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Research paper

Modelling the impact of SuDS on stormwater quality management in the Bongani River catchment, Knysna, South Africa

CD van der Merwe[1] **and NP Armitage**[1]

[1]*Department of Civil Engineering, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa*

The Bongani River is a primary source of polluted stormwater runoff discharging into the shallow Ashmead Channel, a portion of the Knysna Estuary situated on the southern coast of South Africa. 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 improve stormwater management. The feasibility of reducing nutrient loads using SuDS was investigated using a continuous hydrological model of the Bongani River and its catchment. Besides the current situation (Current Scenario), various scenarios were developed in PCSWMM (Personal Computer Stormwater Management Model). The total phosphorus reduction objective for SuDS set by the City of Cape Town (used in the absence of Knysna-specific stormwater quality objectives) is 45%. All the scenarios modelled showed pollutant load reductions of between 47% and 78%, exceeding the 45% target, but none approached the pre-development baseline which indicated some 89% and 90% lower concentrations of total nitrogen and total phosphorus, respectively, compared to current conditions. This performance gap highlights the extent of nutrient enrichment in the Bongani River catchment and suggests that, while SuDS can provide improvements, additional watershed-scale interventions are necessary to restore water quality conditions.

CORRESPONDENCE
NP Armitage

EMAIL
neil.armitage@uct.ac.za

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INTRODUCTION

The Knysna Estuary is a major tourist destination on the Garden Route, located in South Africa's southern Cape region. Its biodiversity includes seagrass meadows and intertidal saltmarsh vegetation, which are excellent carbon sinks and provide habitat, shelter and food for several fish, birds, mammals, and invertebrate species (Adams et al., 2016). The ecosystem in the shallow eastern section of the estuary between Thesen Island and the mainland, known as the Ashmead Channel, has been experiencing recurring macroalgal blooms that threaten the ecosystem's biodiversity (Russel, 1996; Human et al., 2016; Claasens et al., 2020). Human et al. (2016) ascribed the blooms to eutrophication caused by nutrient-enriched flows entering the channel from the Bongani River. Harvey (2019) also identified the Bongani River as the principal source of nutrient-rich and biologically contaminated stormwater flowing into the Ashmead Channel, and recommended further research into determining the pollution levels and potential mitigation measures.

The aim of this investigation was to evaluate stormwater management initiatives that would reduce nutrient loading from the Bongani River to address the eutrophication problems in Ashmead Channel. Total nitrogen (TN) and total phosphorus (TP) were selected as the target nutrients because these are the primary drivers of eutrophication in aquatic systems, and their reduction represents the most direct approach to addressing the macroalgal bloom problem. Other potential water quality parameters such as heavy metals and total suspended solids (TSS) were not modelled as nutrient enrichment was identified as the dominant water quality issue.

A continuous numerical model was developed in PCSWMM to analyse and evaluate theoretical reductions of nutrient concentrations under various sustainable drainage systems (SuDS) scenarios. SuDS aim to achieve holistic management of water quantity, flooding, water quality, amenities, and biodiversity (Armitage et al., 2013). A continuous modelling approach was undertaken to account for the natural variability of storm events, which results in differing hydraulic retention times in fixed pond sizes and therefore varying treatment efficiencies throughout the year. The study used the City of Cape Town's total phosphorus reduction target of 45% (in the absence of Knysna-specific guidelines) (City of Cape Town, 2009) to evaluate SuDS performance. The study relates to Commitment 19 of The New Urban Agenda as outlined by the UN (2017) which states that there is a need to invest in protective, accessible, and sustainable infrastructure and services regarding water, drainage, stormwater management, and pollution.

Stormwater management: shifting from conventional conveyance to holistic control

Conventional stormwater systems have historically focused primarily on the rapid removal of stormwater from roads and impervious urban surfaces (City of Cape Town, 2009; Fitchett et al., 2018; DHS, 2019; City of Cape Town, 2021). A significant source of pollution entering streams, rivers, estuaries and oceans comes from the contaminants deposited upon urban surfaces from anthropogenic origins (Shaver et al., 2007; Goonetilleke et al., 2009; Liu et al., 2019; Thurstan et al., 2020). These contaminants build-up during intermittent dry periods to the point of saturation, where further deposition of sediment is swept away, usually by the wind (Di Modugno et al., 2015; Costa et al., 2021). When it rains, the sediments are transported by stormwater networks to downstream aquatic systems (Ashton and Bhagwan, 2001; Barbosa et al., 2012). The increased covering of the

Table 1. Various SuDS objectives for stormwater quality and quantity design

City of Cape Town (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, 24-h 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, 24-h storm	
Melbourne Water (2005) and South Eastern Councils (2013)		
Criteria	**Description**	
Manage stormwater discharge	Keep 1.5-year return period (RP) storm discharges at pre-development levels	
Water quality treatment	TN and TP removal of 45% TSS removal of 80% Gross pollutant (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 24-h storm event released over a period of 24 h.
	Overbank flood protection	Peak discharge control of the 25-year RP storm.
	Extreme flood protection	Evaluate the 100-year RP 24-h storm. Manage the effects with detention controls and floodplain protection.

urban landscape with roads and buildings, coupled with the deposition of many contaminants, increases the concentrations of pollutants in stormwater runoff (Marsalek et al., 2006; Rockström et al., 2014; Palla and Gnecco, 2015). 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 (non-point) sources (Ashton and Bhagwan, 2001; The Civic Federation, 2007; Mahdi and Pagilla, 2021):

- Point-source pollution arises from a specific location, such as an industrial building's effluent or a sewage overflow from a dysfunctional manhole (DHS, 2019).
- Diffuse or non-point-source pollution comes from multiple sources in a catchment area. 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).

Well-planned drainage systems can mimic processes that promote natural flow regimes and appropriate control of stormwater quality in catchment areas (Fletcher et al., 2015; Khadka et al., 2019). Fletcher et al. (2015) advocates the adoption of a more holistic approach such as sustainable drainage systems (SuDS), alternatively called water-sensitive urban design (WSUD), best management practices (BMPs), stormwater control measures (SCMs), low impact development (LID), and blue-green infrastructure (BGI) (Fletcher et al., 2015; Lamond and Everett, 2019), that were first promoted in the 1980s. SuDS offers 4 main stormwater management strategies, viz.: 'good housekeeping', source controls, local controls, and regional controls (Armitage et al., 2013). These should be linked into a treatment train which is a combination of stormwater management interventions that aim to achieve better stormwater quality and quantity management (Fletcher et al., 2015; Atlanta Regional Commission, 2016).

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). Perrin et al. (2009) and Woods Ballard et al. (2015) state that managing post-development stormwater flows in a catchment to levels like those prior to development is an effective way of addressing local water quality problems. The revised Red Book that guides urban infrastructure development in South Africa (DHS, 2019) states that the design of stormwater management interventions in a catchment can be determined by hydrologic simulation using appropriate modelling software (Niazi et al., 2017; Hossain et al., 2019). Comparing models of the catchment with various interventions superimposed with a model of the current system is a way of evaluating the likely impact of improvements. These should then be measured against the objectives set by the authorities (Table 1).

The consensus is that managing stormwater at the source is the best approach to improving quality and quantity management; however, a stormwater management treatment train is usually necessary to achieve the desired objectives (Armitage et al., 2013; Woods Ballard et al., 2015; Atlanta Regional Commission, 2016). In the case of TN and TP, removal generally requires interventions such as retention ponds and constructed wetlands.

A link between pollutant removal and hydraulic retention time (HRT) