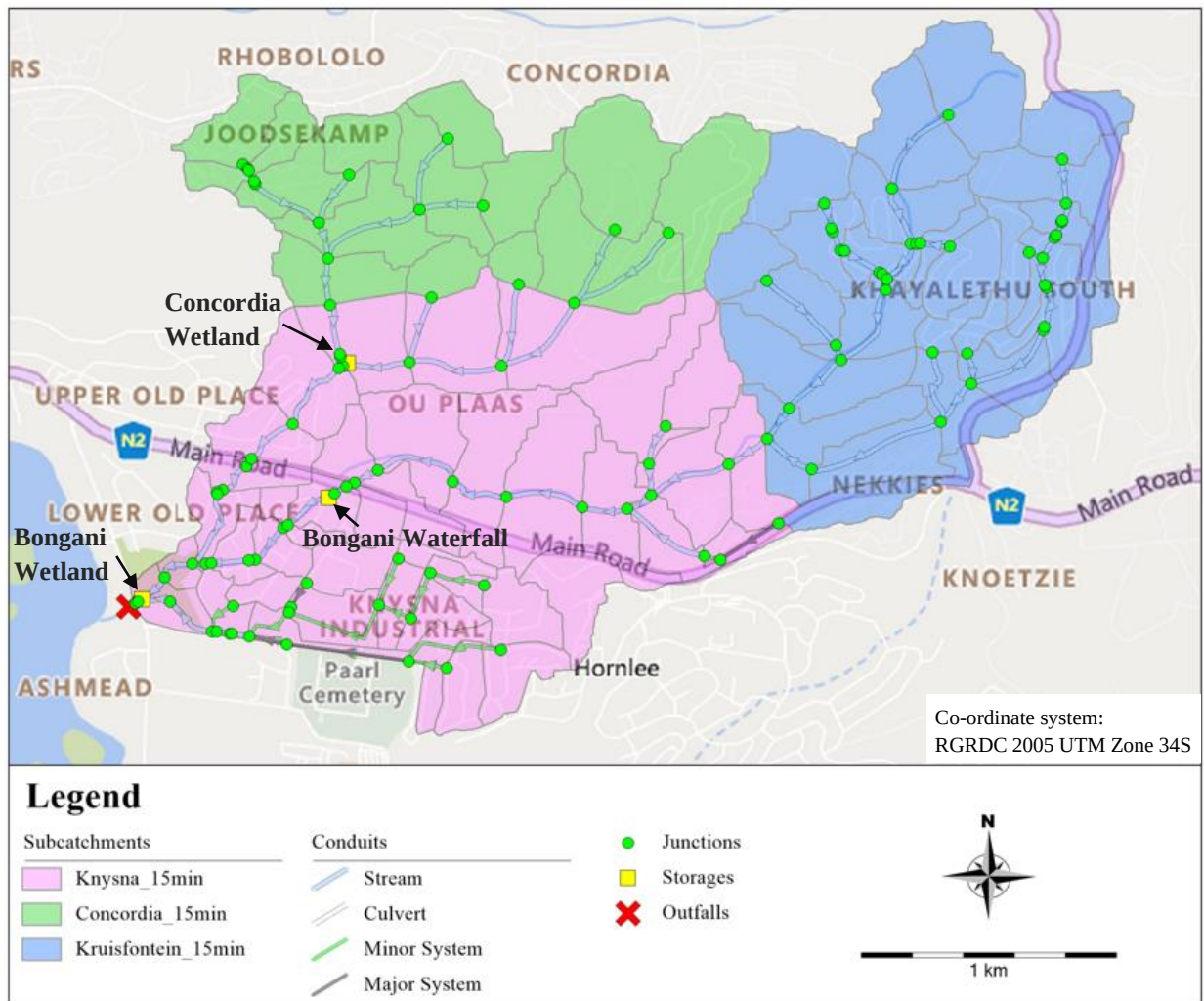


Figure 8-4: The hydrological model of the Bongani River's Current Scenario
(Bing Map Roads, n.d.)

Figure 8-4 shows the relative cover of the rain gauges in the model, and the conduits, junctions, storages, and outfall. There were three storage components in the Current Scenario model: the Concordia Wetland, the Bongani Wetland, and the Bongani Waterfall. The Concordia Wetland is an extensive reed bed – located above Ou Plaas in Figure 8-4 – whereas the Bongani Wetland is more like a vegetated retention pond almost completely filled with sediment.

8.2 Pre-development Scenario

The Pre-development Scenario aimed to represent, as closely as reasonably possible, the likely state of the Bongani River catchment before human development. The Pre-development Scenarios served as an idealised best-case situation for comparing with the current and proposed scenarios. It was modelled by assigning similar hydraulic and water quality parameters to those of the natural vegetation types of the Current Scenario. The resulting pollutant loads predicted by the model indicated the likely water quality before development. Figure 8-5 shows the vegetation types used for the sub-catchments in the Pre-development Scenario.

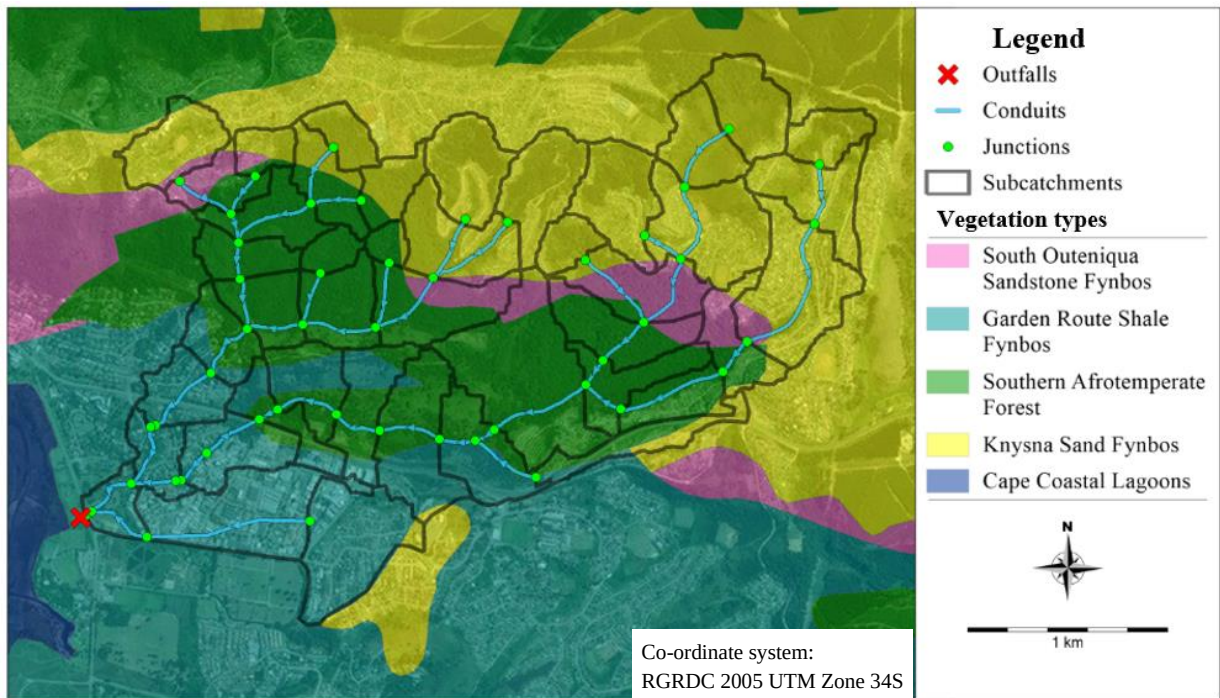


Figure 8-5: Vegetation types used for the pre-development scenario
(Bing Map Satellite, n.d.)

The parameters of the conduits of the Pre-development Scenario had Manning's roughness coefficients similar to those assigned to the natural stream sections in the Current Scenario.

8.3 Site characteristics and available open space

The current land use in the Bongani River catchment includes the following:

- Low-income settlements in the higher elevation areas in the north-eastern parts of the catchment, where the headwaters of the tributaries of the Bongani River and Old Place Stream are located.
- The Bongani River and Old Place Stream's tributaries then flow through Afromontane Forest as they flow through the steeper parts of the catchment.

- The Bongani River flows through the Heidevallei, of which the land use is a mixture of dense and open Afromontane Forest, scattered grassed areas and the Knysna Green Waste Site and Reservoir before it flows beneath the N2.
- Once the Bongani River crosses beneath the N2, it enters the Lower Old Place suburb, a formal residential area.
- The Old Place Stream flows from the Afromontane Forest before flowing through both Upper and Lower Old Place, which are formal residential areas, before its confluence with the main tributary of the Bongani River upstream of the Bongani Wetland.
- The Knysna Industrial area is drained by a conventional stormwater system and discharges into the Vigilance Canal, which also contributes to the current Bongani Wetland.

Identifying the areas of the Bongani River catchment that contributed significant amounts of pollution was an important aspect of the study. Figure 8-6 shows several of the problem areas identified in the catchment and some locations where there was open space available for SuDS.

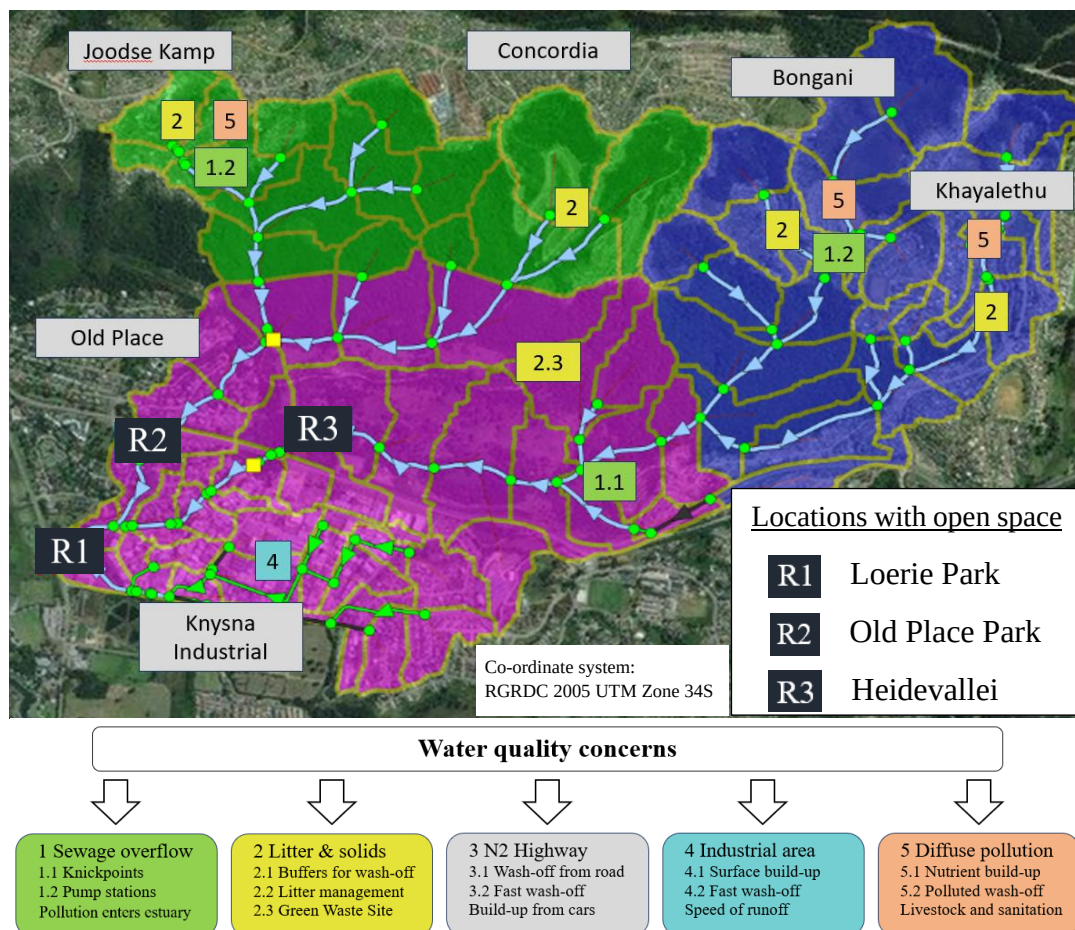


Figure 8-6: Water quality concerns and open space in the Bongani River catchment
(Bing Map Satellite, n.d.)

Available open space was an essential consideration in developing the SuDS interventions. The available open space at Loerie Park (Figure 8-7) is where the existing Bongani Wetland lies and is earmarked as an appropriate site for a considerable regional control. Because constructed wetlands can reduce pollutant loads significantly, this option at the bottom of the Bongani River would contribute significantly to reducing the pollutant load entering Ashmead Channel from the catchment.



Figure 8-7: Open space around Loerie Park, adjacent to the Bongani Wetland

In terms of the streams located in the headwaters of the catchment, there needed to be more open space available for SuDS interventions, which was exacerbated by the presence of existing conventional and informal drainage systems along surfaced and gravel roads alike. Therefore, in the situation shown in Figure 8-8, it would be advisable to first ensure the functionality of existing infrastructure prior to the development of SuDS.



Figure 8-8: The poor drainage of the low-income settlement of Bongani

8.4 Selecting various return period storm events

SuDS design is usually premised on the hydraulic control and water quality treatment of flows up to a specific return period (RP). Therefore, lower RP flows are usually used as the basis of treatment and can inform the sizing of a SuDS. The water quality volume (WQV) is the typical amount of stormwater that needs to be treated by a SuDS and is typically the volume of water associated with a 6-month RP storm event, ensuring sufficient storage volume is provided for water quality treatment. Estimating the WQV for a SuDS site requires the rainfall depth of a particular RP storm. Three methods of acquiring a RP storm depth for calculating the WQV are discussed below:

- i) Using a RP rainfall depth extrapolated from local rainfall records.

This method involved obtaining the rainfall depth for a 6-month RP storm event with the 100-year rainfall records available for the Knysna (TNK) and Concordia (BOS) rain gauges. These two rainfall records were available in the Daily Rainfall Estimate Database File (Design Rainfall in South Africa, 2012). The mean rainfall depths for the 2, 5, 10, 20, 50, 100, and 200-year RP events were provided with upper and lower limits. The 24-hour duration storms for these RPs were graphed, and power function trend lines were generated to estimate the rainfall depth expected for the 1-year and 6-month RP storm events for both rainfall gauge locations. Figure 8-9 shows the curves for the Concordia (BOS) and Knysna (TNK) rainfall gauges.

The mean values of the upper, lower, and median rainfall depths were used to estimate the rainfall depths for the WQV storm event for each rain gauge using Microsoft Excel. The outcome of the calculation was that Knysna (TNK) had an average 6-month RP rainfall depth of 39 mm in 24 hours, and Concordia (BOS) had an average 6-month RP rainfall depth of 43 mm.

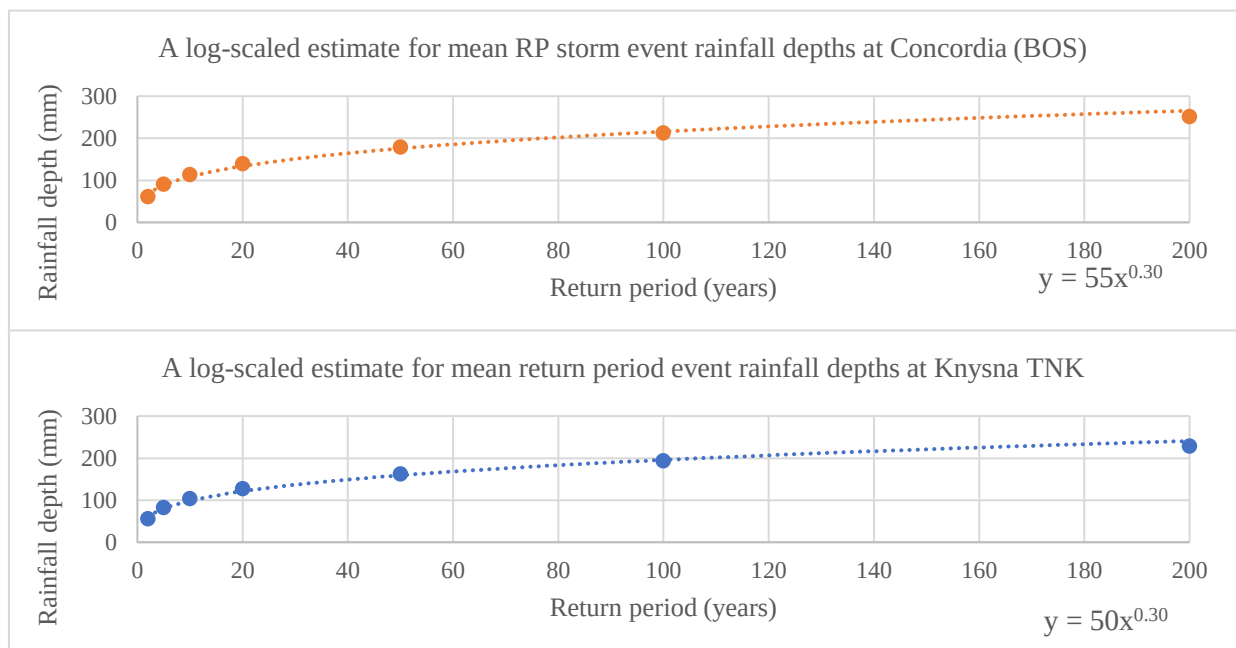


Figure 8-9: Variable RP 24-hour duration rainfall depths for Concordia and Knysna

The 1-year RP storm event rainfall depths estimated from the Knysna (TNK) and Concordia (BOS) rainfall gauges were 48.4 mm and 53.5 mm, retrieved respectively from the functions shown in Figure 8-9. The 1-year RP storm event occurred on the 2nd of January 2008 and was used for sizing the forebays of the modelled SuDS interventions.

- ii) PCSWMM generated RPs for the maximum rate of rainfall or flow rate from a set of defined events.

PCSWMM has the capability of auto-selecting storm events from a time series. Furthermore, modellers can use PCSWMM to generate values for various RPs from the storm events auto selected by the software. The period of the storm events selected by PCSWMM can be edited to ensure that both the system's rainfall and flow rate peaks are captured in the event initially auto selected by the software.

The PCSWMM Events Creation tool was thus used to auto select 2000 24-hour duration storm events from the Knysna (TNK) rainfall gauge, representing roughly 100 events per year from the historical rainfall timeseries. Once there were storm events from each of the 20 years of the rainfall time series, the Interpolate Event Return Periods tool was used. The tool estimated values for various RPs for the maximum rainfall intensity and maximum runoff flow rate based on the Gringorten Plotting Position Formula, which was the PCSWMM default.

In this study, two model outputs from the Interpolate Events Return Period tool were considered for estimating the rainfall depths for RPs ranging from the 1-month to 20-year storm events. The outputs were the maximum rainfall intensity and maximum runoff flow rate. Both of these outputs were used to determine the RP storm events, even though it is customary to use the runoff volume to design SuDS for water quality treatment (Armitage *et al.*, 2013). After that, the runoff volumes for the respective RP storm events were obtained from the model, given that the flow volume from a 6-month RP storm event typically represents the optimum size of a SuDS intervention (Woods Ballard *et al.*, 2015), particularly for the objective of water quality treatment. The total rainfall of these storms was then compared with the 6-month RP rainfall depths calculated in MS Excel in method (i).

- iii) Thirdly, an 85th or 90th percentile storm could be selected in terms of the runoff total to define a storm event likely to carry a large portion of the annual pollutant load.

The Green Building Council (US) (2021) provides an Excel spreadsheet tool called the LEED v4.1 Rainfall Events Calculator, which calculates percentile rainfall depths. The rainy days of a rainfall time series are inputted into a table and used to acquire the 85th and 90th percentile rainfall depths. This method assumes that storms were fully contained between the daily recording intervals.

The outcomes of the three methods are summarised in Table 8-1, which provides the management objectives used in the design of the SuDS interventions in the following section.

Table 8-1: Candidate design storm events for the Bongani River at its outfall

Management objective	24-hour storm label	RP value from PCSWMM	Date (dd/mm/yyyy)	Max rain intensity (mm/hour)	Total rain (mm)	Total runoff (ML)	Maximum runoff rate (L/s)
Water quality volume	85 th percentile	20.1 ML	22/10/2010	9.03	17.5	20.1	3270
	90 th percentile	27.1 ML	29/11/2008	10.3	26.8	27.1	3400
	6-month maximum runoff	7750 L/s	11/07/2010	20.3	57.5	79.0	7740
			21/09/2019	19.7	28.3	38.2	7770
	6-month maximum rainfall intensity	20 mm/h	23/07/2006	20	36.4	50.4	7820
Channel protection volume	1-year total rainfall	52.2 mm	02/01/2008	20.9	52.2	71.0	8240
	1-year maximum runoff	9530 L/s	08/10/2017	26.6	46.7	58.9	9730
	2-year maximum runoff	12,400 L/s	08/06/2003	31.6	41.0	55.9	12,300
Minor storm control	5-year maximum runoff	15,200 L/s	05/06/2012	38.4	34.4	48.0	15,200
	10-year maximum runoff	24,700 L/s	06/11/2005	58.1	58.5	80.4	22,800
			08/10/2008	70.3	70.6	96.4	27,400
Major storm control	25-year maximum runoff	41,300L/s	21/12/2004	116	170.	265	53,900

*The storm event characterising the management objective; used for sizing outlets of SuDS intervention

The SuDS interventions modelled were designed using the storm events provided in Table 8-1, the design process was thus iterative, and it was ensured that each SuDS intervention could attenuate and convey these storm events. The largest storm event was considered when developing the SuDS intervention scenarios to ensure sufficient capacity for severe storm events. The 6-month RP storm event has been defined as a target storm for water quality improvement (Woods Ballard *et al.*, 2015; CCT, 2009; South Eastern Councils, 2013). Of the storms given in Table 8-1, the total runoff for the 6-month RP maximum rainfall intensity, according to the 24-

hour storm label, was chosen to establish an estimate for the WQV for the Current Scenario at the locations where SuDS were to be located. This storm was chosen because it overlapped the 6-month RP maximum rainfall intensity and maximum runoff rate calculated by the Interpolate Event Return Periods tool. The 1-year RP storm event flow rate was needed for the sizing calculations of the forebays for the various SuDS interventions. The method used was from Melbourne Water (2005), and an explanation of it can be found in Appendix E.3.

8.5 Recommended stormwater management interventions

Two major concerns were observed during the study, including sewerage pump station failure and sewerage overflows. It should be noted that these concerns were not part of the modelled solutions but that addressing the issues would have significantly reduced the pollutant loading caused by poor infrastructure management and maintenance.

8.5.1 Sewerage pump station failure

The issue of sewerage pump station failure is a concern for the water quality of the Bongani River. These systems do not have overflow ponds or any management systems in place. Therefore, to add a failsafe in the case of overflows, developing prevention measures would help provide technical support with time to fix the pump station. This allows technical support the opportunity to pump the sewage back into the sewer system once it has been fixed rather than letting the sewage flow directly into the stormwater system. An illustration of a pump station failing and overflowing with sewage towards the Joodse Kamp Stream is provided in Figure 8-10.



Figure 8-10: Point source pollution from an overflowing manhole in Joodse Kamp

8.5.2 Sewerage overflows

A recurring issue was manhole overflows during storm events, particularly in the Heidevallei, where steep pipelines change gradient and become flatter. During storm events, sewage overtops these manholes, and raw sewage flows into the stream in overland channels (Figure 8-11). The solution envisioned for these manholes included investigating which of these manholes overflow and determining appropriate management techniques to improve the water quality as best as possible prior to it flowing into the Bongani River.



Figure 8-11: Sewage overflow from a manhole at a change in gradient in the sewerage, flowing overland towards the Bongani River

8.6 SuDS intervention scenarios modelled

This section details the development of the three stormwater management intervention scenarios placed in the Bongani River catchment model.

8.6.1 Settlement Upgrade Scenario

Waste management was seen to be problematic in Knysna and was noticed across the headwaters of the Bongani Catchment (Figure 8-12). The primary waste reclamation site is in the Mossel Bay District Municipality, which is located 100 km west of the town along the coastline.

However, some construction companies and other local businesses are prone to dump locally in open areas like the fringes of streams and undeveloped land. This is likely driven by the costs of transporting their waste to the reclamation site. Moreover, some parts of the poorer communities in the Bongani Catchment's townships do not have formalised waste removal services. An example from Kanonkop is that waste removal services do not drive down the 500m dirt road to service their homes. This leads to solid waste concerns as shown in Figure 8-12.



Figure 8-12: The litter problem in Kanonkop and Concordia

The Settlement Upgrade Scenario was developed as a scenario that represents an improvement to the management of stormwater, sewage, and solid waste in the peripheral areas of the town of Knysna. The sewerage overflow and waste management concerns are two other problems associated with poor water quality stormwater runoff from informal settlements. Other examples include water quality issues linked to poor provision of proper sanitation, the abundance of livestock within informal settlements, and the mismanagement of byproducts from the automotive and other industries. If the municipality addresses these issues at a household level then there is potential to improve the quality of water coming from peri-urban areas. Thus, the Settlement Upgrade Scenario involved the conversion of peri-urban land use to suburban land use to show the achievable water quality improvement if stormwater is managed at a household level.

Two scenarios were developed for the Settlement Upgrade Scenario in PCSWMM. Both alternatives converted the pollutant wash-off parameter coefficients for EMCs from peri-urban to suburban levels. Their differences are described below:

- The first scenario kept the runoff parameters from the Current Scenario.
- The second scenario converted the runoff parameters for the peri-urban areas to mimic those of the suburban areas.

By creating two scenarios within the Settlement Upgrade Scenario, a range of volume, flow rate reductions and pollutant reductions could be found. The range was later compared to the other scenarios.

8.6.2 Tributary Management Scenario

This scenario encompassed the development of a wetland on each of the two primary tributaries that drain from the headwaters of the catchment, namely on the Old Place Stream and the main stream of the Bongani River (Figure 8-13).

Due to the space constraints of the site, different types of wetlands needed to be considered. There was space available for a detention wetland in the suburb of Upper Old Place and was sufficient space to design a constructed wetland in the Heidevallei. Both systems developed incorporated sediment forebays to capture coarse sediment and acted as pre-treatment systems for stormwater before it entered into the main body of the wetlands.



Figure 8-13: The locations of the wetlands modelled for the Tributary Management Scenario

The ponds are upstream of the suburb of Old Place, and the sizes of the ponds are provided in Appendix E. The forebays developed for the scenarios with wetlands were designed with side slopes of 1:3, which was slightly flatter than the 1:2 slope recommended by NCDOT (2014). In addition, a flatter slope is usually easier to maintain and promotes vegetation growth. An overflow depth between the forebay's aquatic berm and the wetland downstream was set to be 0.2 m, which was slightly deeper than the 0.15 m depth recommended by Armitage *et al.* (2013). The forebays were modelled as storages with a tabular storage curve (See Appendix E).

The Old Place Detention Wetland (Figure 8-14) was aimed at providing an offline storage facility for the Old Place Stream. This allowed for polluted water from Concordia upstream to be detained and treated during storm events. It was also designed to throttle overflow during storm event flows. The stormwater in the model was then directed towards the Old Place Detention Wetland, which was placed in the open space in the suburb of lower Old Place through a 0.5 m deep and 0.5 m wide rectangular channel that connects the flow to the detention wetland.

The following areas were incorporated into the design of the Old Place Detention Wetland:

- A temporary wet pool that made up 10% of the total area
- An undulating vegetated bench that made up 50% of the total area
- A temporary storage area for larger storm events that made up 40% of the total area

For the 6-month storm event, the wetland was developed to contain the WQV to a depth of 0.5 m. As a result, the spillway released surplus water from the pond for the larger events and the wetland was able to convey the 20-year maximum storm event flow.

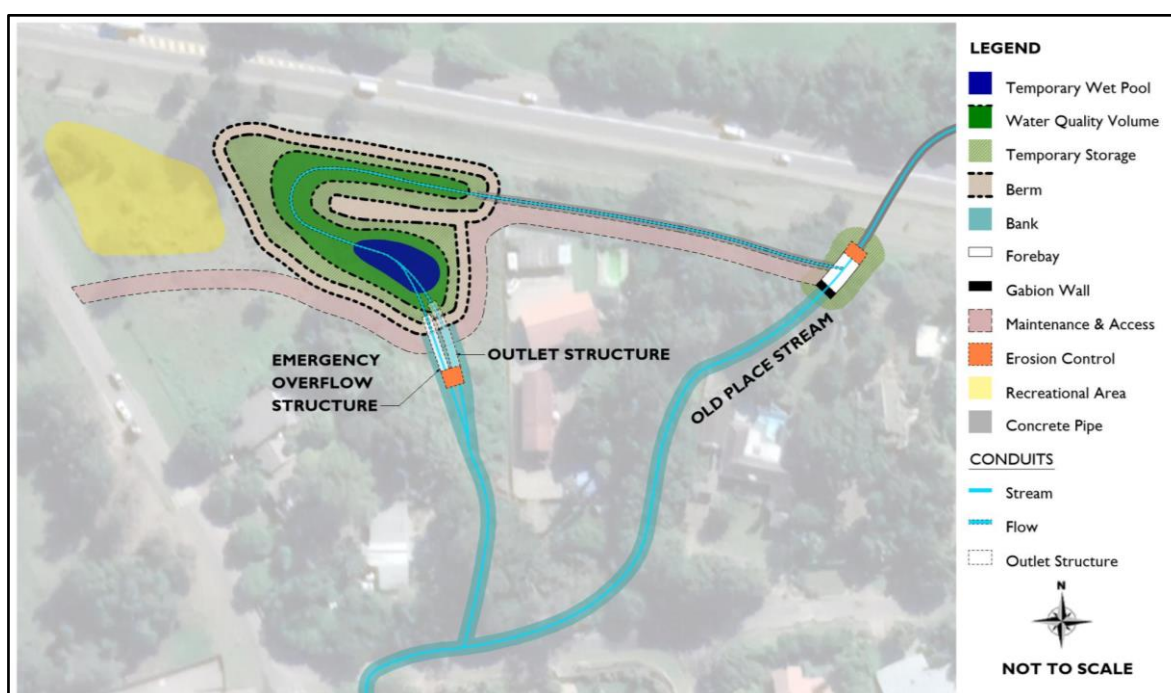


Figure 8-14: The proposed Old Place Detention Wetland

The Heidevallei Constructed Wetland (Figure 8-15) was aimed at collecting the drainage from the Bongani River's major tributary. Initially, the modelling of the Heidevallei Constructed Wetland was considered at two or three locations along the Bongani River tributary, and a site located downstream of sample site Bo 5 in the Heidevallei was chosen. The final location of the Heidevallei Constructed Wetland can be seen in Figure 8-13.

In terms of the sizing of the Heidevallei Constructed Wetland, to cater for the WQV storm event, roughly 1 m of temporary depth would be required if the volume required is to be effectively stored within the system. A spillway would then release surplus water from the pond and was modelled as an overflow weir.

TN and TP removal equations were used for the wetlands and represented the likely water quality treatment range within the model (refer to Table 4-4). These equations were assigned to the relevant storage representing the wetlands in PCSWMM for all the relevant scenarios.

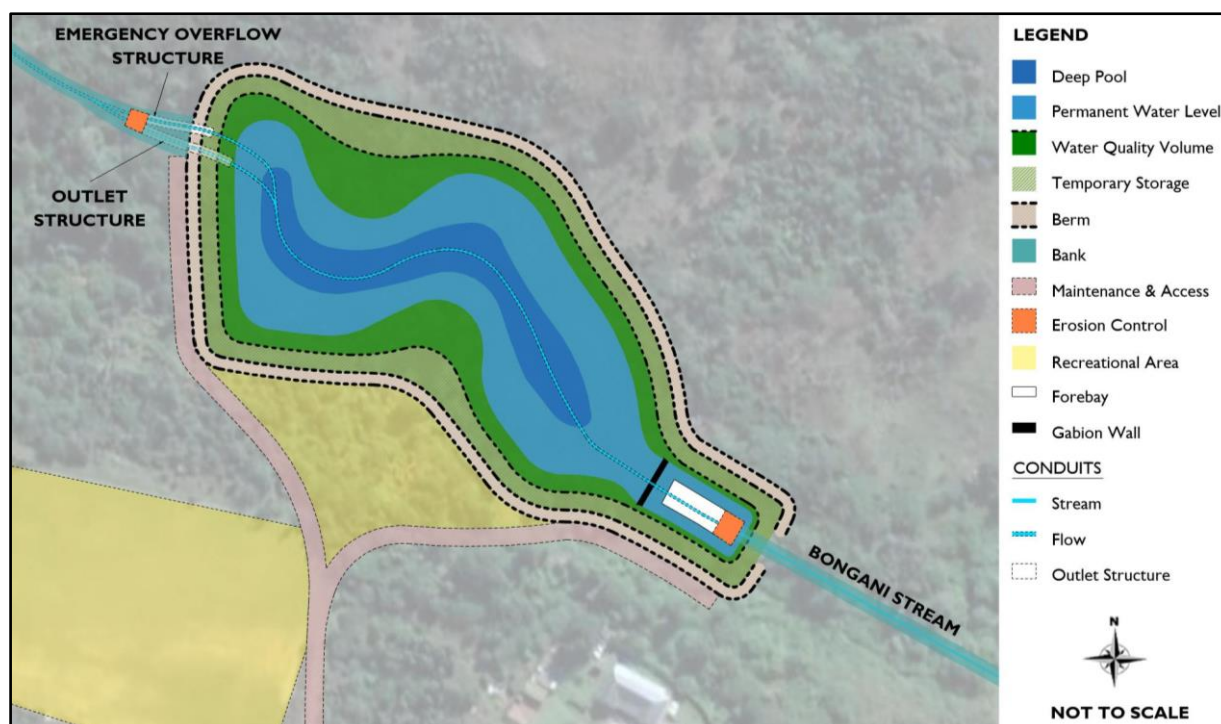


Figure 8-15: The proposed Heidevallei Constructed Wetland

8.6.3 Bongani Wetland Upgrade Scenario

Four wetland solutions were considered at the location of the existing Bongani Wetland for the Bongani Wetland Upgrade Scenario:

- i) The Extended Shallow Detention Wetland option considered creating two detention wetlands, one between the Bongani River and the Vigilance Canal upstream of Bongani Wetland and the other in the open space to the north of the Bongani River (Figure 8-16).
- ii) The Cascading Pond Wetlands Option involved the potential modelling of a series of retention ponds cascading from one into the next for each of the tributaries that flow into Bongani Wetland, namely the Bongani River and the Vigilance Canal (Figure 8-17).
- iii) The Wetland Channel Option involved the potential widening of the current two streams and two meandering wetland systems with long and gradually sloping flow paths that combine in a permanent pool at the site of the existing Bongani Wetland. These systems were envisaged to have baffles along the edges, ensuring a longer flow path which encourages treatment, in contrast to shorter, steeper configurations (Figure 8-18).
- iv) The Bongani Constructed Wetland Scenario, the scenario selected for modelling (Figure 8-19), involved a retrofit of the current Bongani Wetland. This involved modelling two sediment traps which collect particulates from the Bongani River and Vigilance Canal before spilling into a shallow marsh downstream. The shallow marsh links the sediment forebays to the deep pool downstream, and an exceedance channel aided attenuation.

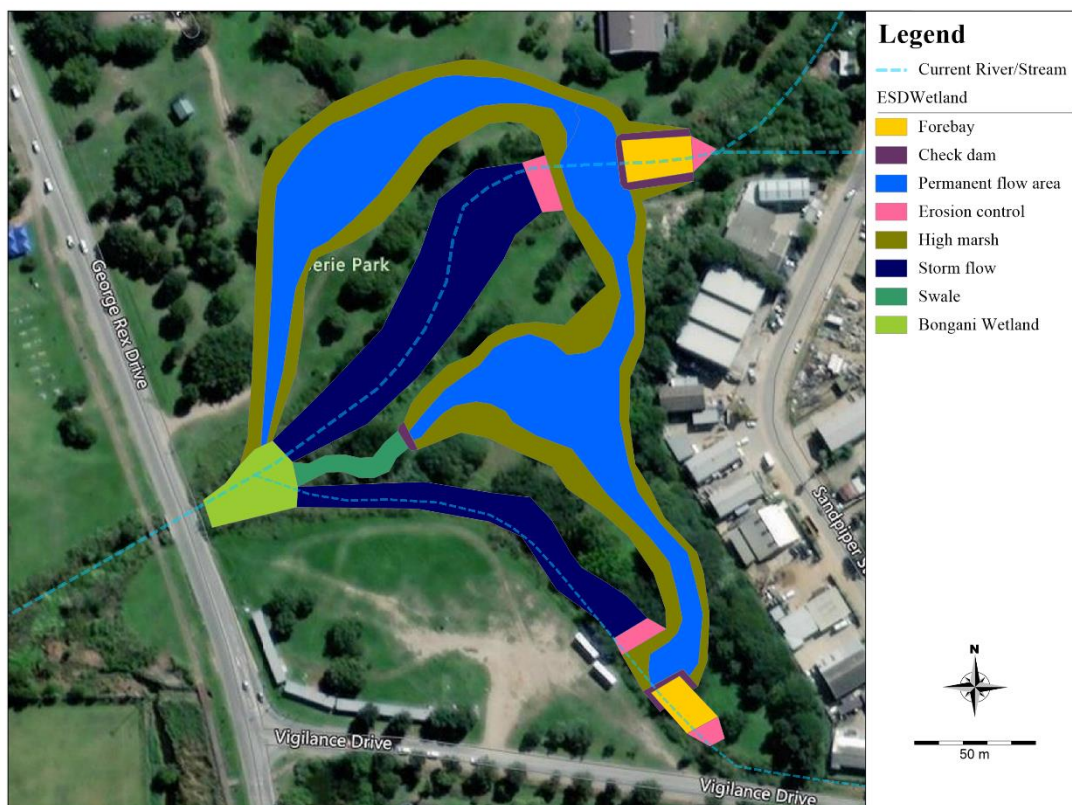


Figure 8-16: The Extended Shallow Detention Wetland option considered

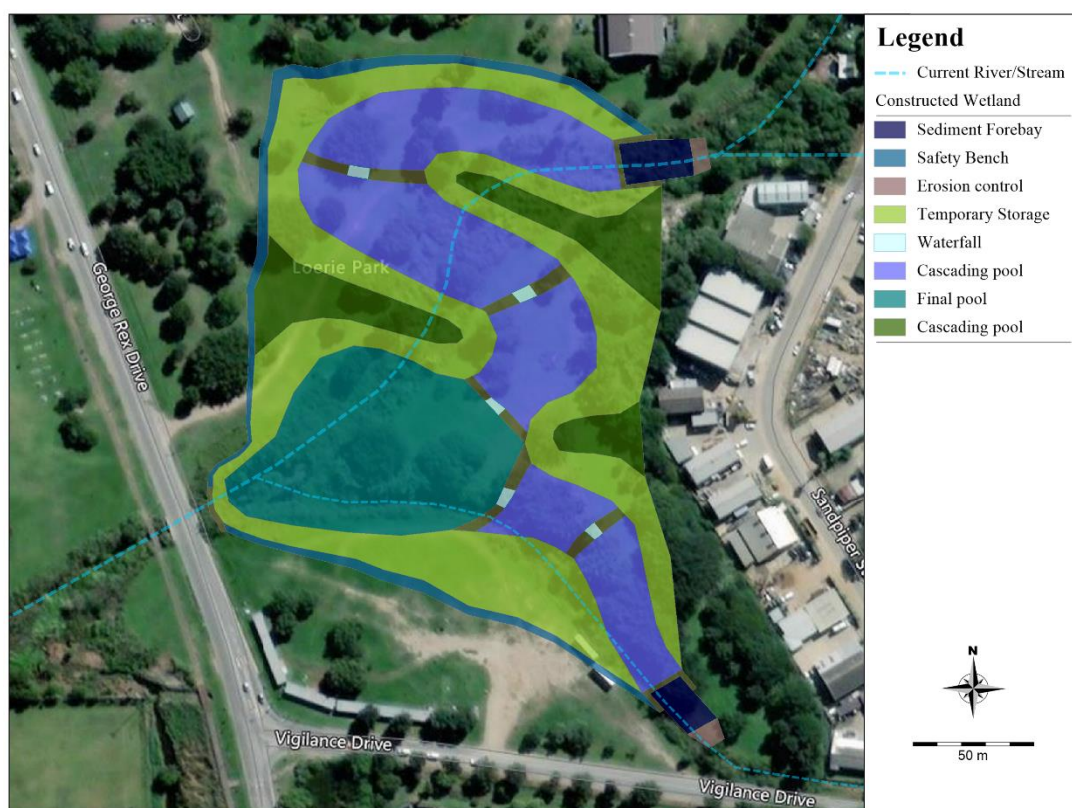


Figure 8-17: The Cascading Pools Wetland option considered

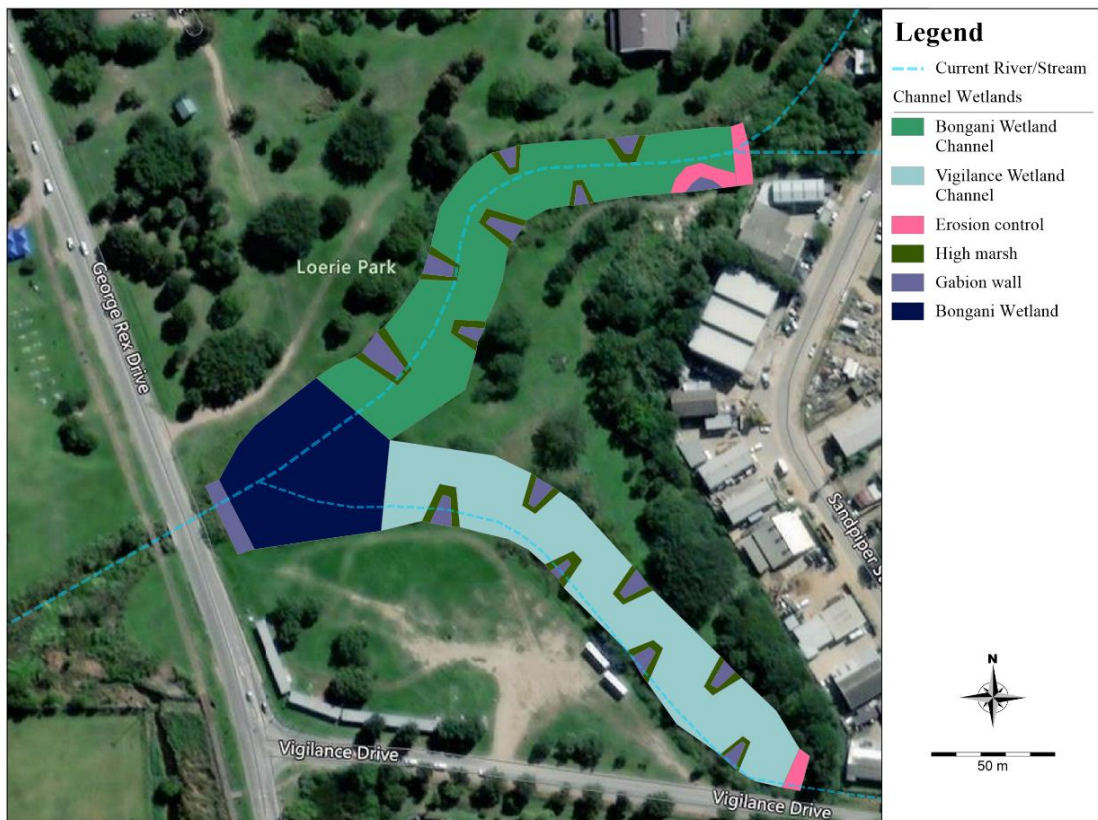


Figure 8-18: The Channel Wetland option considered

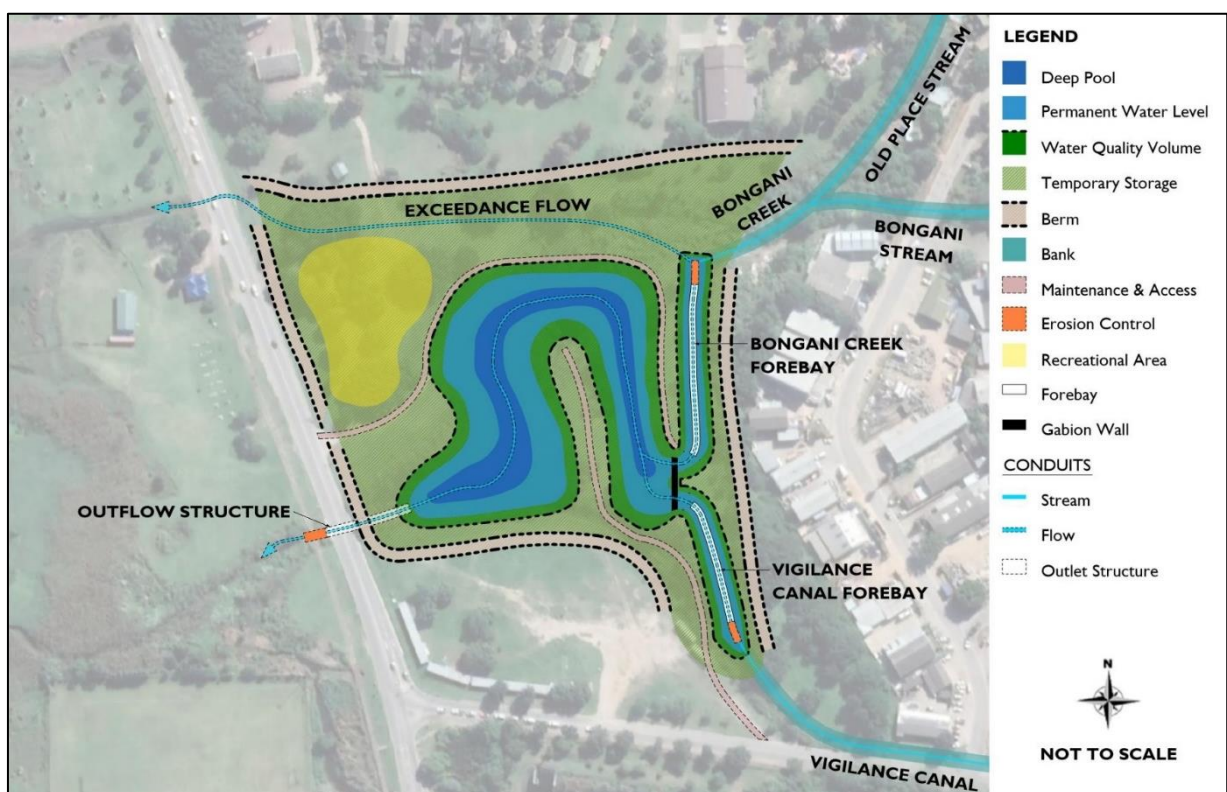


Figure 8-19: The proposed Bongani Wetland Upgrade Scenario

The Bongani Constructed Wetland (Figure 8-19) was chosen for the Bongani Wetland Upgrade Scenario as it was regarded as the most appropriate intervention for the space. The sizing and sloping of the wetland system needed to be considered alongside the forebay at the inflow. NCDOT (2014) recommended that it was reasonable to have 40% of the total area of the system for temporary storage. The total area available was about 36,000 m². This meant that about 14,400 m² was required for temporary storage. The system's outlet was modelled as a submerged weir of width 1 m and height 1 m. A berm was envisioned to surround the system so larger storms could be hydraulically controlled. The system was modelled by assigning Bongani Creek Forebay and Vigilance Canal Forebay as storages, which were drained by trapezoidal weirs. The temporary storage area of the system was large enough to store the WQV calculated at a depth of about 0.5 m. The wetland was designed to accommodate the 85th percentile storm which occurred on the 23rd of June 2002 with a rainfall depth of about 20 mm, a maximum runoff rate of 2400 L/s, and a total volume of runoff equal to 26 ML, according to the model. This event was deemed the WQV event, as drawn from Atlanta Regional Commission (2016).

To ensure that the system could handle a channel protection volume event, a 1-year RP storm event needed to be sufficiently managed in the model. The storm that occurred on the 1st of January 2000 had a rainfall depth of 49 mm. This storm event was hydraulically controlled to a depth of 0.9 m above the permanent pool depth.

9. Results and discussion

This section reports and discusses the results of the SuDS scenarios modelled in PCSWMM. The intervention scenarios aimed to evaluate the theoretical impact of different interventions on the reduction of flow rates, volumes, and loads of TN and TP from the Bongani River.

The Settlement Upgrade Scenario was a transition from peri-urban land uses pollutant EMCs to those of the suburban land use. This represents the potential pollution reduction if sewerage and litter management are improved to levels like those of the suburban areas in the Bongani River catchment.

The Tributary Management Scenario involved managing runoff from Bongani River's major tributaries in two locations, one in the Heidevallei and another in the suburb of Lower Old Place. The Heidevallei option was developed as a constructed retention wetland located on-stream along the main tributary of the Bongani River. On the other hand, the option located in Lower Old Place was developed as a detention wetland and was located off-stream along the Old Place Stream. Identifying a flatter area where the storage of some of the storm flows was key for both the water quality treatment of smaller storm events and the attenuation of larger storm events. In terms of water quality treatment, storing stormwater in a vegetated basin allows plants to absorb nutrients and for the sun to kill pathogens. Thus, by creating areas for stormwater to be detained, water quality improvements will likely be achieved.

The Bongani Wetland Upgrade Scenario involved developing a regional control at the downstream section of the Bongani River, just upstream of George Rex Drive, adjacent to the Bosuns Pub and the Knysna African Crafts Market. There were several options considered for this scenario; however, the Bongani Constructed Wetland was the alternative chosen as the final modelled intervention. The constructed wetland developed included forebays on the Bongani River and Vigilance Canal tributaries. A meander was proposed for the wetland to increase flow length and promote vegetation growth on the banks of the system. It would also likely increase pollutant removal capabilities of the wetland.

The hydrological model of the pre-development, current, and proposed scenarios were run in three distinct ways:

- The long-term 20-year time series simulation was run to compare the different scenarios' maximum flow rates and total volumes.
- Five consecutive 2-year continuous time series simulations were run for continuous water quality assessment.
- The results of a 6-month RP storm event that occurred on the 22nd of September 2019 are presented and show a flow hydrograph and pollutographs for TN and TP at the outflow of the model for all scenarios.

9.1 Flow results of the 20-year time series

The results of the five scenarios concerning total volume and maximum flow rate are provided in Table 9-1. In addition, the comparisons were made to better interpret the volume and flow reductions of the various scenarios modelled.

Table 9-1: Total volume and maximum flow rate for all scenarios modelled (2000-2019)

Model output	Total volume		Maximum flow rate	
Scenario	(Million m ³)	(% reduction)	(m ³ /s)	(% reduction)
Current	29,250	-	32.1	-
Pre-development	2,710	91	20.1	37
Settlement Upgrade	16,040	45	23.1	28
Bongani Wetland Upgrade	6,820	77	9.3	71
Tributary Management	18,880	35	23.4	27

The following was deduced from Table 9-1 in terms of the reduction of flow volume in the model:

- The Pre-development Scenario was seen to produce roughly a tenth of the volume of the Current Scenario – likely because of the differences in their percentage impervious areas, which affect the amount of infiltration and evapotranspiration that would have occurred before the development of the various hard-surfaced areas in the catchment area.
- By upgrading the settlements in the Bongani River's headwaters, the flow volume was reduced by nearly half compared to the Current Scenario.
- By upgrading the Bongani Wetland, a reduction of flow volume by almost 80% was seen in the model. This can be attributed to the infiltration and evaporation of small and large storm events preventing much of the flow from leaving the stormwater system.
- By developing wetlands on the two larger tributaries of the Bongani River, over a third of the flow volume was reduced.

The maximum flow rate occurred during the largest storm event in the 20-year rainfall time series (Table 8-1) during December 2004. The following can be deduced from Table 9-1 in terms of the peak flow rate reduction relative to the Current Scenario at the outflow of the model:

- The Pre-development Scenario peak flow rate was nearly 40% lower than that of the Current Scenario
- By upgrading the settlements in the Bongani River's headwaters, the peak flow rate was reduced by almost 30% relative to the Current Scenario.

- By upgrading the Bongani Wetland, a reduction of flow by about 70% was seen in the model relative to the Current Scenario, which was the largest peak flow rate reduction of all the scenarios. This was likely as it has a larger storage volume than the other scenarios and releases stormwater at a controlled rate near the system's outflow.
- By developing wetlands on the two larger tributaries of the Bongani River, the peak flow rate was reduced by almost 30% relative to the Current Scenario.

9.2 Pollution reduction results

Figure 9-1 presents the results of the pollutant load reductions for total Nitrogen (TN) and total Phosphorus (TP). The pollutant loads for the scenarios were compared with those of the Current Scenario for the ten years between the 1st of January 2010 and the 31st of December 2019.

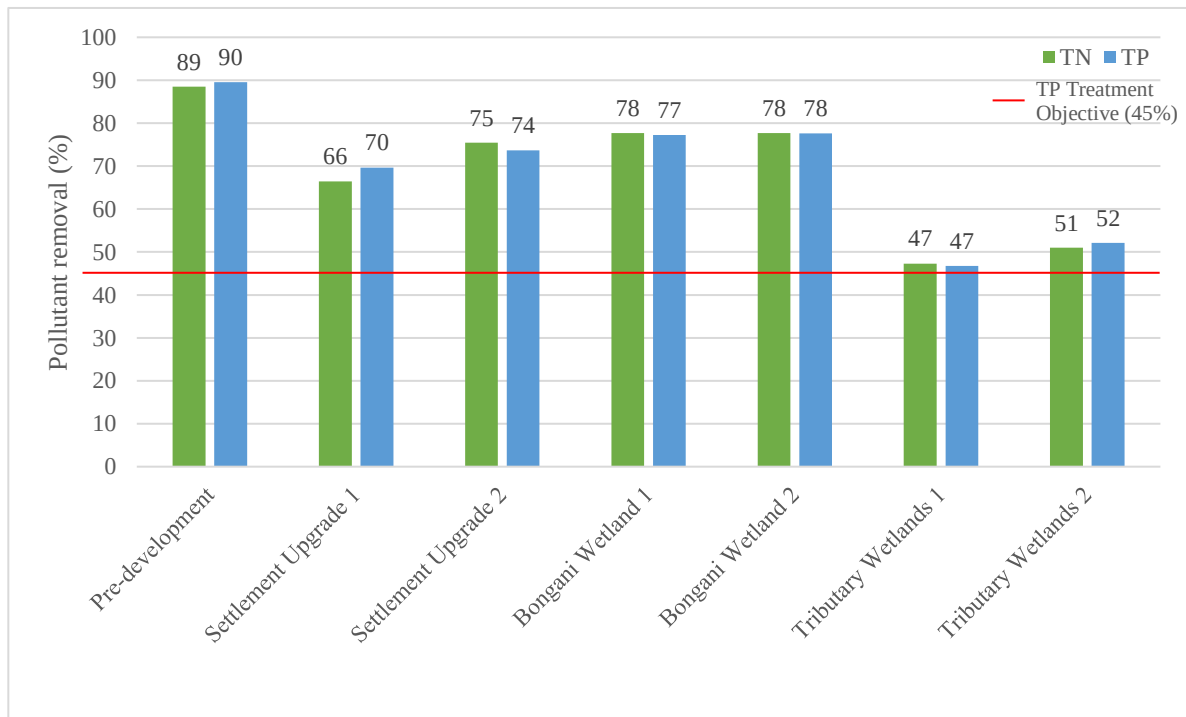


Figure 9-1: TN and TP reduction results for the period between 2010 to 2020

The following describes the pollutant load reductions for the Bongani Streams pollutant load data for the period between 2010 and 2020:

- For both TN and TP, the Pre-development Scenario's pollutant loads were determined to be roughly 10% of those seen in the Current Scenario in the model.
- By upgrading the level of service in terms of stormwater management and solid waste management in the settlements in the Bongani River catchment the reduction was 66-75% for TN and 70-74% for TP in the model.

- By upgrading the Bongani Wetland – the wetland would be wedged between George Rex Drive, the Knysna African Crafts Market, and Bosuns Pub – the modelled pollutant load reduction was 78% for TN and 77-78% for TP in the model.
- By constructing wetlands on the two major tributaries contributing to the Bongani Wetland – the first on the corner of the N2 and Bokmakierie Street on the Old Place Stream and the second on the Bongani Stream upstream of the N2 – the modelled pollutant load reduction was 47-51 % for TN and 47-52% for TP in the model.

9.3 Results of a representative 6-month RP storm event

This section presents the results of a representative 6-month RP storm event that occurred on the 23rd of July 2006. The graphs provided include a flow hydrograph (Figure 9-2), and two pollutographs (Figure 9-3 and Figure 9-4).

The storm event chosen occurred in late July 2006 and was deemed a representative storm event as it had the rainfall intensity and maximum runoff rate of a 6-month RP storm event (Table 8-1). The storm events were organised in Table 8-1 by using the return period (RP) generator available in PCSWMM as well as by graphing the long-term rainfall time series in Microsoft Excel. Figure 9-2 presents the total flow hydrograph for the outflows of the respective intervention scenarios modelled.

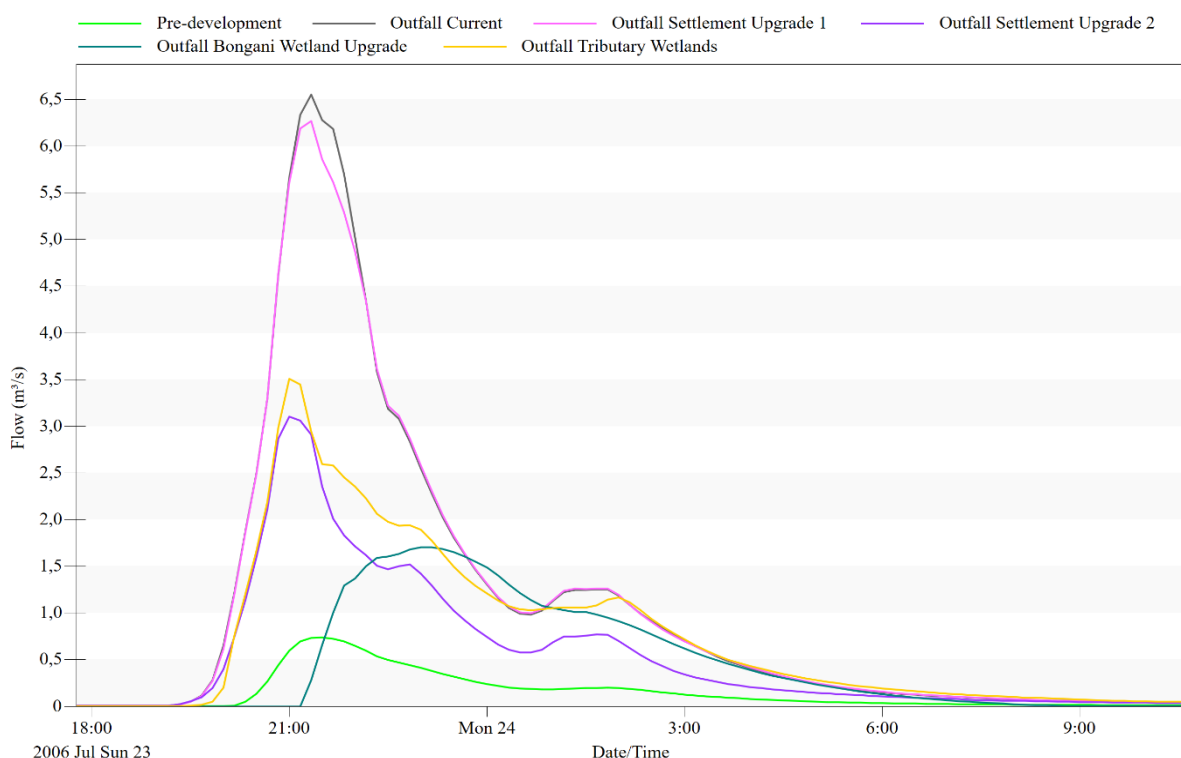


Figure 9-2: Scenario comparison of total flow from the model into Ashmead Channel for a 6-month RP storm event

The following was deduced from Figure 9-2:

- The Current Scenario and the Tributary Wetland Scenario had the highest and longest lasting peak flow through the outfall.
- The Settlement Upgrade Scenario has the next highest flow through the outfall, followed by the Bongani Wetland Upgrade Scenario, which also had a delay on its flow as it contains the initial load within the system for longer than the other scenarios.
- The Pre-development Scenario had the lowest total outflow.

Figure 9-3 presents the TN pollutograph of the various intervention scenarios.

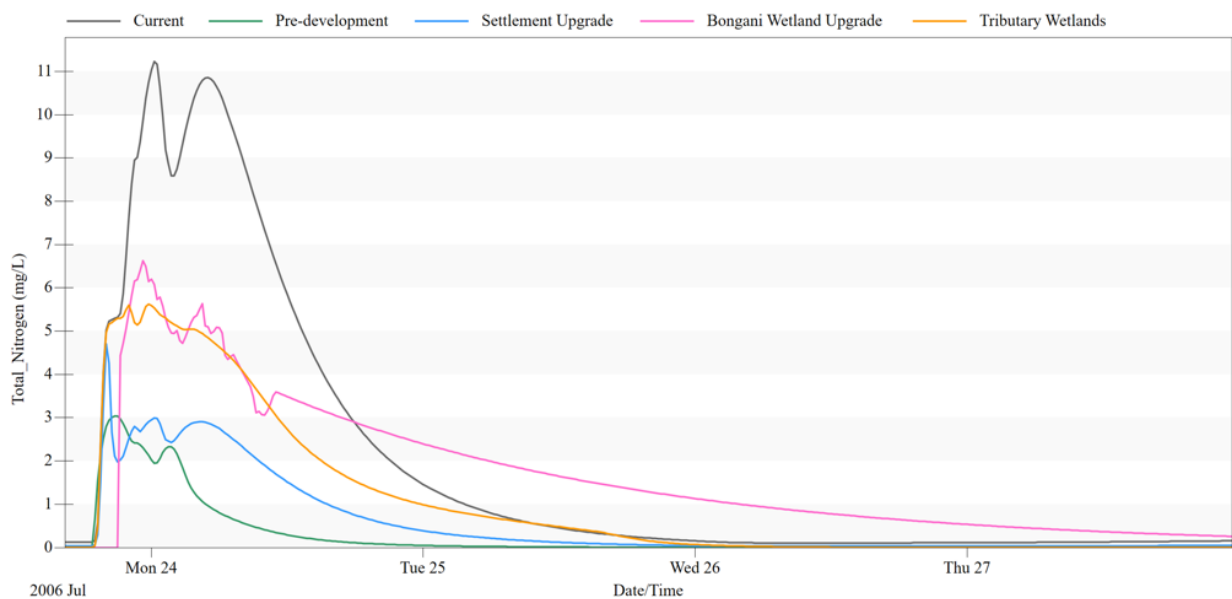


Figure 9-3: TN variation across the scenarios for the 6-month RP storm event

The following was deduced from Figure 9-3:

- The peak TN concentration of the Current Scenario was nearly double that of the second highest peak TN load which was the Bongani Wetland Scenario.
- The Bongani Wetland Scenario and Tributary Wetlands Scenario had a similar TN peak pollutant concentrations. The Bongani Wetland Scenario also had a more gradual reduction of TN in comparison with all of the other scenarios. This can be attributed to the slow release of stormwater from the upgraded Bongani Wetland at a lower flow rate, as shown in Figure 9-2, which also suggests that the Bongani Wetland Scenario would have a lower pollutant load.

- The TN pollutant concentration from the Settlement Upgrade Scenario was similar that of the Pre-development Scenario, although it had a higher peak concentration on the rising limb of the pollutograph.
- Although the Settlement Upgrade Scenario had a significantly lower TN concentration in comparison with the Bongani Wetland Scenario, the Bongani Wetland Scenario had a peak flow rate nearly 70% lower than that shown by the Settlement Upgrade Scenarios flow hydrograph in Figure 9-2.

Figure 9-4 presents the TP variation for the 6-month storm event.

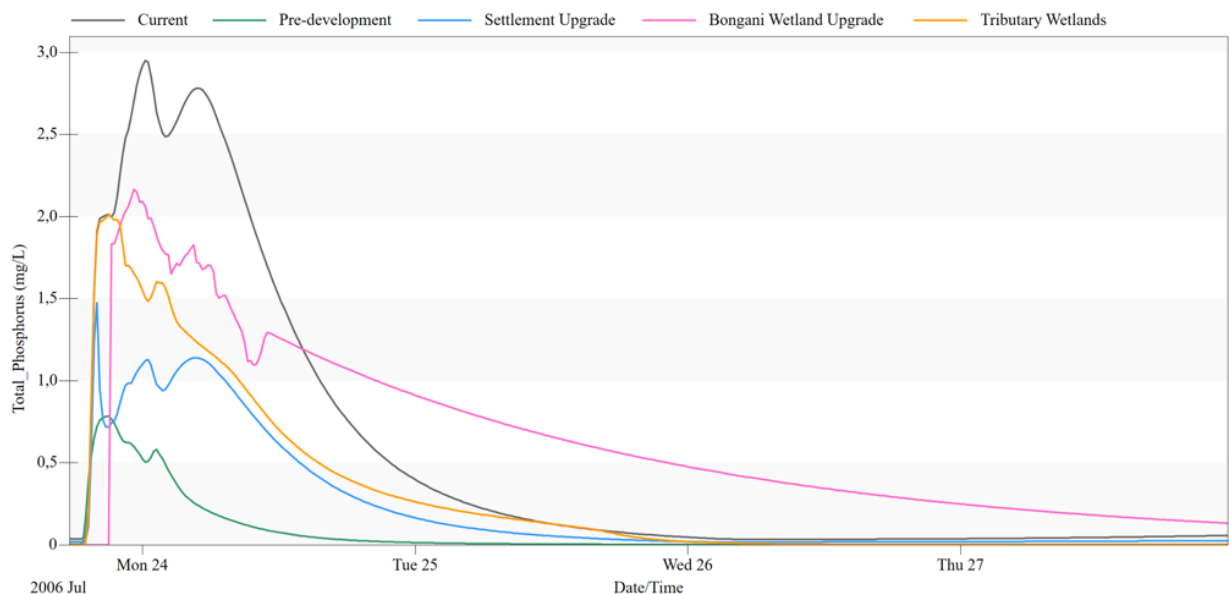


Figure 9-4: TP variation across the scenarios for the 6-month RP storm event

The following was deduced from Figure 9-4:

- The peak TP concentration of the Current Scenario was nearly 50% greater than the peak TP load of the second highest TP load, which was the Bongani Wetland Scenario.
- The Bongani Wetland Scenario and Tributary Wetlands Scenario had similar TP peak pollutant loads; furthermore, the Bongani Wetland Scenario had a more gradual reduction of its TP concentration in comparison to all the other scenarios. This can be attributed to the release of stormwater from the Bongani Wetland at a lower flow rate (Figure 9-2).
- The TP pollutant concentration of the Settlement Upgrade Scenario was the second lowest of all the scenarios modelled, however, due to its peak flow rate and overall flow volume being significantly higher than the Bongani Wetland Scenario in the hydrograph shown in Figure 9-2, it is likely that the TP pollutant loads of the Settlement Upgrade Scenario would still be higher in comparison, as suggested by the results in Section 9-3.

The nutrient reduction of different wetlands varies depending on the HRT of the respective wetlands. Therefore, the treatment function will produce different nutrient reductions depending on the HRT of the wetland being modelled. This is why the nutrient reductions between the Bongani Wetland Scenario and the Tributary Management Scenario in Figure 9-3 and Figure 9-4 differ, because the nutrient reductions are directly influenced by their fundamentally different HRTs. Another comparison between these two scenarios can be seen towards the tail-end of their pollutographs. It can be seen that there is an initial delay in the Bongani Wetland Upgrade Scenario for both nutrients, which may be from the initial storage within the system. On the other hand, the Tributary Management Scenario had a gradual reduction of nutrients from their peak.

10. Conclusions and recommendations

This section provides the conclusions, the limitations and uncertainty within the research, and several recommendations related to stormwater management in the Bongani River catchment. Steps for future stormwater management research for the Bongani River catchment are proposed, and methods that are recommended to be followed for research of this nature are also outlined.

10.1 Conclusions

The following conclusions were made from the PCSWMM modelling of the various scenarios:

- The Pre-development Scenario indicated a significantly lower pollutant load in contrast with the Current Scenario and, besides the objectives in the literature, was the base case that the other scenarios targeted. The reductions for the scenario in terms of flow volume (by 91%), TN load (by 90%), and TP load (by 90%) were lower than the other scenarios modelled; however, the peak flow rate reduction (by 37%), for the largest storm event in the simulation, was the second highest reduction after the peak flow rate reduction by the Bongani Wetland Upgrade Scenario (by 71%). This was attributed to the depression storage of the Pre-development Scenario having a less significant effect on the reduction of the peak flow rate compared with the additional storage capacity provided by the upgraded Bongani Wetland.
- The Settlement Upgrade Scenario, which incorporated improvements to the level of service in the settlements located in the headwaters of the Bongani River catchment, was the second best-performing scenario with regards to the reduction of the total volume (by 45%), TN load (by 66-75%), and TP load (by 70-74%) when compared to the Current Scenario. In addition, the peak flow rate reduction for this scenario (28%) was alike to the reduction shown by the Tributary Management Scenario (28%).
- The Bongani Wetland Upgrade Scenario, which incorporated a constructed wetland with a forebay for each of the two tributaries entering it, was the best performer with regards to reducing the total volume (by 77%), the peak flow rate (by 71%), TN load (by 78%), and TP load (by 77-78%).
- The Tributary Management Scenario, which managed two of the three tributaries of the Bongani River catchment with constructed wetlands, was the worst performer of the three intervention scenarios. Nonetheless, the scenario reduced the total volume (by 35%), peak flow rate (by 27%), TN load (by 47-51%), and TP load (by 47-52%) quite significantly in comparison with the Current Scenario.
- The difference between the two pollutant removal functions, which used pollutant removal coefficients (k-values) of 0.002 and 0.007 for TN and 0.003 and 0.012 for TP, were relatively insignificant for the Bongani Wetland Upgrade Scenario, but some variance was seen in the Tributary Upgrades Scenario.

Developing a future scenario that mimics the performance of natural systems – natural stream and wetland environments – needs to consider more than just flood protection but also the other important roles that stormwater management entails, including water quality, amenity, and biodiversity. SuDS aims to address this flaw in managing current stream systems and their developing catchment areas and should be considered in the development and management of urban environments.

10.2 Uncertainty and limitations

The Bongani River's hydrological and water quality model is a numerical estimation of the processes that occur in the drainage system. The model was calibrated, validated, and verified with observed data, which improved the reliability of the model. However, uncertainty is always present in this type of modelling due to the inherent complexities involved in the stormwater drainage of a catchment. This section discusses both the key uncertainties in this study, which have been split up into (1) uncertainty in data collection and (2) uncertainty in PCSWMM modelling, as well as the limitations that were identified during the research period.

10.2.1 Data collection

The following uncertainties were identified in relation to data collected during the study:

- The collection of water quality data – A grab sample is a single sample of the stream's flow. Although there were twelve months of grab samples available from the various sample sites, the complexity within the flow of the water means that the samples that were taken are only a snapshot in time at the specific locations. Ideally, more samples could be taken from different depths and time intervals to acquire a more accurate representation of the water quality.
- The data collected during storm events – The flow rate data was retrieved using an ultrasonic flow level sensor which measured the flow depth at a point along the stream with an ever-changing floor bed. The error for the ultrasonic flow level sensor was ± 0.5 mm, which correlated to an uncertainty of 0.4% based on the mean value retrieved from the sensors. The distance measured from the flow level sensor to the floor bed of the river cross-section being studied was also a source of uncertainty. The ruler used was estimated to have an uncertainty of ± 5 mm which correlated to an uncertainty of 4%. Furthermore, the Manning's roughness coefficient, slope, cross-section, and wetted perimeter are included in the flow rate calculation, all of which had inherent uncertainty of varying degrees. The uncertainty of the flow rate data used for the calibration of the model was estimated to be about 10%.

10.2.2 PCSWMM modelling

- The rainfall data used in the model – Only one rainfall time series consisted of hourly measurements within the Bongani River catchment. Ideally, this would be a 5-minute time series which, while available from a nearby rainfall gauge, was not incorporated because there was a rainfall gauge within the catchment.
- The parameters used for the sub-catchment and conduit network – The percentage impervious area, Manning's roughness coefficients, depression storage and other inherent parameters chosen to be used within PCSWMM were based on literature values that may not match the local characteristics. In addition, the calibration of the model was also based on measured data. Thus, the calibrated model likely incorporates some of the underlying uncertainty of the measured flow rate data.
- The soil parameters used in the model – In terms of soil types and the infiltration parameters that represent them, the current soil conditions in the catchment are different and no longer represent the soil that once existed in the area. These changes make it difficult to know how the rainfall retention within the soil has changed.
- The water quality component of the PCSWMM model – The parameters used for modelling water quality were created using local samples and literature. This data only represents the grab samples; although they can be extrapolated, the uncertainty of the outputs would be reduced if more samples were taken from sites with specific land uses upstream.

10.2.3 Limitations

The limitations identified during this study include, but are not limited to, the following:

- The development of the SuDS interventions – Many SuDS options were considered for the modelling, but there are many constraints when designing and inputting SuDS in PCSWMM, preventing their further development in the PCSWMM model. Expertise from professionals with experience in the design of wetlands and other stormwater management interventions would also significantly enhance the potential for improving stormwater management within the Bongani River catchment.
- The challenge of measuring water quality in a stream where sewage is entering the stormwater system was noticed when sewage overflows from poorly maintained pump stations or manholes at gradient changes from steep to gradual occurred. These infrastructure breakdowns are usually brought about during storm events when high flows enter the sewerage and cause blockages, which result in overflows into the adjacent stormwater system. The blockages are brought about because of people that add inappropriate items into household sewage drains. Sewage overflows at changes in gradient are the other example where sewage spills occur and are seen where the steeper hills of the headwaters reach a knickpoint representing a change in gradient to a less steep slope. Solids

in the sewage line fill up the manholes. When stormwater intrudes on the sewerage, the manhole is unable to cope with the extra flow rates involved, which in the case of the Bongani River, leads to an overflow of heavily polluted water into the nearest downstream waterbody.

- *E. coli* was not modelled in PCSWMM as a water quality component, even though it was seen to be a considerable concern. This was because it had the least amount of data available but also because very little literature was found regarding EMC loading rates because bacteria are living organisms and their rate of growth cannot be represented by an EMC rate, especially in environments where sewage enters the stormwater system.

10.3 Recommendations

The recommendations to follow relate to the following two issues:

- Recommendations related to the management of stormwater in the Bongani River catchment.
- Recommendations related to the methods used for sampling and testing, hydrological modelling, and the development of SuDS interventions.

10.3.1 Recommendations for the Bongani River catchment

The recommendations for the Bongani River catchment relate to the need for monitoring and maintenance of both the stormwater system and the infrastructure and services in the peri-urban settlements. The recommendations also directly address the need to investigate and implement SuDS in the Bongani River catchment. The following recommendations were identified:

- The need to manage pollution from the peri-urban headwaters was a key concern, but the lack of space limits the types of SuDS that can be included. Instead, a scenario was modelled to assess the possible water quality improvement if the level of service in the lower-income areas was brought up to the standards of the suburban areas in the lower parts of the Bongani River catchment. It was proposed that improving the management and maintenance of services, such as waste removal, would considerably improve the quality of water disseminating from these areas.
- A major problem in the Bongani River catchment was point source pollution from the sewage system, which either overflows at pump stations or manholes. These point source pollution sites were identified at locations where the sewerage gradient changes from steep to gradual in the Heidevallei, but also where the sewerage was poorly maintained or inundated with items that should not be in the sewerage in the first place. Therefore, maintenance of the sewerage and an education plan to inform the community about what should not be released into the sewerage inflows is recommended.

- Upgrading the Bongani Wetland, which is wedged between George Rex Drive, the Knysna African Crafts Market, and Bosuns Pub, was a key SuDS intervention and, based on the results, will significantly reduce nutrient loads.
- Managing each of the contributing streams was also considered an effective way to improve the nutrient loading of the Bongani River. As a result, two sites were identified for SuDS interventions upstream of the Bongani Wetland including a site in Old Place on the corner of the N2 and Bokmakierie Street on the Old Place Stream and another site on the Bongani River upstream of the N2 in the Heidevallei. The Vigilance Canal is the third contributing stream and was considered for the development of a bio-retention area beneath the industrial area; however, it was not modelled because of its overlap with the Bongani Wetland.
- A site beneath Joodse Kamp along the Old Toll Road where two of the Old Place Stream's tributaries merge was also considered for a SuDS intervention but was not modelled. The culverts conveying stormwater beneath the Old Toll Road here have been filled up by sediment, and it is recommended that they are inspected and possibly upgraded.
- Management of biological contamination can be aided in the Bongani River catchment if the sewage infrastructure is improved in the lower-income areas of Knysna's hillsides. However, this involves the responsibility of constructing enhanced sewerage for the area. Therefore, investigation into upgrading the low-income settlements in the Bongani River catchment needs to be prioritised, and possible actions that the Knysna Municipality could take to alleviate some of the impacts of pollution need to be taken. Addressing waste removal and sewerage issues is possible through effective monitoring. However, action is required if the issue of solid waste pollution is to be addressed.

Proposals for future research in the Bongani River catchment include the following:

- Investigations into the impact and management of the leachate draining from the Knysna Green Waste Site in the Heidevallei.
- Fixing the culverts at Bongani 8 on the Old Toll Road, which has filled with sediment, and at Bongani 13 on George Rex Drive, which slope down to the north.
- Reducing the imperviousness of the Knysna Industrial area by motivating private land owners to implement SuDS initiatives can reduce the speed of runoff into the Bongani River. Ensuring that impervious buildings control the runoff escaping their property could significantly reduce the rate of runoff entering the Bongani Wetland from the Vigilance Canal whilst also reducing the pollutant loads from the Knysna Industrial area.
- Two bio-retention pond options were considered. The first is for the flow of the Bongani River as it passes the N2 highway. A major concern about this solution was maintenance access and space. The second was for the runoff from the Vigilance Canal, which drains the Knysna Industrial area; however, it lacked the necessary space.

Regarding the results of the SuDS intervention scenarios, the Bongani Wetland Upgrade Scenario, followed by the Settlement Upgrade Scenario, had the most significant reduction in nutrients TN and TP in the model. Although the proposed scenarios did not reduce the nutrients TN and TP to levels deemed to the levels seen in the Pre-development Scenario, they were all deemed to be appropriate according to the guidelines both locally (CCT, 2009) and internationally (South Eastern Councils, 2013; Melbourne Water, 2005; Victorian Stormwater Committee, 1999), showing their potential for significant reductions in the pollutant loads entering Ashmead Chanel. Combinations of the different scenarios would undoubtedly have an even greater impact on the pollutant loads, and further investigation is recommended regarding SuDS initiatives in the Bongani River catchment.

10.3.2 Recommendations for similar research endeavours

This section provides recommendations for future research on stormwater systems in terms of sampling and testing, integrated catchment modelling, and SuDS development.

The number of samples that can be collected and tested depends on the funds available; however, the value of the data it provides can be beneficial. Monitoring stormwater systems provides context about potential pollution sources, which can help rapidly address problems.

Integrating hydrological and water quality modelling can help represent the stormwater system and can be useful for interpreting flows and pollutants. Therefore, it is recommended that models be used to evaluate SuDS options so that informed decisions are made regarding drainage infrastructure development. The following specialists are recommended for further investigation into this kind of development: Ecologists; City and Regional Planners, Hydrology, Geomorphic, and Hydraulics Engineers; Developers; and local Municipality and Community Members.

This research focused on the impact of diffuse source pollution on water quality in the Bongani River. Future research that could extend this study would involve understanding the viability of SuDS interventions when exposed to concentrated sewage flows. This could include interpreting if SuDS are effective when receiving highly contaminated sewage and researching the possible modifications needed to address sewage flows.

A more comprehensive understanding of the build-up and wash-off can be established by investigating the amount of time that pollutants accumulate in any respective catchment, land use, or surface and measuring their loads in the drainage system during the first flushing event after the antecedent dry period. This measurement method has been undertaken in the United States of America, where the EPA has been investigating pollutant loading since the 1980s. Their values for build-up and wash-off may not be representative of the South African context, however using their measurements and estimates and then calibrating and verifying this data with measured data from local streams and rivers may provide insights into the local process of pollutant deposition, accumulation, transport, and treatment.

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Appendix A – Research motivations and context

Ensuring clean water and dignified sanitation has the potential to liberate many people in the low-income settlements of the developing world. The current situation for people in these areas is that many of them do not have secure access to basic service provisions which has had – and continues to have – devastating impacts on the people of future generations that will inherit and must manage these degraded and polluted urban spaces. By enhancing clean water and sanitation services in these areas, both in the local streams and ultimately in all the settlements surrounding the Knysna Estuary, there is potential for improvements in the accumulation and transport of poor water quality, which is besides the objective of this study. Stormwater management is one of the components involved in developing sustainable settlements in the headwaters of Knysna and investigating ways to improve the impact that stormwater infrastructure has on communities is what was envisioned in this research. Improving land management is an influential and valuable tool if sustainable change is the aim for the surface water drainage coming from this landscape. This research aimed to understand the best design approaches and solutions for improving the sustainable development and effective management of the Bongani Catchment. The Sustainable Development Goals (SDGs) set out by the United Nations (UN) in 2015, represent the concerns related to the holistic global transition towards sustainable, climate resilient and adaptive communities to promote and create the concept of a sustainable global ecosystem. Furthermore, the principles and tested practices provide a means for bringing the vision of improved sustainable urban development incorporating all aspects of life (United Nations (UN), 2017). Applying the overarching principles of sustainability within the water, urban drainage, and stormwater management domains has an intricate link with climate resilient, safe, and universally accessible green infrastructure. The 17 SDGs are provided in Figure A-1.



Figure A-1: The 17 Sustainable Development Goals (from UN, 2015)

A.1 Sustainable development

The 17 Sustainable Development Goals (SDGs) laid out by UN (2015) all have value in shaping society in a sustainable way. The following primary and secondary SDGs were relevant to the research into stormwater management and the benefits of monitoring of systems like that of Ashmead Basin.

The primary SDGs pertinent to the research on Bongani Catchment include:

- (6) Clean water and sanitation SDG
- (11) Sustainable cities & communities
- (13) Climate action
- (14) Life below water, SDG

Secondary SDGs that have the potential to be influenced by research into stormwater management and green infrastructure development are as follows:

- (3) Good health and well-being
- (8) Decent work and economic growth
- (10) Reduced inequalities
- (15) Life on land

Besides the SDGs, the UN (2017) laid out *The New Urban Agenda* outlining the necessary changes that society needs to make to realise sustainability globally.

The New Urban Agenda represents a participatory, incorporative, and sustainable global vision, one in which all people have equal rights, benefits and opportunities that cities and their surrounding urban environments have to offer. Commitment 119 of the New Urban Agenda focuses on implementing and transitioning toward more sustainable approaches to future urban developments. This report aligns with the following principles outlined by the UN (2017: 119).

- The promotion of adequate investment in protective, accessible, and sustainable infrastructure and service provision regarding water, urban drainage, stormwater management as well as air and water pollution.
- The development of climate resilient, safe, and universally accessible infrastructure which forms part of the integrated urban and territorial development plans. Implementation should be conducted in a participatory manner and the consideration of innovative, resource-efficient, accessible, context specific and culturally and ecologically sensitive solutions.

A.2 Mismanagement of Ashmead Basin: the research context

Besides the goals and visions set out by UN (2015) and UN (2017), investigating sustainable infrastructure initiatives in emerging markets could be an economic stepping-stone for developing cities; particularly in biodiverse settings such as in the case of Knysna. Protecting natural environments from human encroachment has multiple benefits for enhancing tourism, amenity, food security and the potential for sustainable development into the future. Research that links the value of green open space in urban areas and its benefits on the population are thus beneficial for places like Knysna which is known for its unique biodiversity. It is essential to effectively manage urban and rural catchments so that during rainy periods, the stormwater loads of sediments and nutrients entering the estuary are as they were before development of the landscape around it. Mimicking the natural water quality and quantity conditions of the surface water flows into estuary requires redevelopment of the diversity of wetlands and vegetated channels upstream, which once stimulated sedimentation and consumption of the pollutants in the system, ensuring the release of clear water into the estuary (Allanson, 2010).

Human *et al.* (2016) highlighted the major concerns facing the biodiversity of the Knysna Estuary, providing information about the ‘green tide’ which persists in Ashmead Channel. The information relevant to catchment areas that drain into the channel was limited to a note about industrial discharge in the Bongani River. The shortcoming of this is that it did not discuss the health of the smaller streams discharging into Ashmead Channel which are also serious nutrient contributors. Winter *et al.* (2016) noted that there was a need for inquiry into the impact on the hydraulics, water quality, sediment loads and morphology of the rivers discharging into the Knysna Estuary

Research into management of urban stormwater infrastructure and the benefits of monitoring sets of systems like that of Ashmead Basin creates the initiatives and potential for problem identification and other informative data about the management of polluted streams. Data collection and communication of this information is key for identifying issues found in urban infrastructure – especially in informal settlements where very little problem identification takes place effectively. Currently developed and developing regions overlap around the periphery of African cities with large disparities in wealth particularly evident in tourism hotspots like Knysna, and to ensure that infrastructure development is beneficial in the future requires breaking down the financial, cultural, and educational constraints that currently divide society and the inherent standards of living.

Improving land management is a key step if sustainable change is the goal for the community and this research is aimed at discovering a few of the best approaches for improving the sustainable development and management of Bongani Catchment.

A.2.1 Concerns for Ashmead Basin: researching the Bongani River

The University of Cape Town – and others – have been exploring SuDS research opportunities in stormwater pollution loading on sensitive biodiversity sinks (Claasens *et al.*, 2020; Harvey, 2019; Adams *et al.*, 2016). Thus, research linked to drainage, sanitation and infrastructure concerns associated with mismanaged land uses like roadways, informal settlements, and industrial and commercial centres was undertaken in the catchments surrounding the Knysna Estuary. The research resulted in collaboration between University of Cape Town, Knysna Municipality and Knysna Basin Project – a local non-government organisation – with A.L. Harvey as the principal researcher completing a master’s dissertation in 2019 – *An investigation of the pollution contribution of catchments surrounding the Knysna Estuary, with implications for stormwater management* – that investigated water quality constraints at 18 stormwater outlet sites along the north-eastern shores of Knysna Estuary. The stormwater sampling program initially investigated discharges from Salt Stream’s outlet in the north-west to the Bigai Stream’s outlet in the south-east through the monitoring of water quality – see Figure A-2.

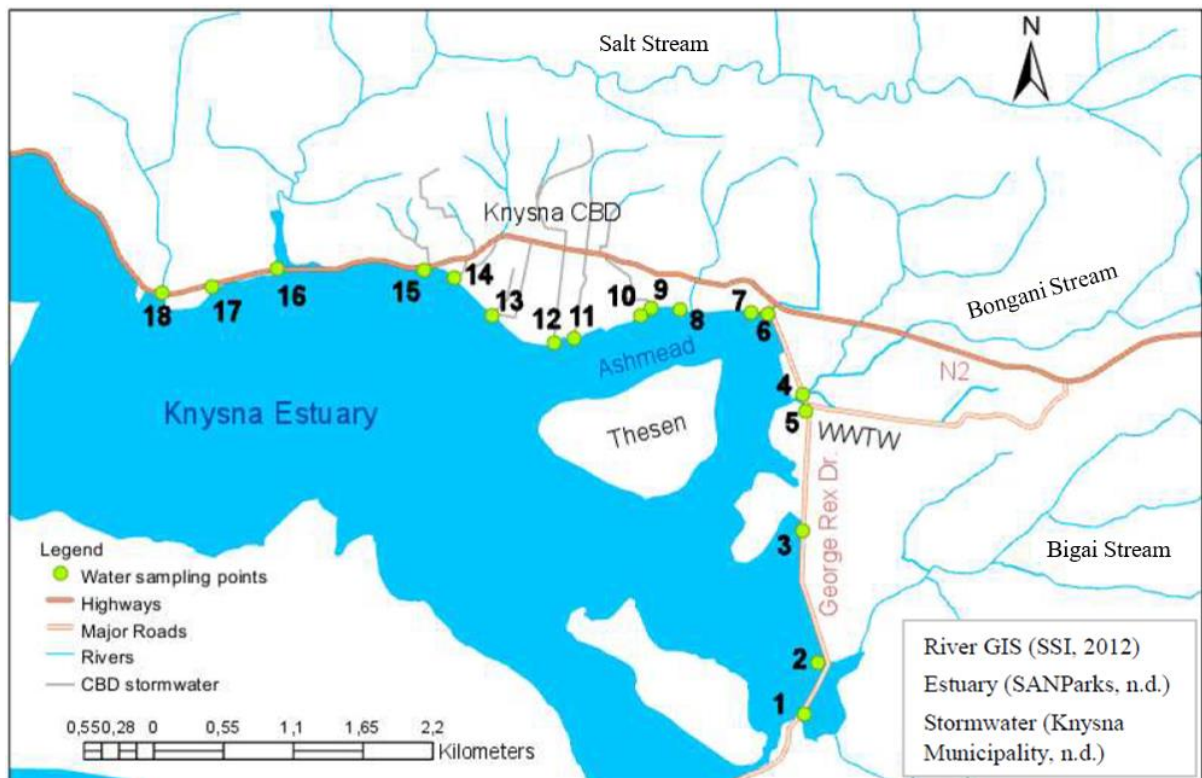


Figure A-2: Original 18 water quality monitoring locations (from Harvey, 2019)

The study was aimed at characterising the pollutant constraints facing the eastern shores of the estuary, measuring nutrients – Ammonium, Nitrites and Nitrates which make up TIN and TP, sediments as TSS, as well as pH, conductivity, and turbidity. Figures A-3 and A-4 illustrate the outcomes of the monitoring scheme on the north-eastern shores of the estuary showing the relative intensity of TIN and TP in the various outlets.

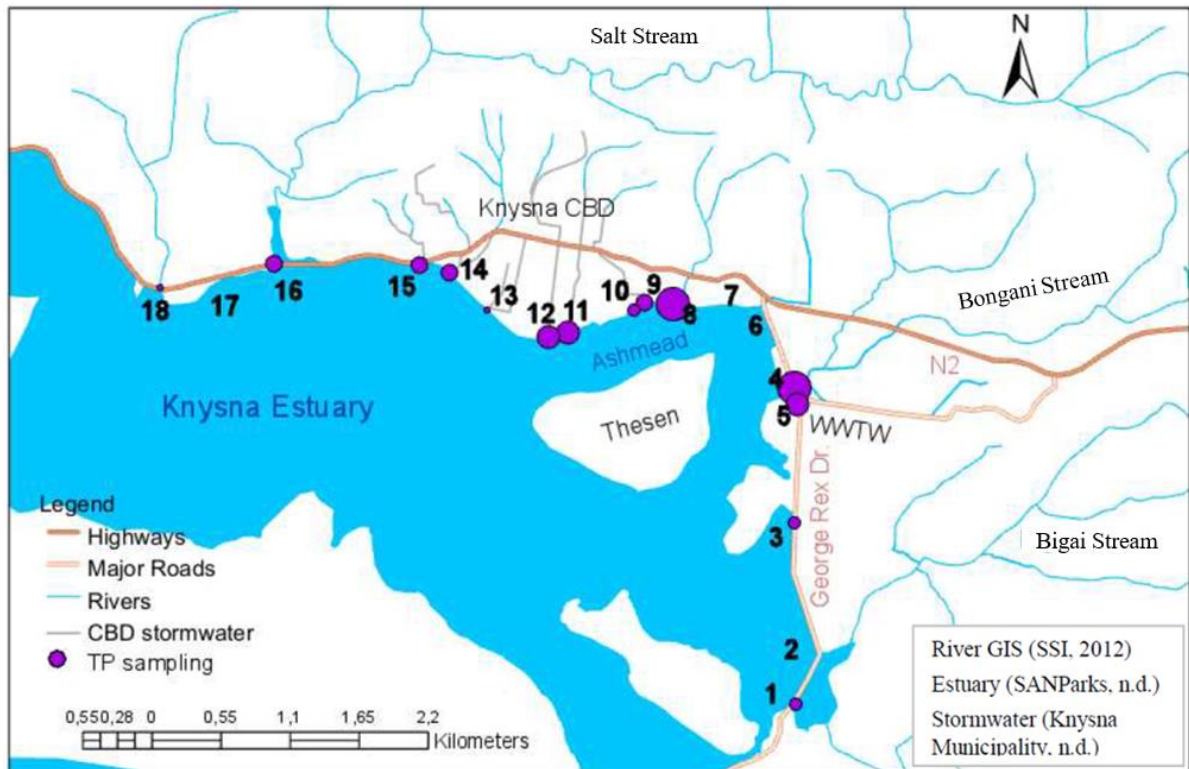


Figure A-3: Relative TIN concentration at 18 monitoring sites (from Harvey, 2019)

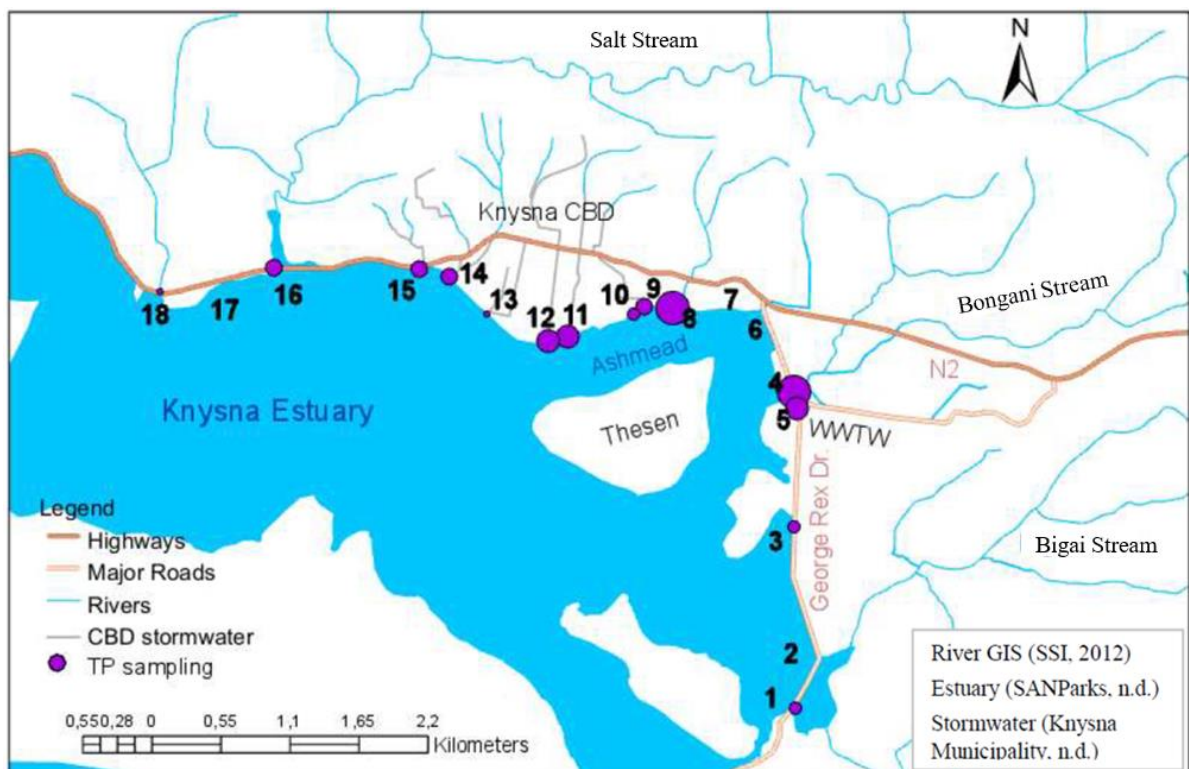


Figure A-4: Relative TP concentrations at 18 monitoring sites (from Harvey, 2019)

The research by Harvey (2019) was revised when it was seen that the major concerns for the shoreline were better understood. The revision shifted the focus to the discharges and catchments from the Salt, Xolweni, Bongani, and Bigai Streams. The stormwater monitoring outcomes noted that Ashmead Channel was under enormous stress from the high nutrient loads. Ashmead Basin has a history of poorly managed informal development in its headwaters and faces the associated risk of a lag in basic service provisions such as effective waste removal and inadequate sewerage provisions. Although Harvey (2019) further investigated the Salt and Xolweni catchments, Figures A-5 and A-6 provide context about the Bongani and Bigai catchments and the adapted stormwater monitoring program for these two streams.

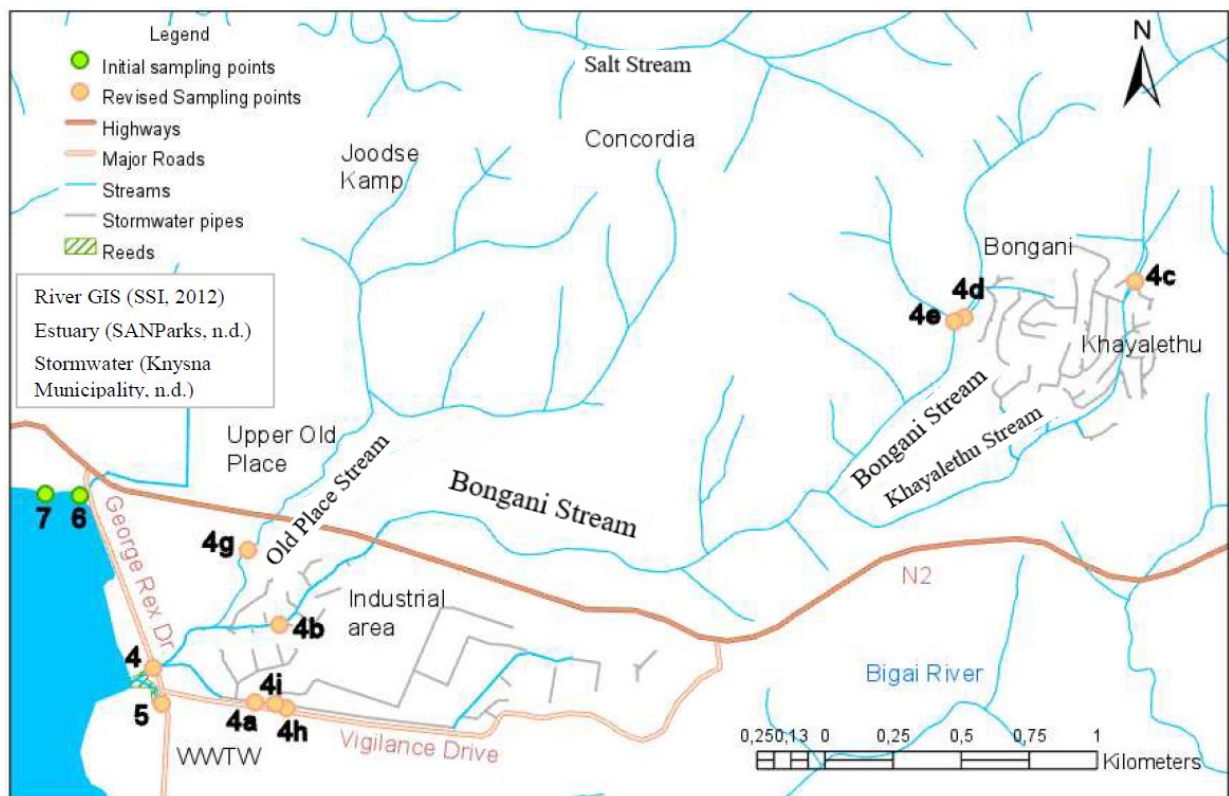


Figure A-5: Revised sampling points in Bongani Catchment (from Harvey, 2019)

The research found that there were serious water quality concerns for the peri-urban settlements in Ashmead Basin from Xolweni in the west to Hornlee in the south-east. The Bongani River was of the highest concern with respect to its elevated pollutant concentrations and deteriorating drainage and sewage infrastructure and was found to have excessive nutrient – TIN and SRP - and *E. coli* concentrations. The levels of which were noted by Harvey (2019) to be eutrophic/hypertrophic for a concerning period across much of the Bongani Catchment.

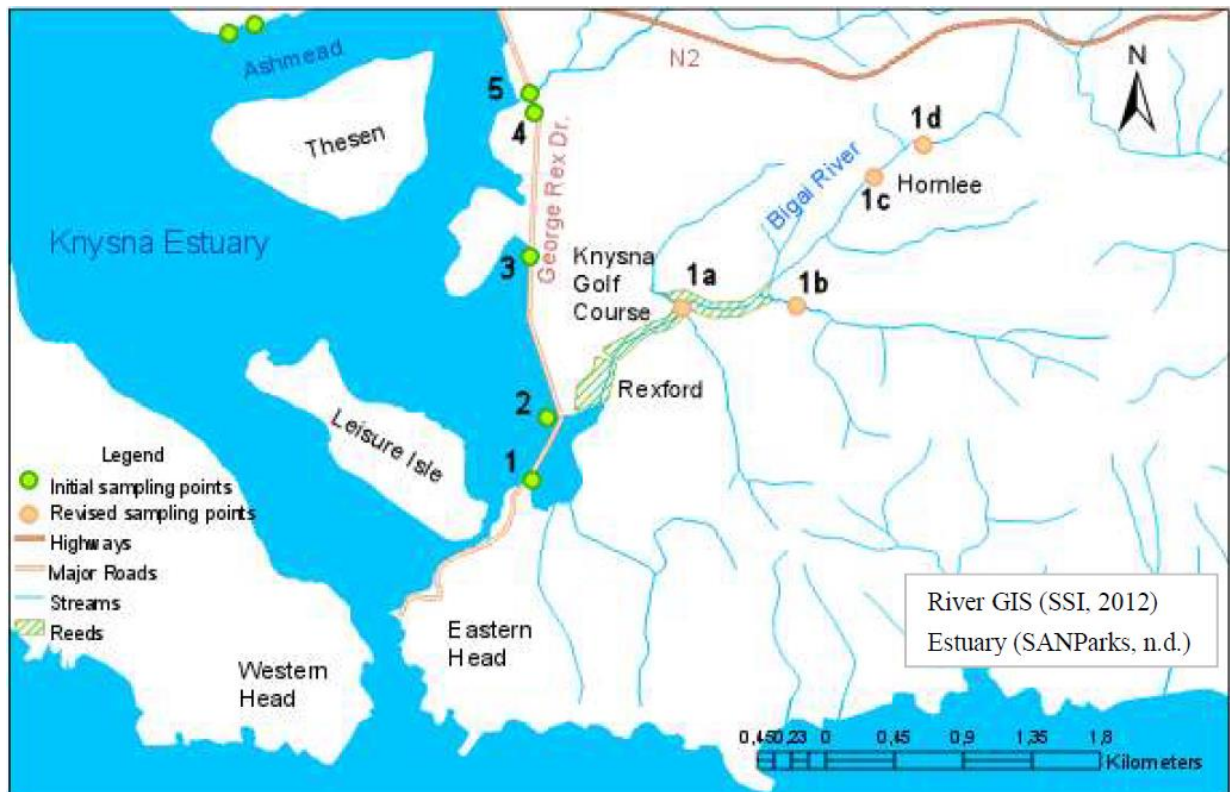


Figure A-6: Revised sampling points in the Bigai Catchment (from Harvey, 2019)

The Bigai Catchment's downstream floodplain is covered by a 2 km reed wetland that controls the stormwater discharge of the Bigai Stream which disseminates from the settlement of Hornlee. Although the settlement faces the same stormwater quality concerns as the other low-income areas across Ashmead Basin's headwaters, this wetland was observed to be making a positive difference to the water quality between Hornlee and the outflow of the Bigai Stream.

This research study, which followed from Harvey (2019) was designed to continue investigating the pollution concerns for Bongani River in terms of stormwater quality and quantity through a strategic stormwater monitoring program that was planned and outlined at the Stormwater Management Workshop (7-8 February 2019). The stormwater research plan included monitoring Bigai Stream to investigate stormwater pollution in Hornlee and the water quality impact of the Bigai Wetlands which act as a regional control prior to the catchment's outflow into the channel.

Although Harvey (2019) managed to discover where the pollution in Ashmead Channel was coming from, she did not complete the inquiry into stormwater management practices to enhance the water quality from these streams. This research develops the basis for a stormwater management plan for comprehensive monitoring and pollutant load characterisation of the Bongani River, and the investigation into SuDS initiatives that may address the problem.

A.2.2 Water quantity data: improving hydrological model uncertainty

Stormwater quantity data collection involves the measuring of flow at downstream points in the stream network for insight into the nature of the stormwater network as well as data for the calibration and verification of the model. Hydrological modelling has a high level of uncertainty, especially when generating flow peaks and volumes throughout storms in a stormwater network. Collecting data from the stormwater network during storm events can thus provide valuable data that can be linked to the hydrological model. Harvey (2019) investigated the flow rate during storm events in a few sections of the Bongani and Bigai Streams as illustrated in Figure A-7. The monitoring of storm events can provide useful information that is valuable for the improvement of model accuracy and complexity through the calibration and validation process.

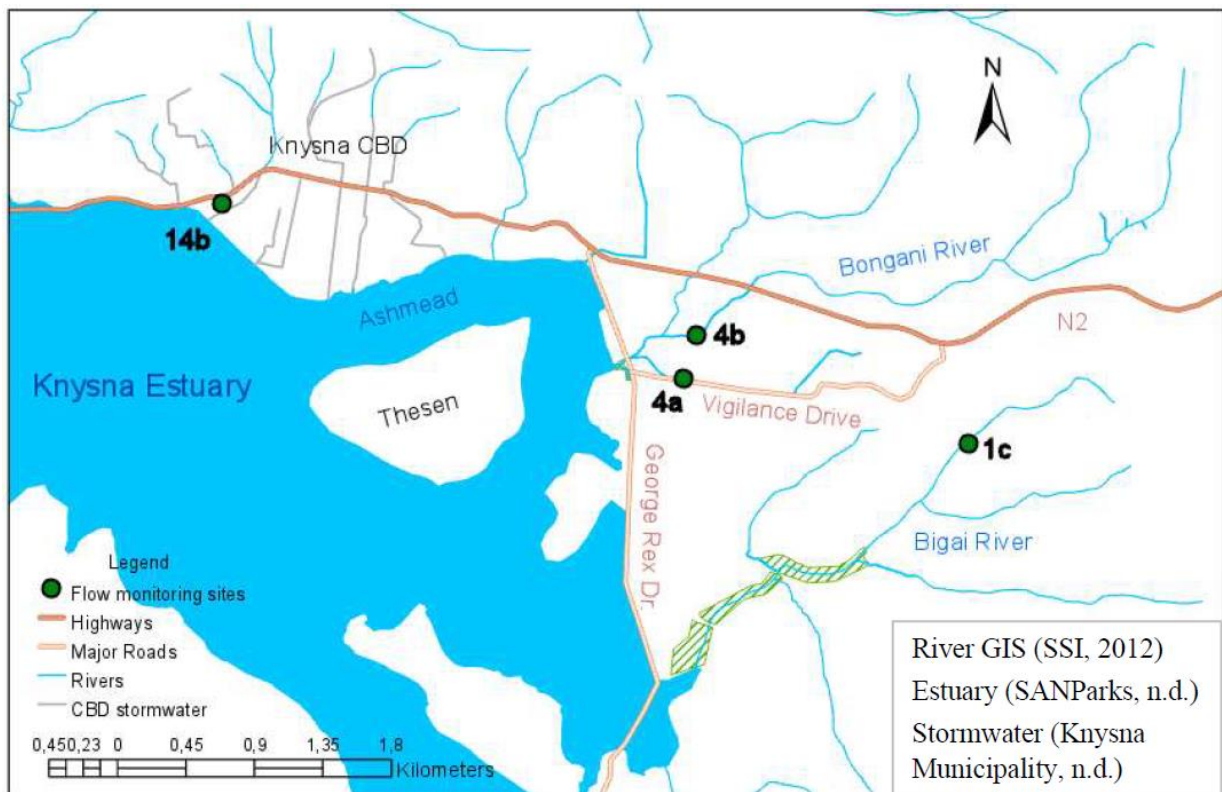


Figure A-7: Location of four flow monitoring devices (from Harvey, 2019)

To acquire continuous flow rate data at a few points in the stormwater network, flow level sensors were developed and placed under culverts that bisect bridges over a relatively stable section of the stream. The flow level sensors were connected to an Arduino micro-controller which sends a stream of GSM flow depth information to the Thingstream.io server where it can be collected, collated, and evaluated. The flow depth is then converted to flow rate if the following conditions are met at the location of the flow level sensor: cross-section of open channel must be known, flow must be steady state with no obstructions to flow (debris or natural sections can be difficult to evaluate for roughness) and the flow should ideally be uniform such that back-calculation using the Manning's equation is possible and reliable.

A second option for flow measurement – also implemented by Harvey (2019) – is higher in uncertainty, but nonetheless provides valuable data on flow depth for the case the flow level sensors do not work. The use of chalk sticks, or chalk against culvert walls, which are encapsulated by a plastic trunking with holes drilled to allow for water to enter the plastic trunking. When water levels rose, the water in the plastic trunking rose, washing off the chalk to the highest water level in the conduit during that event. Measurement lines were drawn along the surface, and the high-water mark was left on the chalked medium, whether it is a lightly sanded and varnished stick with chalk drawn on it, or a chalked wall, an approximation of the maximum flow depth was acquired.

Base flows would also need to be investigated to evaluate the impact of groundwater intrusion into the stormwater network as a general flow assumption for dry periods. The source of streams is not entirely from stormwater runoff, but rather a combination of groundwater supply and runoff. Evaluating the influence of groundwater supply will thus need to be further investigated using the dry weather base flows and comparing this to flow from storm events.

Sampling methods vary for storm event monitoring however, a primary concept that is being investigated is the link between stream flow, nutrient, and sediment peaks, particularly for first flush characterisation which is the increase in concentration of pollutants in a stream from heightened stream flow energy and the associated suspension of solids in the stream bed. Using a continuous automatic sampler enables a rate of change characterisation for the nutrient (TN & TP) and sediment (TSS) concentrations in the stormwater network if both water quality and water quantity are measured simultaneously. Understanding how pollutants behave in the catchments with respect to rainfall and runoff volumes is useful in understanding how pollutants are washed-off catchments and thus statistical comparisons between the estimated pollutant loads in the PCSWMM catchments and the actual mass loads in the stormwater system were attainable.

The definitions of various water quality parameters and their constituents are provided in the following list:

- Total oxidised nitrogen (TOxN) = nitrites (NO_2^-) + nitrates (NO_3^-)
- Total inorganic nitrogen (TIN) = ammonia (NH_4^+) + TOxN
- Total organic nitrogen = total Kjeldahl nitrogen (TKN) = NH_4^+ + organically bound NH_4^+
- Total nitrogen (TN) = TOxN + TKN
- Soluble and reactive phosphorus (SRP) = orthophosphates (PO_4^{3-})
- Total phosphorus (TP) = SRP + organically bound phosphorus (OrgP)
- Total settleable solids (TSS) = total solids (TS) – total dissolved solids (TDS)

Appendix B – Literature relevant to the research

B.1 Stormwater quality management

Research by UCT into managing stormwater drainage with a systems approach to mitigate sanitation problems and environmental concerns, and the investigation into the challenge of providing sustainable drainage to the informal settlements of South Africa, has led to the uptake of projects related to stormwater management for biodiverse estuaries, their ecosystems, and ways in which to best uplift the communities that have settled in their catchment areas and basins.

PCSWMM is an application that assists with dynamic rainfall-runoff modelling. The program simulates urban runoff quality and quantity for multiple scenarios enabling comparisons of rainfall events, as well as improvements and upgrades to existing stormwater networks. There are two major components in the PCSWMM program. The first is the runoff component which simulates continuous or event rainfall over multiple sub-catchments, with unique characteristics, to generate runoff and pollutant loads at the outlet node of each sub-catchment. The second component is routing, which simulates the transport of runoff and its constituents through the network factoring in the build-up and wash-off of pollutants from the landscape.

The transition to high functioning and low maintenance streams requires a shift in the way drainage infrastructure is designed. Although conveyance is important, function and ecology have value too. Therefore, defining the ecological and geomorphological corridor at the planning stage is an important consideration alongside the design of an effective stormwater conveyance system.

In a literature review by Milandri *et al.* (2012) based on vegetative species and their removal efficiencies, the uptake efficiencies of various plant species were reported with respect to the removal of inorganic P and N constituents. Table B-1 is a summary of the results from the review.

Table B-1: List of species (and soil control highlighted in grey) of the mean percentage removal for each nutrient (from Milandri *et al.*, 2012)

Rank	PO ₄ ⁻³	NH ₄ ⁺	NO ₃ ⁻
1	Agapanthus (92%)	Pennisetum (99%)	Pennisetum (81%)
2	Pennisetum (91%)	Stenotaphrum (98%)	Stenotaphrum (80%)
3	Stenotaphrum (91%)	Typha (93%)	Agapanthus (72%)
4	Phragmites (86%)	Agapanthus (91%)	Zantedeschia (69%)
5	Typha (86%)	Phragmites (91%)	Carpobrotus (63%)
6	Zantedeschia (85%)	Zantedeschia (91%)	Ficinia (62%)
7	Control (79%)	Ficinia (89%)	Typha (56%)
8	Carpobrotus (77%)	Control (85%)	Elegia (36%)
9	Elegia (46%)	Elegia (83%)	Phragmites (25%)
10	Ficinia (15%)	Carpobrotus (80%)	Control (22%)

B.2 Interesting observations from the Ashmead Basin

This section details the interesting bio-geo-chemical observations of iron-accumulating bacteria and foaming water bodies in the Knysna Estuary's eastern catchment areas.

B.2.1 Iron-accumulating bacteria

A reddish-brown scum was found in the seeps disseminating from iron-rich mountainsides. According to Fair (2019) citing Harder (1915), the scum is an iron eating bacterium which may be encountered in iron-bearing waters where they appear as a deposit of yellowish-brown scum. The bacteria thrive by taking the dissolved iron in the water and converting it to ferric material and are found naturally in soils and water in low numbers (Harder, 1915). Iron bacteria are no threat to human health but can have a bad smell which is caused by the growing and dying of bacteria. Thus, the bacteria are not actually pollution itself, but may be indicative of pollution. The reason for a concern is that the bacteria can accumulate in pipes/storage tanks (Brandt *et al.*, 2017). This can block pipes, inhibit flow, and discolour water downstream.

B.2.2 Foaming of water bodies

The foaming of water bodies is created by the accumulation of Phosphorus in surface water which physically reduces surface tension in water. When energy is expelled into water through waves, rapids, or waterfalls, the reduced surface water tension allows air molecules to get stuck between the liquid particles creating a foaming phenomenon as shown in Figure B-1. Countries in the Danube River Basin in Europe have been concerned about P in detergents for at least two decades with Horth *et al.* (2006) noting that Germany and Austria had complete bans for P at that time. On the other hand, a lack of regulatory concern in places like Bengaluru in India, where foam accumulation from contaminated stormwater runoff has covered entire lakes have had cases where froth overflows into parts of towns near to lakes due to (Sengupta, 2017).



Figure B-1: Foaming at Bongani Waterfall downstream of the N2 at Bo 6 sampling site

B.2.3 A summary of Ashmead Channel's stormwater polluters

The benthic flux of contaminants from Ashmead Channel was discussed in detail the introduction, the Knysna WWTW and their historic and current non-compliance is well recognized in literature, and the concerns with the management of the algal bloom has also been investigated. This summary is focused on the pollution entering Ashmead Channel from stormwater, which starts as fresh water in the air, becomes contaminated during surface runoff, and participates in the flushing of the stormwater networks to their discharges. It is known that infrastructure mismanagement causes damage to communities and settlements through their downstream impacts, but what is causing the damage? Community dependence on goods and services puts them at the forefront of the problem, and thus investigating these issues through the community itself is the most effective and responsible way to understand the reasons for concern.

Lepota (2019) investigated the pollution problems faced by the peri-urban settlements of the Ashmead Basin. This findings by Lepota (2019) helped this study to narrow down on what problems are currently being faced in the informal settlements of Knysna, and where possible mitigation measures might lie. The key for understanding the problems and solutions for stormwater management concerns in these areas lies with stakeholder engagement, which provides context and insight into what are truly impacting these communities, their settlements, and the ecosystems on which they depend.

The research by Lepota (2019) involved two main components, site investigations and stakeholder engagements, both of which were overseen by this researcher. The two components overlapped, but they comprised of different point of views. Site investigations provided insights to the researchers about the landscape and visual representations of the problems that were occurring at the time. Stakeholder engagement on the other hand provides a wealth of information from their perspective – including problems that occurred previously and those which continue to happen on a temporary or persistent basis. A valuable aspect of the research was the investigation of how much the local communities understood about stormwater management initiatives and their implications (Figure B-2).



Figure B-2: Research endeavours in the Ashmead Basin

Appendix C – Data collection and analysis

C.1 Storm event data collection

The water quality data collection process involved collecting samples during storm events which were being analysed for flow level concurrently to have data for flow rate for calibration of the hydrological model. The samples that were collected during the storm events needed to be stored in a cold environment to ensure that the constituents being measured did not change too much between the collection of the sample and the testing of that sample in Cape Town a day or two later.

The build-up and wash-off of pollutants describes the theoretical development of pollutants in a catchment and their transport downstream through overland and stream flows. Variability in these developments depend on the types of pollutants being considered, the surface that they accumulate on, the land use which influences their deposition, as well as the surfaces downstream which capture, store, treat or release their loads.

Storm events were monitored during the storm event data collection using various weather prediction websites. Yr.no was used particularly

Today, Thursday 07/03/2019

Time	Forecast	Temp.	Precipitation	Wind
15:00–18:00		23°	0.7 mm	Gentle breeze, 4 m/s from southwest
18:00–00:00		21°	23.9 mm	Gentle breeze, 4 m/s from southwest

Tomorrow, Friday 08/03/2019

Time	Forecast	Temp.	Precipitation	Wind
00:00–06:00		19°	8.7 mm	Gentle breeze, 4 m/s from southwest
06:00–12:00		18°	6.0 mm	Gentle breeze, 5 m/s from southeast
12:00–18:00		19°	0.9 mm	Moderate breeze, 6 m/s from east-southeast
18:00–00:00		18°	0.9 mm	Moderate breeze, 6 m/s from east

Saturday, 09/03/2019

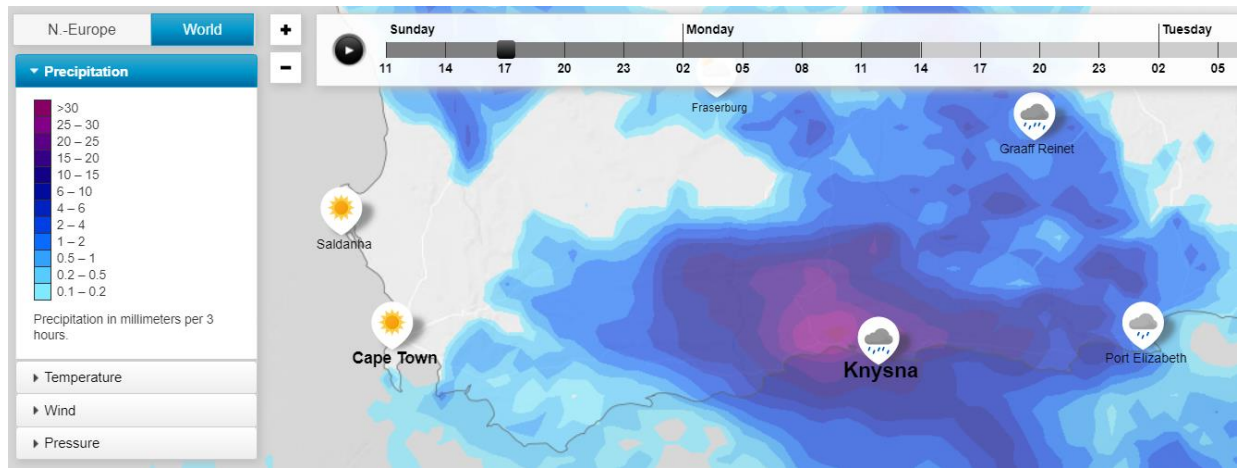
Time	Forecast	Temp.	Precipitation	Wind
00:00–06:00		17°	1.5 mm	Gentle breeze, 4 m/s from east
06:00–12:00		17°	1.8 mm	Gentle breeze, 5 m/s from east-southeast
12:00–18:00		19°	2.2 mm	Moderate breeze, 6 m/s from east-southeast
18:00–00:00		18°	0.9 mm	Gentle breeze, 5 m/s from east-southeast



Sun and moon, 07/03/2019

Sun	Moon
Sunrise 06:20	Moonrise 06:48
Sunset 18:57	Moonset 19:41

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Hourly forecast for

Knysna, Western Cape (South Africa)

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Overview

Hour by hour

Detailed

Long term

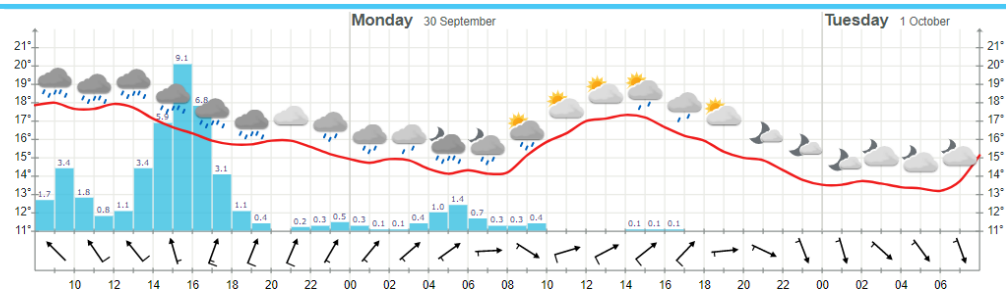
Maps

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Meteogram, next 48 hours

Hourly forecast for

Knysna, Western Cape (South Africa)

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Overview

Hour by hour

Detailed

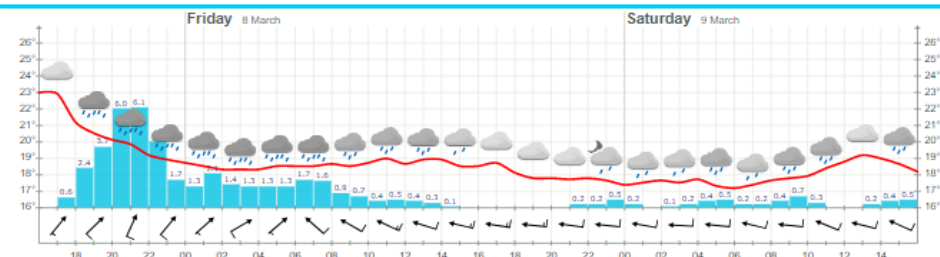
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[Touwsrivier](#)

Meteogram, next 48 hours

Hourly forecast for

Knysna, Western Cape (South Africa)

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Overview

Hour by hour

Detailed

Long term

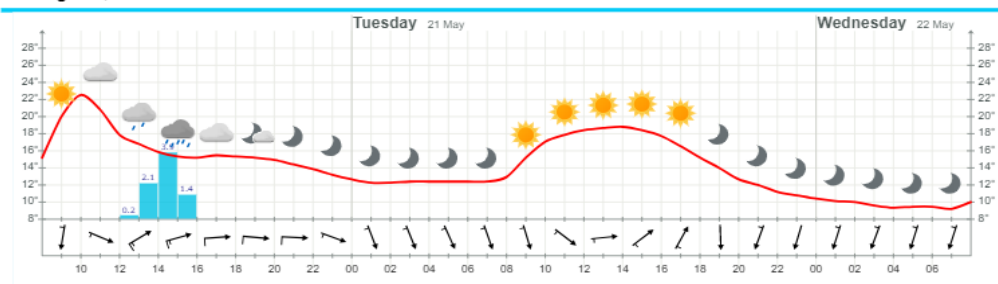
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Meteogram, next 48 hours**Figure C-1: Weather prediction summary (yr.no, n.d.)**

C.2 General data needs for a hydrological model

The following list is a summary of the general data requirements of a hydrological model:

- Previously developed hydrological models for the catchment
- Existing stormwater drainage and sewage systems and any stormwater master plans
- Land parcel or land use maps
- Contour Map or Digital Elevation Model (DEM).
- Water quality data for the estuary and its contributing catchment areas.
- Rainfall data from rain gauges in the area (Sub-daily data is ideal)
- Climate data from public or private weather stations
- Flow rate data from any available flow stations
- Soil, geological and vegetation data, maps, and data from any prior catchment studies

C.3 Value of sampling and testing for SuDS research

The monthly stormwater sampling provided the research with not only the location and intensity of water quality issues, but also assisted the Knysna Municipality with monitoring for overflowing sewerage and water reticulation pipes along the routes followed.

Developing an understanding of the landscape required time spent walking or driving through the catchment areas. This exposure to the stormwater drainage system provided valuable insights which aided with identifying problematic sections of the stormwater network. Problems can be identified in several ways. Visual indicators are different in that they are not direct measurements that identify the problem, but rather point to a certain concern or issue. They provide a wealth of anecdotal information.

An example of this can be seen in the upper parts of the Bongani River where sediment has filled several culverts in the drainage network. It was not observed to be a problem in the initial monitoring of the system but was discovered as an issue during a site visit to the upper parts of the streams whilst culverts were being measured for the hydrological model of the network. This is evidence that simple monitoring – or site investigations that entail mapping out or noting various issues – can provide valuable insight into problems that may not have been identified up to that point.

The inquiry into potential SuDS locations was based primarily on the monitoring of the system, as well as the desktop study needed for the development of the hydrological model.

C.4 Data shortages before this research

This section discusses the data that is currently lacking in the various databases for Bongani River catchment. It highlights what data needed to be acquired by this research and explains the reasons for the methods chosen for data collection.

C.4.1 Missing stormwater data

An understanding of stormwater runoff concentrations for a stream's catchment requires in-depth studies of various flow areas of the stream and the concentrations or counts of the contaminants entering the system. Data collection needs to have been consistently followed for a fairly long period of time before a true grasp of the base flows, storm flows, and pollutant loads of the stream could become available. Though there was data available for Bongani River catchment thanks to Harvey (2019), long-term data of the system was still lacking, and more collection of data was required. Water quality and flow rate data from a few locations was collected, but the data collection period was short and the distribution of the points at which data was collected was limited to locations in the lower areas of the catchment. The western tributary of the system – Concordia Stream – had no flow data available and thus investigating this stream was novel and necessary (this stream does not even show up on google maps (Google Maps, 2021)).

The base flow of a stream quite often depends on the groundwater system which is always changing based on both the occurrence of rainfall and the dynamics involved with the geology and soil. Although the geology provides context of where the water table may be, a lack of groundwater information was a limitation of this investigation due to a lack of resources as well as in terms of hydrogeology experience. Antecedent dry periods are the times where there are no rainfall events over the catchment area and signify the occurrence of base flows in the stream. Measurements of the flow depth in the stream during these periods was needed, as it would provide a basic understanding of the flows of the stream.

The storm flows depend on practical storm event data throughout the catchment with rainfall intensity and distribution requiring several fine-scale rain gauges, flow rate requiring ultrasonic long-lasting flow sensors, and the concentration variation of pollutants requiring well-predicted time stamped measurements of water quality both during storm flows and base flows.

C.4.2 SuDS data

Shortages of data do not only apply to stormwater data but also to data about the development of stormwater management initiatives that are sustainable and located in the area. Much of the development of stormwater systems has historically focused on a conventional approach, leaving gaps in understanding with regards to the development of sustainable alternatives. This research attempted to create local SuDS options for water quality problems using various sources of literature that have been summarised in Section 2.3.

C.5 Survey cross-sections data

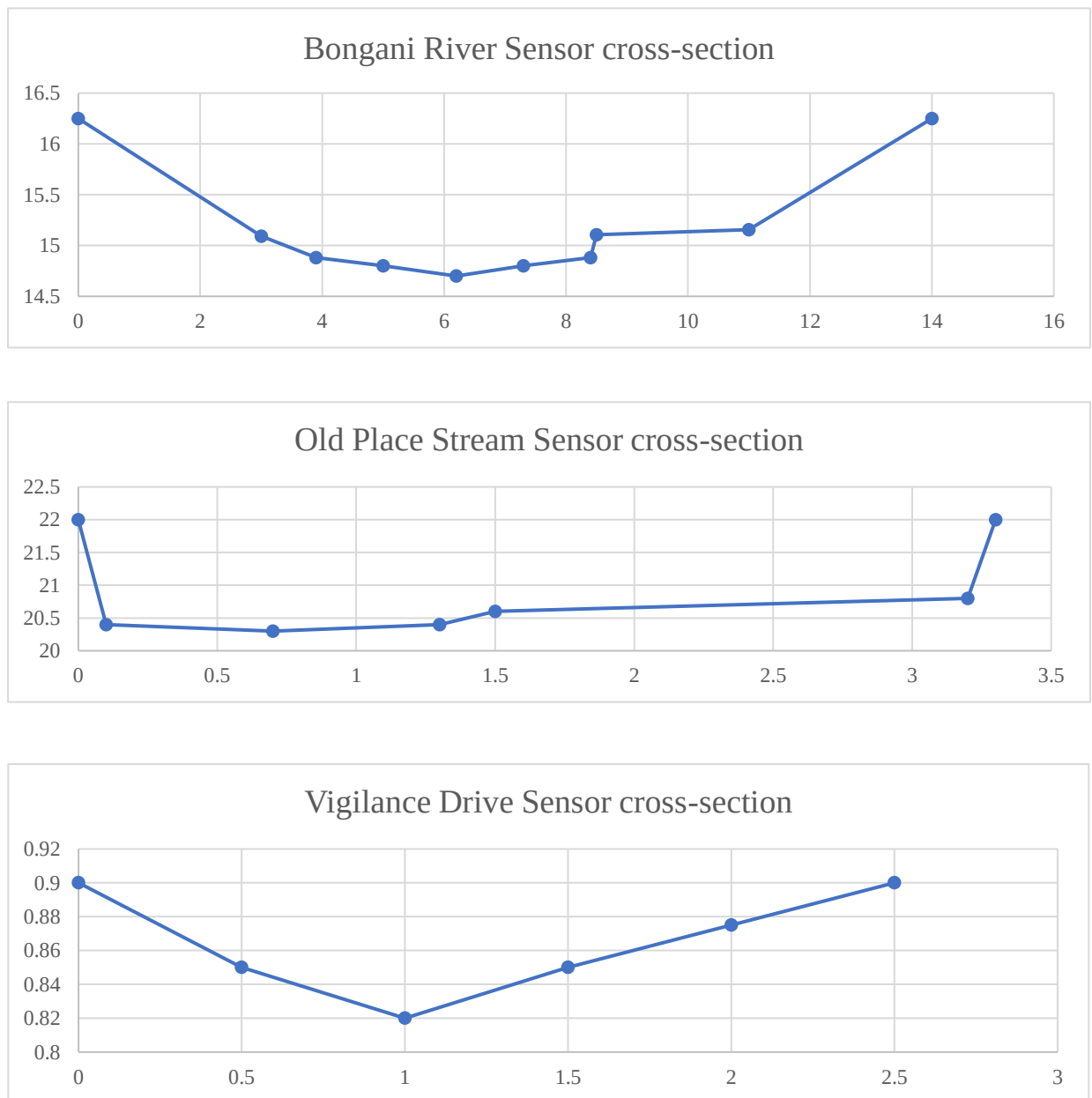


Figure C-2: The cross-sections for the three flow sensor sites

Appendix D – Modelling the Bongani River

The largest flood event in terms of rainfall occurred from 19-23 November 2007.

The scenarios

i) Pre-development scenario

Note that for very large storms, the saturation of the soil throughout the model would mean that the nature of runoff becomes very similar to that of an impervious surface. Thus, the difference between the pre-development and current scenarios for infrequent storms can be similar. Sometimes the current scenario may prevent intense flooding downstream because of roadways crossing the stream which create barriers for flood reductions incidentally.

ii) Current scenario

iii) Proposed SuDS scenarios

D.1 Model data

Table D-1: Texture Classes and parameters (Krebs *et al.*, 2014 after Rawls *et al.*, 1983)

Soil Texture Class	Hydraulic Conductivity (mm/hr)	Suction Head (mm)	Initial Deficit (fraction)
Sand	120.34	49.02	0.413
Loamy Sand	29.97	60.96	0.39
Sandy Loam	10.92	109.98	0.368
Loam	3.3	88.9	0.347
Silt Loam	6.6	169.93	0.366
Sandy Clay Loam	1.52	219.96	0.262
Clay Loam	1.02	210.06	0.277
Silty Clay Loam	1.02	270	0.261
Sandy Clay	0.51	240.03	0.209
Silty Clay	0.51	290.07	0.228
Clay	0.25	320.04	0.21

Table D-2: Texture Classes for ARC land types (after Land Type Survey Staff, 2006b)

IA39		DB26		GA2	
Description	Fraction	Description	Fraction	Description	Fraction
Loam fine Sand - Sandy Clayey Loam	0.32	Fine/ medium Sand - Sandy Clayey Loam	45%	Medium Sand	66.40%
Loam fine Sand - Sandy Loam	0.2	Fine/ medium Sand - Loamy Sand	24%	Loam fine/ medium Sand - Sandy Loam	16.10%
Medium Sand	0.15	Loam fine/medium Sand - Loam	11%	Medium Sand - Loamy Sand	6.40%
Loam medium Sand - Sandy Clayey Loam	0.1	Loam fine/medium Sand - Sandy Loam	6%	Loam medium Sand - Sandy Loam	4.00%
Fine/medium Sand	0.09	Fine Sandy Loam - Clayey Loam	4%	Fine/medium Sand - Loamy Sand	2.70%
fine Sand - Loamy Sand	0.08	Clayey Loam - Clay	3%	fine Sand - Sandy Loam	2.40%
Medium Sand	0.03	Rocks	4%	Loam fine Sand - Sandy Loam	2.00%
Streams	0.03	Medium Sand	2%		
		Loam fine Sand - Sandy Loam	1%		

D.2 Calibration of the hydrologic-hydraulic model

D.2.1 Sensitivity analysis

The following figures represent the relevant sensitivity gradients for the various parameters.

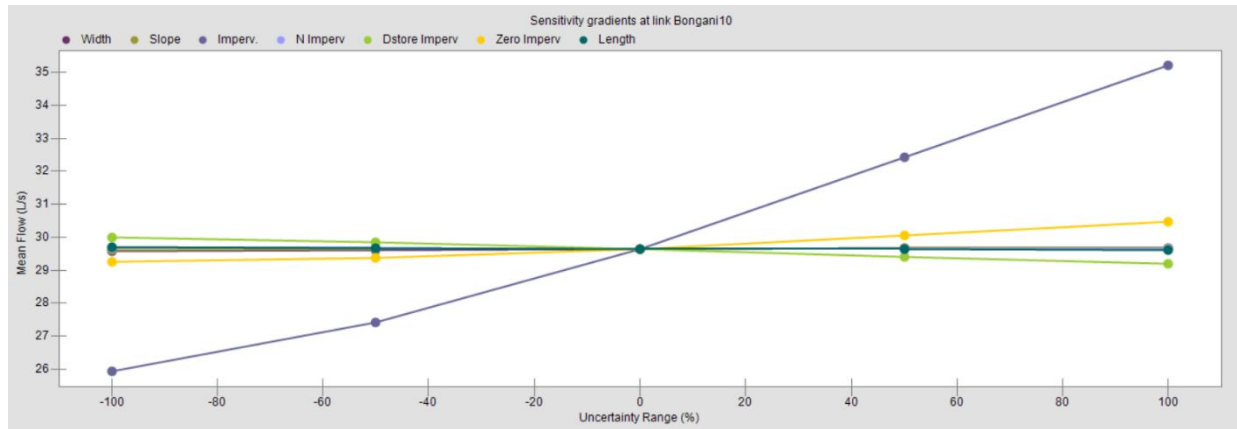


Figure D-1: Sensitivity gradients for mean flow at Bongani River Sensor

Sensitivity at Bongani 10 showed the model was most sensitive to changes in Impervious Percentage Area, and Zero-Impervious Area was the second most sensitive parameter. This implies that incrementally changing this parameter, varies the outputs of the model more than any of the other parameters of uncertainty. The following figure shows the mean normalised sensitivity for Bongani River Sensor (Bongani 10).

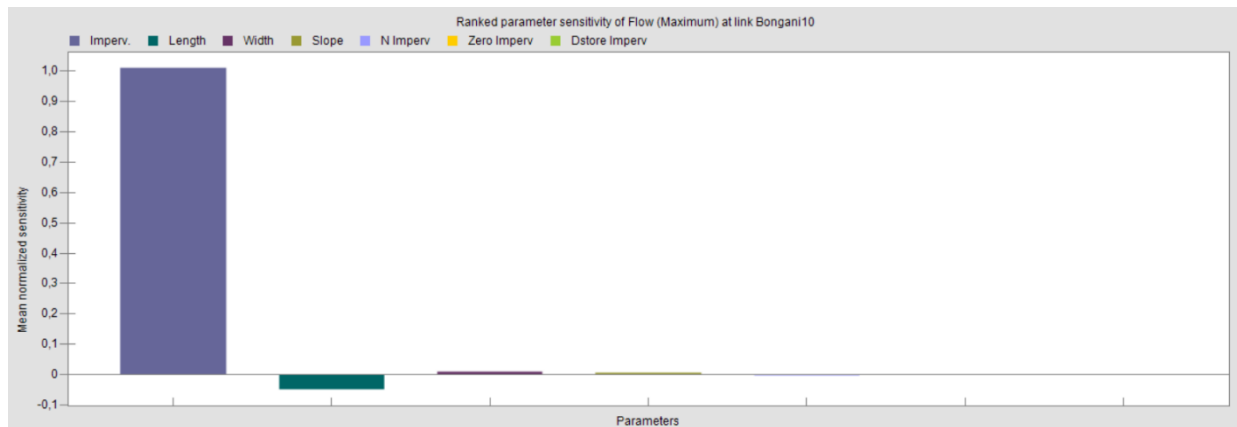


Figure D-2: Maximum flow mean normalised sensitivity at Bongani River Sensor

Bongani 7 had very similar looking sensitivities and was thus its sensitivity graphs have been omitted.

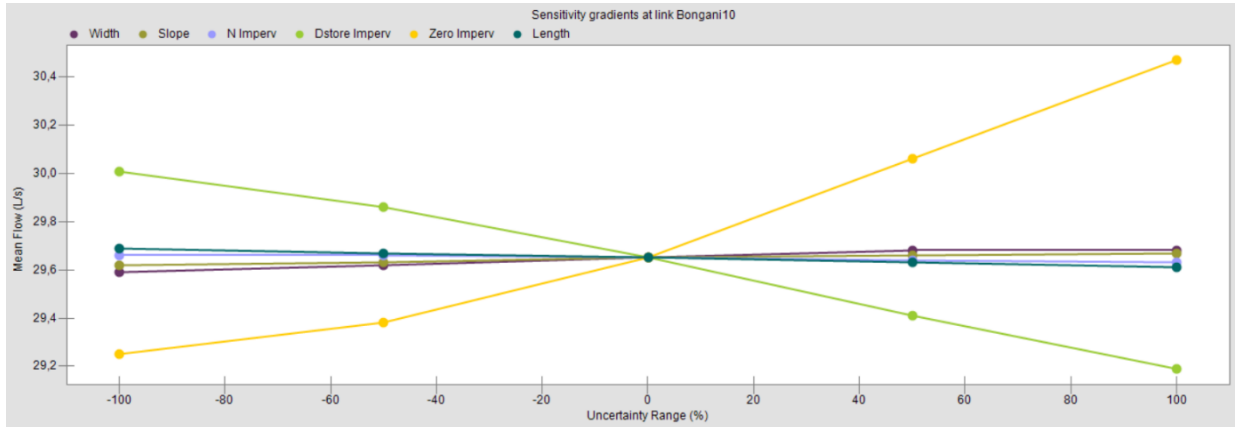


Figure D-3: Mean flow sensitivity gradients at Bongani River Sensor without Imperv %

D.2.2 Calibration process

The storm event periods used for calibration were assessed based on their inherent statistics. The calibration of groups of storm event periods and individual periods are presented below.

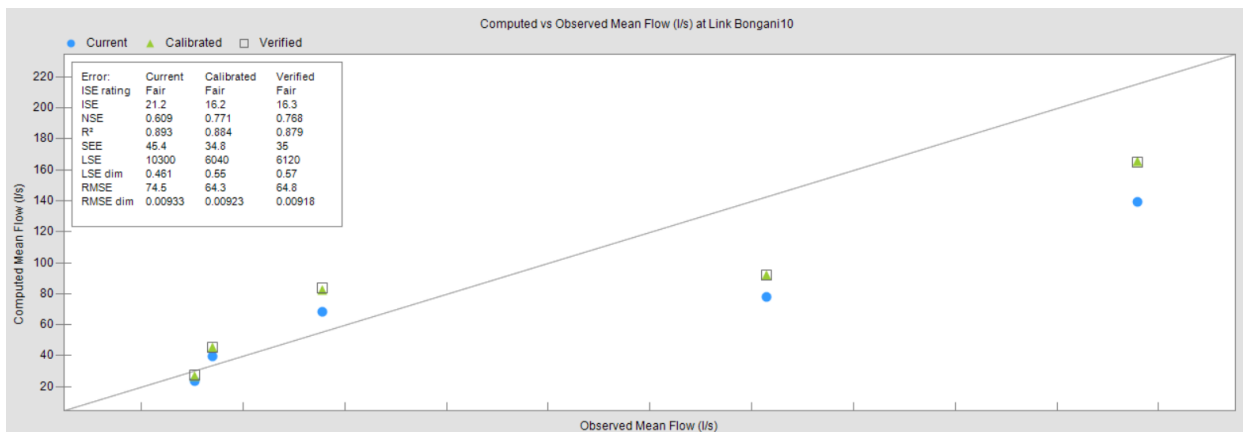


Figure D-4: Objective calibration graph for mean flow at Bongani River Sensor

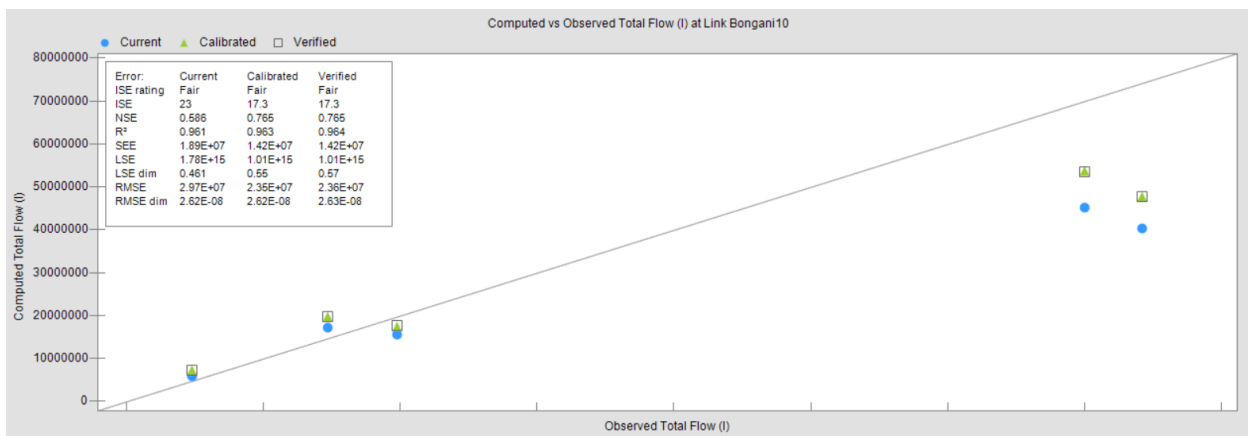


Figure D-5: Objective calibration graph for total flow at Bongani River Sensor

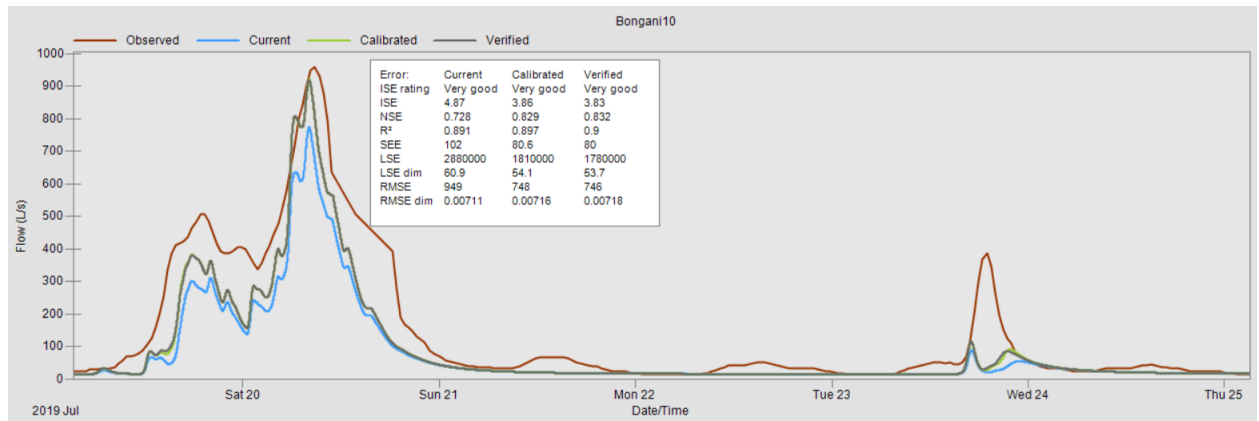


Figure D-6: Calibration event 2 in late July 2019 at Bongani River Sensor

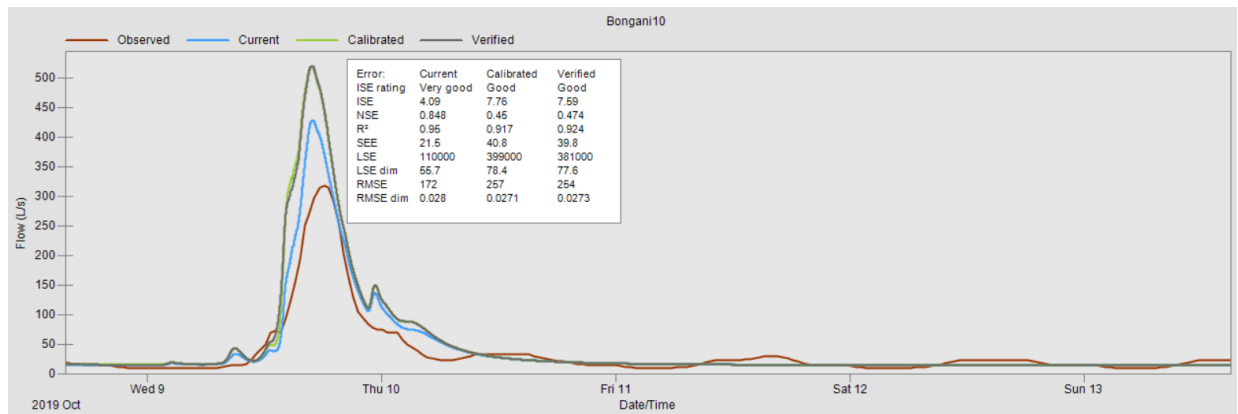


Figure D-7: Calibration event 3 in early October 2019 at Bongani River Sensor

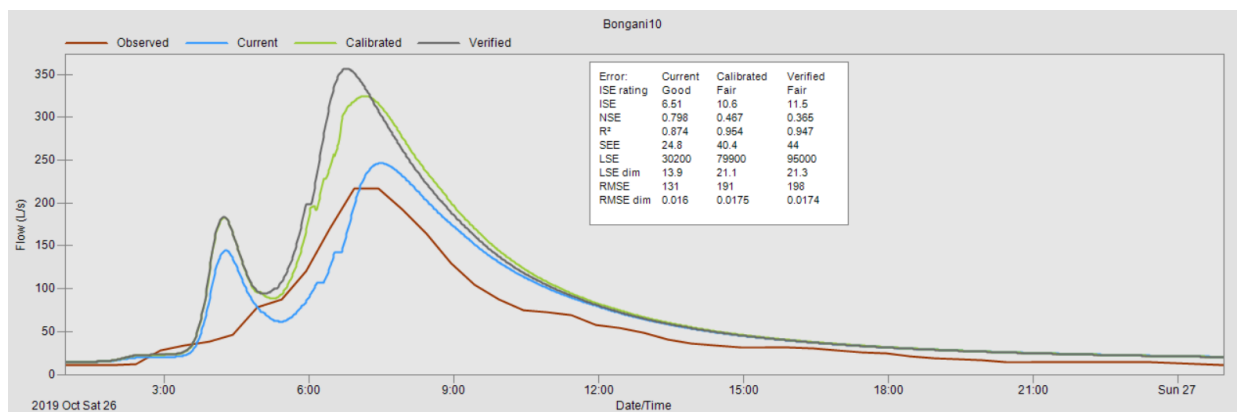


Figure D-8: Calibration event 4 in late October 2019 at Bongani River Sensor

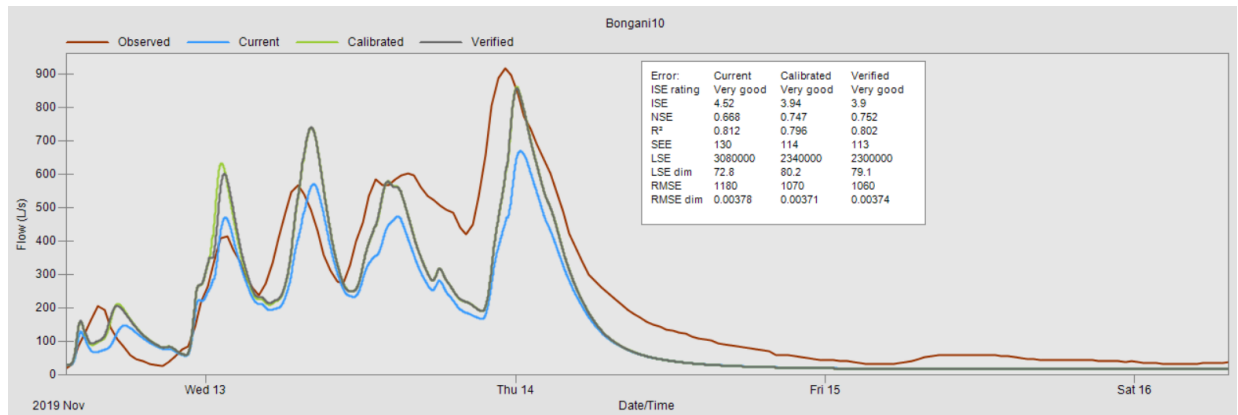


Figure D-9: Calibration event 5 in November 2019 at Bongani River Sensor

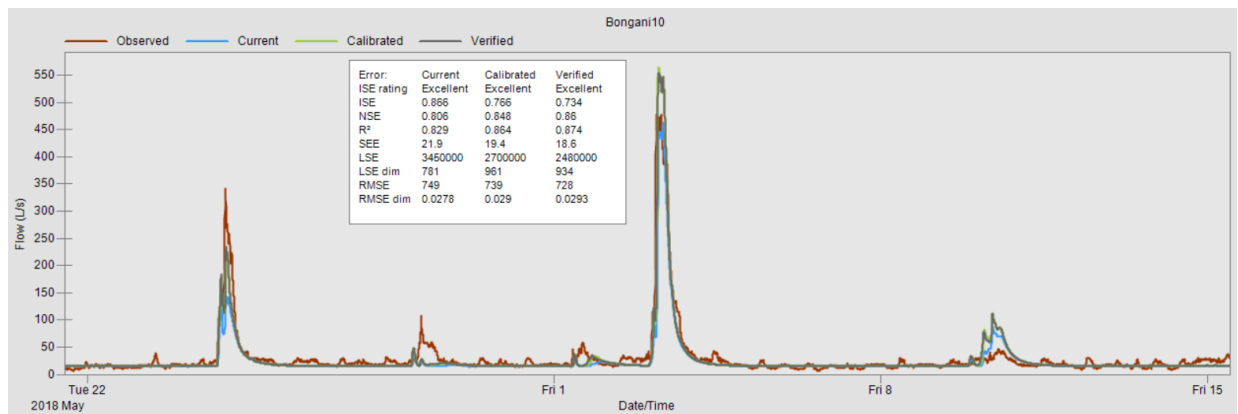


Figure D-10: Validation event 1 from late May to mid-June 2018 at Bongani River Sensor

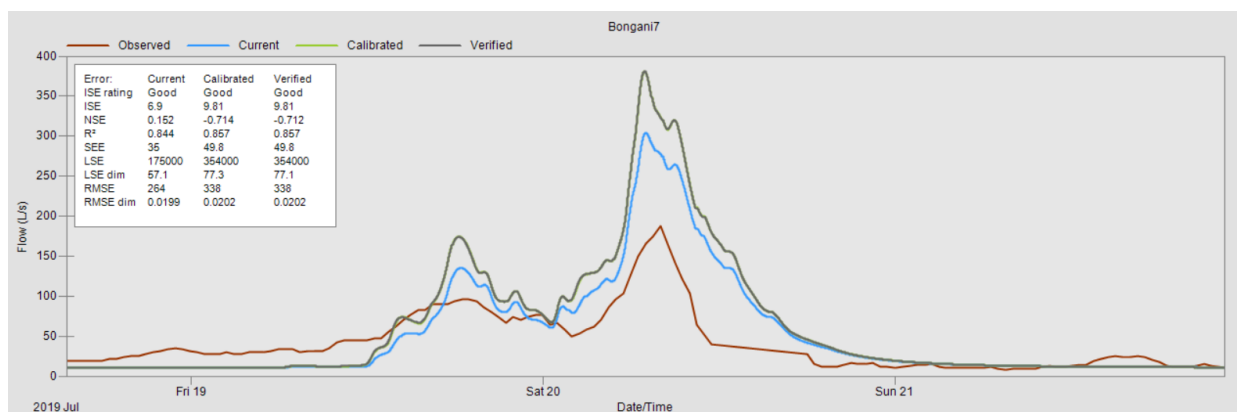


Figure D-11: Validation event 4 in late July at Old Place Sensor

The final value changes for the four parameters of uncertainty were as follows:

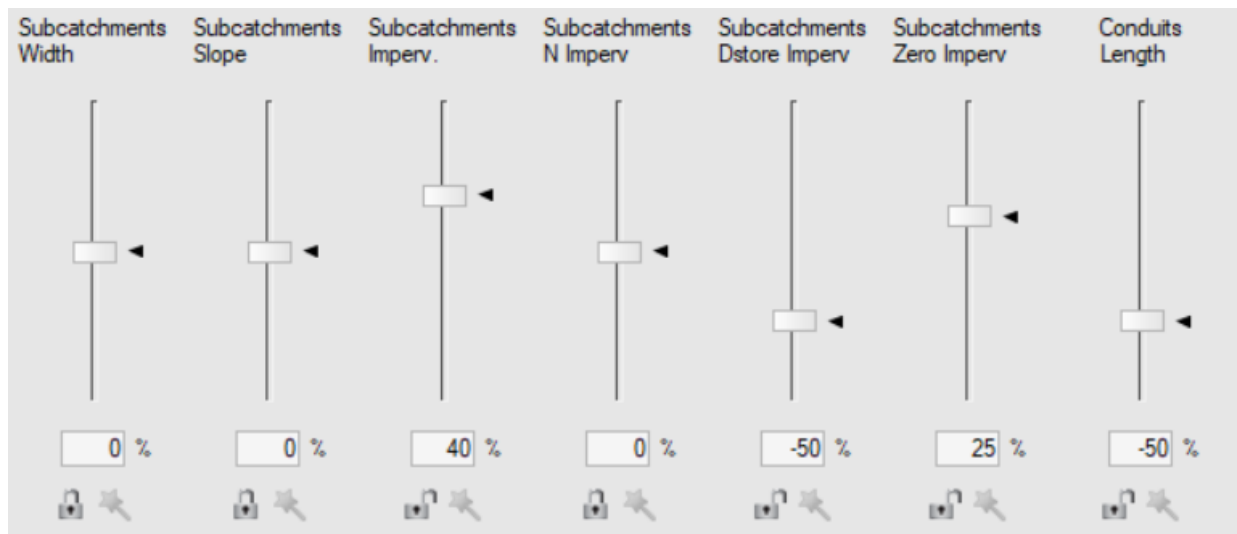


Figure D-12: Final parameter uncertainties

Once each calibration storm event had been adjusted to achieve the optimum statistical index for the parameter, the variations in the parameters were recorded and averaged out to acquire the mean parameter variation across the storm event periods. This was deemed to be the first iteration, acquiring the averaged parameter variations. The second iteration involved inspecting the calibration storm event periods, and determining which statistics were regarded as poor. The storm event periods that were noted to be poor either had ISEs that were too high ($ISE > 10$) or NSE's that were too low ($NSE < 0.2$). For these storm event periods, the parameters were varied again, to determine the best way of improving their statistical indices, without negatively affecting the indices of the other storm event periods. Once the indices of ISE were regarded as very good ($ISE < 6$), this is when the verification run could be made.

D.2.3 Optimisation process

The SRTC tool was used to optimise the parameters of uncertainty to get the best statistic possible. Once the time series and their events were loaded, the SRTC tool was ticked for each parameter which essentially loads the tool for each parameter with uncertainty. This calibration selected the NSE as the optimisation parameter but used ISE in the calibration process as well. R^2 was used to check the optimisation but was not directly calibrated for.

Once the SRTC tool had been loaded for each parameter, the sensitivity graphs were loaded. These graphs show which parameters affect the models flows the most and was assessed particularly for maximum flow as well as mean flow (which is proportional to that of total flow). The most sensitive parameters were calibrated for maximum flow first, and those for mean flow last. The method for this calibration was as follows:

- i) To start off, the statistics – Index of Simulated Efficiency (ISE), Nash-Sutcliffe Efficiency (NSE), and Root Mean Squared Error (R^2) for each storm event were tabulated. The ISE and NSE were given a rating based on those statistics from 1-3, with 1 representing Excellent, 2 representing Good, and 3 representing Average. These were then added for each storm event and used to weight the SRTC tools adjustments for each storm event.
- ii) The storm events used for the calibration were all collected in 2019 at Bongani 10, whereas the verification events were collected in 2018 for Bongani 10 and in 2019 for Bongani 7 and 12.
- iii) Starting with the most sensitive parameter – Percentage Impervious Area – the calibration initially tabulated the change to the parameter for each storm event. This change, generated by the SRTC tool, represents the shift needed for that parameter to best optimise the statistics for that storm event.
- iv) Once the changes were noted, they were weighted based on the storm events that had the worse statistics. Once these factored percentage changes were calculated, their average was input into the SRTC tool for Percentage Impervious Area, and the next most sensitive parameter could be addressed following the same method, and the same weighting's. Furthermore, the percentage change for the first parameter remained constant in the remainder of the calibration.
- v) The next step of the method was to calibrate the Conduit Length, then the Sub-catchment Width, Slope, n Impervious, Percentage Zero-Impervious Area, and Depression Storage for Impervious Areas.
- vi) Once the calibration was complete for each of the parameters, the final statistics were tabulated next to the original statistics and assessed to see which storm events were calibrated well and which ones the calibration was not as effective.
- vii) Verification follows calibration. This entailed an assessment of the independent storm events and locations and the impact that the calibration had.

D.3 Water quality modelling

D.3.1 Wash-off parameters

One of the methods used for wash-off parameter estimation was as follows:

- i) Acquire wash-off data from different international sources for nutrients & sediments
- ii) Determine which of the land use parameters relate to the model's land use groups.
- iii) Average relevant estimates from land uses for each land use group
- iv) Complete an aggregation to get a ratio of the land use wash-off parameter estimates from the previous step to represent the spread of pollutants.
- v) Calculate factors for each average wash-off value for each land use group.
- vi) Acquire a multiplicative factor for each land use group to scale in-situ data.
- vii) The land use groups were represented by sampling locations that primarily have that land use group making up a sizeable portion of their catchment (how much?)
- viii) The land use groups measured EMCs were then taken out by averaging the data from the sites that represent that habitat.
- ix) The conversion of the measured EMC to the different habitat EMCs was then complete by multiplying each multiplicative factor into the measured EMC to get the EMC value for each habitat that would later represent the wash-off from that land use group in the model.
- x) A check of the results in PCSWMM is recommended before finalising these values, this ensures that the measured and modelled pollutant loads were not obscured by the method.

The multiplicative factor represents the ratio of the wash-off coefficients between different land use groups to one another. This adjusts measured EMCs by relating each habitat to a scaling factor based on the literature available. This factor then represents the difference in concentrations measured and coefficients used in literature. Allowing for a scaling of the measured data to represent a trends between land uses have been used in similar research. For all measured samples, the measurement of TN, TP, and TSS was not always prioritised due to financial restrictions. Rather than test for those parameters, inorganic nutrients were rather tested for to acquire more widespread data measurements. This led to the data used being modified and adapted to best represent the water quality in the stream. The following descriptions provide insight into the pollutants measured and their estimated parameters.

For the development of the TP wash-off parameters, the following method was followed: :

- i) TP EMCs came from averaging the SRP measurements and multiplying them by a factor.
- ii) The SRP:TP factor was acquired from taking the average TP result (of which there were fewer samples than for SRP) and dividing them by the average SRP result.

The motivation for using TP over SRP was mainly attributed to the fact that TP has a larger importance bestowed upon it, both in the literature, as well as in the *Stormwater Management Impacts Policy* (CCT, 2009).

For TN parameters, the method was:

- i) TN EMCs came from averaging out the NH₄ and TOxN (their sum is TIN) measurements and multiplying them by a factor.
- ii) The TIN->TN factor was acquired from taking the average TN result (of which there were fewer samples in comparison to TIN) and dividing them by the average TIN result.
- iii) This was also done for build-up.

For TSS wash-off coefficients, the method was:

- i) Although TS was the primary measurement, TSS is generally more common in literature values and policy recommendations.
- ii) Thus, TSS was modelled, and there were no changes to the wash-off method, other than the adapting of Peri-Urban and Bare Earth which were seen to be contributing too much TSS in the model and were scaled down as a result.

D.3.2 First order decay functions in PCSWMM

Decay Coefficient – a first order reaction coefficient (in units of 1/days) used to compute the rate at which the constituent decays due to reaction or other processes once it enters the conveyance portion of a SWMM model.

D.3.3 Pollutant build-up in PCSWMM

A summary of different sources provided coefficients for the build-up of the pollutants were found in a study by Tu & Smith (2018). There are two types of build-up modelling, namely area-based and curb-based. The data collected in this study was used to develop area-based build-up and because Tu & Smith (2018) only provided area-based coefficients for TSS and TN, and curb-based coefficients for TP, a conversion factor was used for the TP data which used the relationship between TN measurements and was compared to TP measurements. The TN concentrations were five times that of TP, and thus a factor of 0.2 was used scale TN build-up coefficients into TP build-up coefficients. The build-up coefficients were calculated, however, due to the uncertainty of their true relation to the local context, were removed from the final model.

Appendix E – SuDS development

Sustainable Drainage Systems (SuDS) aim towards managing stormwater runoff in a way that reduces downstream flooding, allows for infiltration into the ground, minimises pollution, improves the quality of stormwater, reduces pollution in water bodies, and enhances biodiversity. Rather than merely collecting and discarding stormwater through a system of pipes and culverts, this approach recognises that stormwater can be used as a resource. SuDS involve a network of techniques aimed at controlling velocity and removing pollutants as runoff flows through the system. These interventions can form a natural part of open spaces in a settlement and contribute to the quality of the environment and the character of a neighbourhood (Armitage *et al.* 2013). This Appendix provides the calculations and sizes of the various SuDS developments investigated in this study.

E.1 Water quality volume methods

i) The WQV method from the *SA Guidelines for SuDS* (Armitage *et al.*, 2013)

The method for WQV can be calculated as shown in Equation E-1 (Debo & Reese; 2003):

$$WQV = \frac{P * Rv * A}{1000} \quad \text{Equation E-1}$$

Where: WQV = Water Quality Volume (m^3); P = Rainfall depth (mm); Rv = Volumetric runoff coefficient; A = Drainage area (m^2)

The volumetric runoff coefficient (Rv) can be calculated as shown in Equation E-2:

$$Rv = 0.05 + 0.009 * I \quad \text{Equation E-2}$$

Where: Rv = Volumetric runoff coefficient; and I = percentage of impermeable cover.

There were three methods found for acquiring the rainfall depth (P) for the WQV calculation:

- A predetermined rainfall depth can be chosen, which is usually related to the amount of rainfall that is capable of generating a significant level of pollutant wash-off, with rainfall depths ranging from 10-30 mm (Atlanta Regional Commission, 2016; Wilson *et al.*, 2004). This is not a very specific method, and thus, only the following two were considered for the SuDS developments.
- A rainfall event analysis to acquire a daily rainfall depth in the 85th to 90th percentile of the storm events that occur in a year. This is motivated by Atlanta Regional Commission (2016) who use the 85th percentile rainfall depth to calculate the WQV and Armitage *et al.* (2013) who noted that smaller storm events which convey much of the pollution from a catchment and are usually less than the 90th percentile storm event.

- The use of a 6-month RP 24-hour rainfall event. This was determined using PCSWMM which provides respective RP storm events for both maximum rainfall depth and maximum runoff flow rates. There was one 6-month RP 24-hour duration storm event which was used as an estimate for the WQV. This storm event had a maximum rainfall depth and runoff flow rate that were both close to the 6-month RP values from the PCSWMM model.

There were thus two distinct rainfall depths that were found to represent the precipitation for the calculation of the WQV. The 90th percentile rainfall depth from 24 years of data was found to be 17.4 mm, whilst the 6-month RP rainfall depth was found to be 36.4 mm. The two rainfall depths were used to calculate a WQV range which was used to assess whether the SuDS developed within the Bongani River catchment could sufficiently store the amount of water required at a depth below 0.5 m (Woods Ballard *et al.*, 2015).

ii) The WQCV method from the Mile High Flood District (2019)

Mile High Flood District (2019) provided a method for calculating water quality capture volume (WQCV) – the volume of runoff that carries a large portion of the pollutants from a catchment – which considers the contributing catchment area, the percentage impervious area upstream, and the type of SuDS option under investigation to calculate the required volume for storing and releasing storm flows. The method calculates the WQCV in Imperial units but was used to calculate the amount of storage required for the SuDS option, which was then converted to metric units. The WQCV can be calculated using Equation E-3, and the parameter is used to calculate the volume required for storage in a pond or wetland as shown in Equation E-4.

$$WQCV = a * (0.91 * i^3 - 1.19 * i^2 + 0.78 * i) \quad \text{Equation E-3}$$

Where: $WQCV$ = Water quality capture volume (watershed-inches); a = coefficient corresponding to SuDS type; and i = impervious percentage area as a decimal.

The coefficients are presented in Table E-1.

Table E-1: A table presenting the coefficient, a , for various BMPs
(Mile High Flood District, 2019)

Drain time	Coefficient, a
12 hours (Filtration BMPs and retention ponds)	0.8
24 hours (Constructed wetland ponds)	0.9
40 hours (Extended detention)	1
No attenuation (e.g., grass buffer or swale)	1

Once the WQCV was calculated for the locations where SuDS were to be placed, the required storage volume could be calculated (Equation E-4).

$$V = (1 / 12) * WQCV * A \quad \text{Equation E-4}$$

Where: V = required storage volume (acre-feet); $WQCV$ = water quality capture volume (watershed-inches); and A = watershed tributary area upstream.

Once the required storage volume was calculated in acre-feet, it was converted to cubic meters (m^3) to assess if the desired SuDS locations were spatially viable. This required storage volume for the various SuDS interventions was used to assess whether the SuDS interventions were large enough for the WQV calculated.

E.2 SuDS design summaries

Table E-2: Key design features of swales

Armitage <i>et al.</i> (2013)	
Design feature	Description
Side slope requirement	Less than 30°, for maintenance purposes
Longitudinal slope	Gentle slopes (< 5%) generally perform better than short, narrow configurations.
Additional capacity	Berm height should exceed flow depth by 150 mm
Woods Ballard <i>et al.</i> (2013)	
Design feature	Description
Vegetated side slopes	A slope of 1:3-4
Sand/Gravel/Mulch layer	Aids with conveying subsurface flow whilst providing additional treatment
NCDOT (2014)	
Design feature	Description
Sizing	Typically sized to treat the 2-year RP storm and to convey the 10-year RP storm
Flow velocity	The velocity of the flow for the 2-year RP storm should be less than 2 ft/s (0.6 m/s)
Conveyance	Capable of conveying the 10-year RP storm with 6 inches (0.15 m) of freeboard
Non-erosive flows	4 ft/s (1.2 m/s) is considered a non-erosive flow velocity
Longitudinal slope	Longitudinal slopes should be about 0.3-4% with a maximum width of 6 ft (1.8 m)
Swale length	The length of the swale should be roughly 100 ft (30 m) per 1 acre (4000 m ²)

Table E-3: Key design features of bio-retention areas

Armitage <i>et al.</i> (2013)	
Design feature	Description
Contributing catchment sizes	Typically, between 1000-4000 m ² , with multiple, smaller cells implemented for larger areas
Flow routes	By-passes should be incorporated for higher stormwater surges, ensuring alternate flow routes are considered
Storage period	Bio-retention areas should empty out in less than 48-72 hours after a storm event
Vegetation resilience	Not only should plants be able to withstand high flows of contaminated stormwater, but survive during periods of low rainfall in the dry season
Slope stability	Ensure that there are no structural or foundation issues
Woods Ballard <i>et al.</i> (2015)	
Design feature	Description
Surface area	Enough to treat a storm event which encompasses 150 mm of runoff from impervious areas in the contributing catchment
Filter bed depth	The minimum depth for the filter bed should be 1m
Flow through filter bed	Should take less than 24-48 hours to empty
Longitudinal slope	Slope should not exceed 1:20
Drop from adjacent impervious surface	The drop from an adjacent impervious surface should be at least 50-100 mm

Table E-4: Key design feature descriptions of detention basins

Armitage <i>et al.</i> (2013)	
Design feature	Description
Temporary storage period	Typically: 24-72 hours
Outlet structure	Typically: a hard-engineered structure that can regulate discharge
Pre-treatment facilities	Typically: pollutant removal can be improved through capturing as much sediment as possible at the entrance
Surface area	Typically: at least 2% of the contributing impermeable surfaces
Woods Ballard <i>et al.</i> (2013)	
Design feature	Description
Length to width ratio	Length: width should be more than 2:1
Side slope	Gradient should be less than 1:3
Longitudinal slope	Gradient should be less than 1:40
Water depth	Maximum depth for a 100-year RP event should be 1 m
30-minute, 1-year RP storm event	Mean residence time should be more than 9 minutes Flow depth should be less than 100 mm Flow velocity should be less than 0.3 m/s

Table E-5: Key design feature of retention ponds

Armitage <i>et al.</i> (2013) for Retention Ponds	
Design feature	Description
Dam wall and weir system	Typically, these structures dam the watercourse and control the outflow
Performance improvements, pre-treatment	Sediment forebay at the inlet of the pond
Flood control measures	Additional storage volume, with flood water spillage controlled over a 3 m vegetated buffer around the pond
Storage and outlet structure considerations	Allowing for temporary storage (24 hours), and allowance for complete draining for maintenance purposes.

Table E-6: Key design features of constructed wetlands

Woods Ballard <i>et al.</i> (2015) for pond-wetland systems	
Design feature	Description
Planted edges	Damp bench, the area above the permanent water level, of 1:3 or 1:4 slope Aquatic bench depth 400 mm of 1:3 or 1:4 slope
Non-planted edges	Pond margin of 1:3 or 1:4 slope leading to permanent pool with a slope of 1:3
Flow width to length ratio	Width: length of 3:1 or 4:1 to 5:1
Pond depth maximum limits	Maximum 2 m to prevent stratification and anoxic zone development, 1.2 m is recommended for safety
Depths to be included	0.6-1.0 m depths are recommended for inclusion
Max temporary storage depth	0.5 m for storage of WQV above pond level, more for larger events
Safety bench width and slope	3.5 m width at a slope of 1:15
Hydraulic exceedance design	Freeboard of 300 mm for storm event
Armitage <i>et al.</i> (2013) for Constructed Wetlands	
Design feature	Description
Inflows	If base flow is not present, ensure sufficient water supply to support the ecosystem. Inlet and outlet structures can be used to bypass for floods
Flow regulation	Meandering and evenly distributed flow through the wetland to extend detention times and increase contaminant removal as well as preventing unwanted stagnation, maximise flow path with inlets and outlets
Vegetation options	Considerations for vegetation that aids in pollutant removal, tolerates water-logged conditions, and moderate risk for weed/ alien growth
Sediment forebay	Prior removal of debris, litter, coarse sediments, and toxic pollutants
Geometry	Ratio of flow path length: width should be greater than 3:1. Baffles, wetland shaping, and islands can increase flow path and maximise WQV treatment
System depth distribution	50% of the pond area should be shallower than 0.5 m 30% of the pond area should have depth of 0.5-1 m 20% of the pond area should be 1-1.2 m in depth

NCDOT (2014) for Constructed Wetlands	
Design feature	Description
Contributing area	Best for areas larger than 5 acres (2 ha)
Permanent water level	Within 6 ft (1.8 m) of the seasonal high-water table
System depth distribution	40% should comprise the shallow water zone 3-6 inches (75-150 mm) 30-40% should comprise the shallow land-zone (temporary storage) 15-20% should comprise the forebay and deep pool at 1.5-3 ft (450-900 mm)
Outlet control	Designed for 10-year RP event, 2-3 inches (51-76 mm) ($H = \frac{1}{2} * WQV$ depth)
Emergency spillway	Designed for 50-year RP event
Drawdown period	2-5 days, outlet control can be replaced if spillway if designed accordingly
Embankment design	1 ft (305 mm) freeboard and a width of 10 ft (3.05 m) for maintenance

E.3 Forebays

Forebays are considered as standard practice as pre-treatment facilities in the design of regional and local controls. The need for pre-treatment facilities upstream of the SuDS developed is also motivated for because they can remove sediment and gross pollutants from stormwater entering the downstream SuDS interventions. A few design guidelines are provided in Table E-6.

Table E-7: Key design features of forebays (NCDOT, 2014)

Design feature	Description
Forebay size	Should be sized to manage a 1-inch (25 mm) runoff depth from upstream impervious areas
Materials	Should have erosion control at the inlet and be lined with an appropriate geotextile
Depths	Recommended depths for forebays are 3-5 ft (0.9-1.5 m)
Sizing for rectangular forebays	Length to width ratio of 2:1 to 6:1 and have a minimum width of 3 ft (0.9 m) Circular forebay diameter is minimum to be 5 ft (1.5 m)
Side slopes	Side slopes should be flatter than 1:2

The method from Melbourne Water (2005) calculates two key variables using three equations. Firstly, the storage volume for a particular location is calculated using $V_s = A_c * R * L_o * F_c$ Equation E-6. The contributing upstream area and sediment loading rate for two years – from the 1st of January 2018 to the 31st of December 2019 – were acquired from PCSWMM for the specified node. A sediment removal fraction of 0.8 was used and is linked to the 80% removal efficiency noted by Melbourne Water (2005) as well as Armitage *et al.* (2013). A clean-out frequency of 1 year was chosen, which would be a required maintenance activity. Secondly, the minimum area of the forebay was calculated using Equation E-7 which was rearranged as shown in Equation E-5 below. Besides keeping the sediment removal fraction at 0.8, the calculation was

informed by $n = \frac{1}{1 + \lambda}$

Equation E-8 which provided a

turbulence factor which is a factor related to the hydraulic efficiency of a forebay depending on the width, length, shape, and control structures within it. An illustration of the hydrodynamic flow conditions is presented in Figure E-1, from which a hydraulic efficiency was chosen for the forebays based on the desired shape of the basin.

$$Af = \frac{[1/[1-R]^{1/n} - 1] * n * Q}{vs} \quad \text{Equation E-5}$$

Where: Af = Surface area of basin (m^2); R = 0.8 (Sediment removal fraction); n = Hydraulic efficiency; Q = Flow rate for 1-year RP event (m^3/s); and vs = Typical settling velocity (mm/s).

The 1-year RP storm event used for the flow rate was acquired using the storm event from the 2nd to 3rd January 2008 (Table 8-1) and accounted for flow through the representative junction. Furthermore, the typical settling velocity was checked for two of the smaller particle sizes including fine silt ($16 \mu m = 0.18 mm/s$) and very fine silt ($8 \mu m = 0.04 mm/s$) (Melbourne Water, 2005). This allowed for depth to be calculated for the system by dividing the storage volume by the minimum area calculated or the area available at the site chosen

About 50-80% of suspended solids carried in urban stormwater are $125 \mu m$ or larger and have lower concentrations of contaminants compared to smaller particle sizes (Melbourne Water, 2005). Furthermore, analysis of particulate nutrients and metals indicate that these contaminants are generally smaller than $50 \mu m$ and effective removal is best undertaken by treatment measures like constructed wetlands rather than forebays. The frequency for desilting a forebay varies between sites, however, a frequency of five years was provided by Water by Design (2012) and Fair & Geyer (1954).

The sediment loading range provided by Melbourne Water (2005) is $50-200 m^3/ha/year$ for catchments that are developing whereas a developed catchment was noted to be about $1.6 m^3/ha/year$. They noted that desilting should occur when the permanent pool is around half full of deposited sediment. The design discharges that should be used to size a sedimentation basin include design flow for sizing the required basin size; minor system design flow for the design of the inlet structure; and major flood flows for the design of the basin overflow structure.

A forebay design procedure was provided by Melbourne Water (2005), with the forebay storage volume calculation in Equation E-6. The recommended sediment removal of 80% is appropriate for a particle size of $1mm$ for the water quality design event and should provide sufficient storage for coarse sediment between maintenance events. The forebay should also provide energy dissipation for incoming flows.

$$Vs = Ac * R * Lo * Fc \quad \text{Equation E-6}$$

Where: Vs = Storage volume (m^3); Ac = Contributing area (Hectares); R = Sediment removal (often 0.8); Lo = Sediment loading rate ($m^3/ha/year$); and Fc = Clean-out frequency (years).

The area of the forebay calculation was determined by Equation E-7, which was presented by Fair and Geyer (1954) as cited by both Melbourne Water (2005) and Woods Ballard *et al.* (2015):

$$R = 1 - \left[1 + \frac{v_s * A_f}{n * Q} \right]^n \quad \text{Equation E-7}$$

Where: R = Recommended sediment removal (0.8); v_s = Typical settling velocity (m^3); A_f = Surface area of basin (m^2); n = Turbulence parameter; and Q = Flow rate for 1-1year event (m^3/s).

The turbulence parameter depends on the hydraulic efficiency of the water body which ranges from 0-1 based on the flow conditions present. Persson *et al.* (1999) related the shape of a basin to its hydraulic efficiency (Figure E-1), with Equation E-8 providing the calculation for the turbulence parameter.

$$n = \frac{1}{1 + \lambda} \quad \text{Equation E-8}$$

Where: n = Turbulence parameter; and λ = Hydraulic efficiency of the basin.

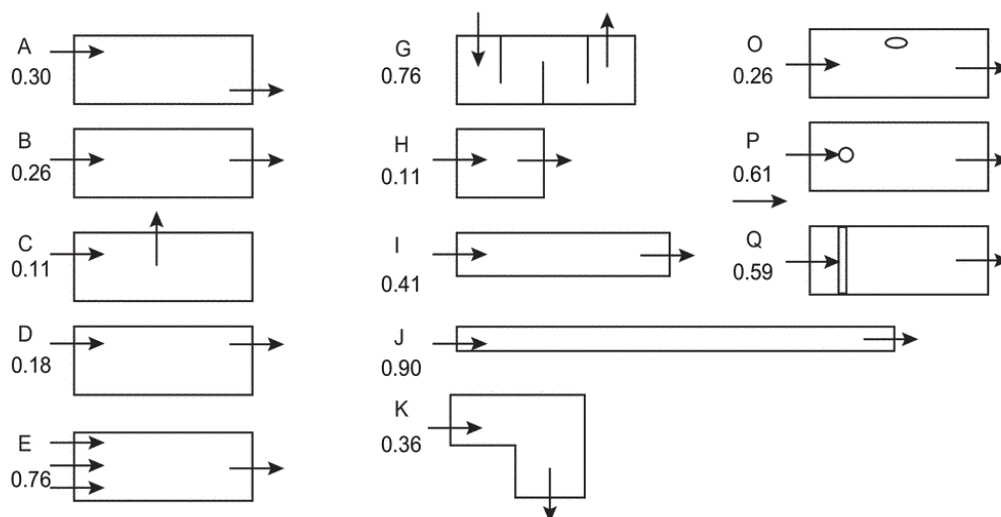


Figure E-1: Hydrodynamic conditions and the respective hydraulic efficiencies
(Persson *et al.*, 1999)

Woods Ballard *et al.* (2015) used a duration of 15 minutes for a 1-year RP flow rate to acquire the design flow rate. This design philosophy differs to the flow rate of a 24-hour duration that was recommended by CCT (2009) and Atlanta Regional Commission (2016). The depth of the forebay can be calculated by dividing the volume by the depth. Furthermore, it was noted that to prevent resuspension of sediment, the design can be developed using a higher RP storm event.

The following two tables describe the calculations and parameters used for the development of the forebays:

Description	Formula	Bongani Creek	Vigilance Canal
Sediment trap location		J239	J12
Contributing area (ha)		555.2	57.7
TSS load in 2 years (kg)		697200	213300
Convert to volume/year (m ³ /year)	TSS2y/(2y*BulkDensity)	266	81.4
Lo (m ³ /ha/year)	Vol/y/Contributing area	0.479	1.41
Vs (m ³)		426	130
Design flow 1-year RP (m ³ /s)		3.59	2.15
Chosen shape code		K	K
Af (m ²) (vs = Fine Silt)		89.2	53.6
Af (m ²) (vs = Very Fine Silt)		401.5	241.1
Depth (m) (vs = Fine Silt)	Depth = Vs/Af	4.77	2.43
Depth (m) (vs = Very Fine Silt)	Use bigger area...	1.06	0.54
Length of base (m)		40	40
Width of base (m)		10	8
Area of base (m ²)		440	320
Volume (m ³)	L x B x D	> 440	> 144
Description	Heidevallei Retention	Old Place Detention	
Sediment trap location	J127	J129	
Contributing area (ha)	303.7	199.3	199.3
TSS load in 2 years (kg)	50500	155900	155900
Convert to volume/year (m ³ /year)	19.3	59.5	59.5
Lo (m ³ /ha/year)	0.0635	0.3	0.3
Vs (m ³)	31	28.43	28.43
Design flow 1-year RP (m ³ /s)	2.00	1.49	1.49
Chosen shape code	Q	C	B
Af (m ²) (vs = Fine Silt)	83.4	37	43
Af (m ²) (vs = Very Fine Silt)	375.4	166	195
Depth (m) (vs = Fine Silt)	0.37	0.77	0.66
Depth (m) (vs = Very Fine Silt)	0.08	0.17	0.15
Length (m)		Using 30 m ³ & 200 m ²	100
Width (m)		3:1 L:W	0.30

Parameters for forebays	Values			
Bulk density of soil(kg/m ³)	1310			
Sediment removal rate R	0.8			
Clean out frequency Fc (years)	2			
Settling velocity (Fine silt 16um)	0.18			
Settling velocity (Very fine silt 16um)	0.04			
Side slopes	1:5			
Shape code:	Q	K	C	B
Hydraulic efficiency - λ	0.59	0.36	0.11	0.26
Turbulence parameter - n	0.63	0.74	0.90	0.79

E.4 Water quality volume calculation

WQV calculation rainfall alternative	Rainfall (mm)
90th percentile	17.4
6-month RP	36.4

Bongani Creek (J239)			
Upstream catchment area (m²)	Impervious %	Rv	WQV (m³)
5530	17	0.21	20,900
			43,700
Vigilance Canal (J12)			
Upstream catchment area (m²)	Impervious %	Rv	WQV (m³)
606,000	61	0.60	6380
			13,300
Bongani wetland WQV = WQV (J239) + WQV (J12)			WQV (m³)
			27,200
			57,000

Heidevallei Pond (J127)			
Upstream catchment area (m²)	Impervious %	Rv	WQV (m³)
3325,000	18	0.21	12,200
			25,500
Old Place Detention (J129)			
Upstream catchment area (m²)	Impervious %	Rv	WQV (m³)
2090,000	12	0.16	5860

			12,300
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E.5 Heidevallei Constructed Wetland

The Heidevallei Constructed Wetland was located along the main tributary of the Bongani River upstream of where it crosses the N2 Highway. A berm was introduced at the interface between the sediment forebay and the rest of the wetlands pond area. The sediment forebay had a volume of 271 m³ beneath the designated overflow depth of 0.2 m that connects the forebay and the wetland. The side-slopes of the sediment forebay were 1:3 between the floor and the berm height (1 m) and a slope of 1:5 for the aquatic bench surrounding it. The water then spills over the berm into the retention pond which had the following design specifications:

- i) A safety bench of 4.5 m width and a slope of 1:15
- ii) A planted edge of depth 0.4 m and a slope of 1:5
- iii) A permanent pool of depth 1.2 m and a slope of 1:3
- iv) An overflow weir with a length of 6 m

The forebay developed

Description	Parameter	Inflows from forebay	
Forebay slope	chosen to be 1:3, min 1:2	Depth (m)	Width (m)
Forebay length	20 m	0	22
Forebay width	5 m	0.2	14
1m bottom width	2 m side width		
Depth	1.2 m		

Pond area-depth distributions

Area description	Area (m ²)	% Total area	Permanent depth (m)
Deep pool	1000	11	- 1.2
Marsh	2700	15	-0.5
Shallow marsh	1500	16	-0.2
Permanent storage	5500	58	0
Temporary storage	9000		+0.5
Total storage	9500	100	+1.8

Outflows from wetland

Description	Offset (m)	Depth (m)	Width (m)	Height (m)	Length (m)
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Closed rectangular outflow	1.2	0	0.9	0.45	
Overflow weir	1.7	-0.5	2.5	1.3	

E.6 Old Place Detention Wetland

Forebay development

Description	Parameter
Forebay slope	chosen to be 1:3, min 1:2
Forebay length	20 m
Forebay width	5 m
1m bottom width	2 m side width
Depth	0.3m

Pond area-depth distributions

Area description	Area (m ²)	% Total area	Permanent depth (m)
Temporary wet pool	200	11	-1.0
Undulating shallow bench	1000	43	-0.5
Temporary storage	1500	27	0.0
WQV storage	1800	16	+0.5
Total storage	1850	100	+1.8

Inflow to forebay

Description	Depth (m)	Width (m)
Closed rectangular beneath N2	2.2	3.0

Inflow from forebay to detention wetland

Description	Depth (m)	Width (m)
Closed rectangular	0.5	0.5

Inflow from forebay to Old Place Stream during large storm events

Description	Depth (m)	Width (m)
Closed rectangular	2.0	0.3

E.7 Bongani Constructed Wetland

Generalised flow rates	Bongani Creek	Vigilance Canal
Description		
1-month RP (L/s)	679	729
3-month RP (L/s)	1519	1401
6-month RP (L/s)	2401	1949
1-year RP (L/s)	3211	2435
2-year RP (L/s)	3968	3115
5-year RP (L/s)	4961	3574
10-year RP (L/s)	6863	4674
25-year RP (L/s)	12,693	6298

Parameters	Deep pool excl. FB	Shallow marsh	Shallow land	Flood storage	Total
% Area distribution requirements	20%	30%	20%	30%	100%
Area's	3960	7200	4800	7200	24,000
Depth permanent	1.2	0.5	0	0	
Volume permanent	4752	1800	0	0	6552
Depth WQV	1.7	1	0.5	0	
Volume WQV	6732	5400	1200	0	13,330
Depth flood storage	3	2.3	1.8	1.3	
Volume flood storage	11,880	14,760	7440	4680	38,760
System areas and lengths		WQV land area		Permanent area	
Area (m2)		15,960		11,160	
Length (m)		44		31	
System considerations:					
When WQV, only flows to Wetland		Weir controls, 0.2 m depth		Same width as forebay = 4	
Considerations:		System design		Invert elevation (m)	
Length to width ratio aimed for 1:10		Bongani Creek outflow		6.5	
The top of the wetland can start at the level of the lip, with a particular width		Bongani Creek SF		4.3	
Consider a narrow stream until the full pond depth?		Vigilance Canal outflow		5.5	
This is where the deep pool starts?		Vigilance Canal SF		4.9	
Weir at the waterfall has a 1m drop, aeration...		Bongani Wetland		4.3	
		Bongani Wetland weir		5.5	

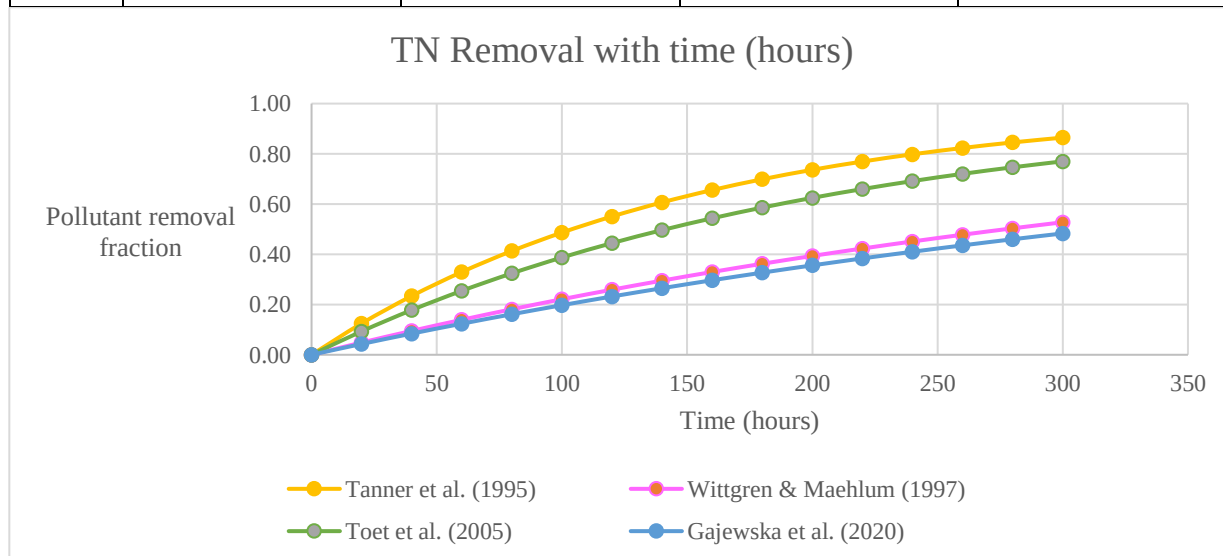
The size of the various parts of the Bongani Constructed Wetland are summarised below:

- The shallow marsh was given a depth of 0.5 m at its deepest. The overflow from the forebay to the deep pool was 16 m wide and at the permanent pool level would have a depth of 0.2 m. It was assigned an area of 1000 m² at the depth of 0.5 m, and an area of 6000 m² at the depth of 0.2 m. The area of the shallow vegetated bench surrounding the deeper parts of the system was about 10,500 m² around the shallow marsh and including the deeper parts.
- The deep pool was assigned a depth of 1.2 m, at its deepest with an area of 6000-7000 m². The area for permanent pool depth around the deep pool was assigned to be 9500 m².
- The temporary storage area surrounding the shallow marsh and deep pool components was 14,500 m². This included the temporary land area as well as the berm that surrounded the system which could store storm events up to the maximum 24-hour storm which occurred on the 21st of December 2004 in the rainfall time series.

E.8 Pollutant removal coefficient data

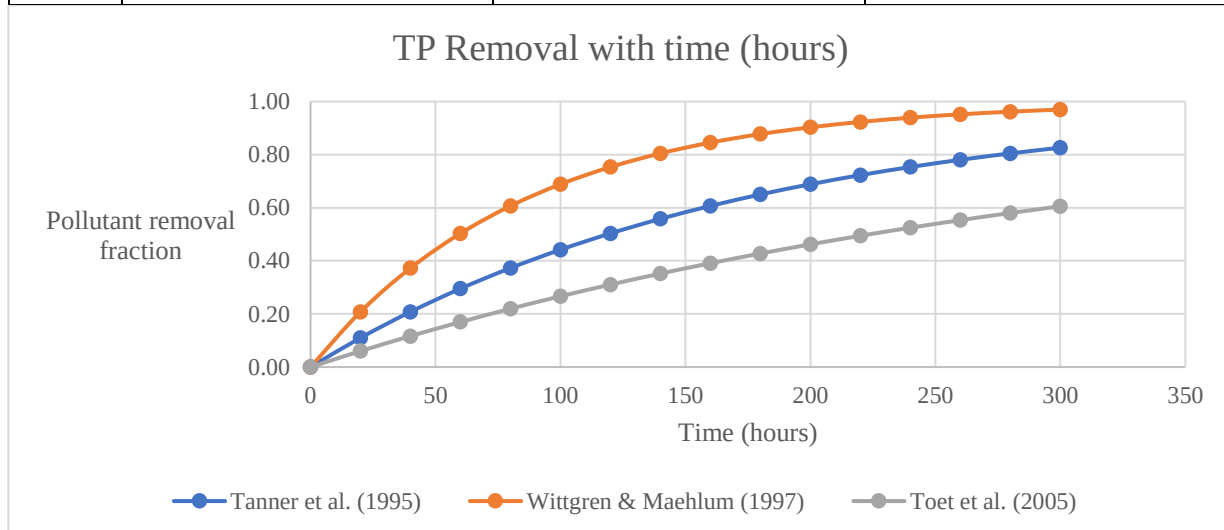
The following table and graph present the pollutant removal coefficients (k-values) for total Nitrogen (TN) removal:

Source	Tanner et al. (1995)	Wittgren & Maehlum (1997)	Toet et al. (2005)	Gajewska et al. (2020)
k-value	0.0067	0.0025	0.0049	0.0022



The following table and graph present the pollutant removal coefficients (k-values) for total Phosphorus removal:

Source	Tanner <i>et al.</i> (1995)	Wittgren & Maehlum (1997)	Toet <i>et al.</i> (2005)
k-value	0.0058	0.0117	0.0031



Appendix F – Ethics clearance

Application for Approval of Ethics In Research (EIR) Projects
Faculty of Engineering and the Built Environment, University of Cape Town

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:		Calvin van der Merwe	
Department:		Civil Engineering	
Preferred email address of applicant:		vmrca1001@myuct.ac.za	
If Student:	Your Degree: e.g., MSc, PhD, etc.	MSc.	
	Credit Value of Research: e.g., 60/120/180/360 etc.	180	
	Name of Supervisor (if supervised):	Professor Neil Armitage	
If this is a research contract, indicate the source of funding/sponsorship			
Project Title		Stormwater management for Knysna's polluted urban catchments	

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	Calvin van der Merwe		29/10/2019

SUPPORTED BY	Full name	Signature	Date
Supervisor (where applicable)	Prof Neil Armitage		30/10/19

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).	Dyllon Randall		11 Nov 2019
Chair: Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the questions in Section 1.			

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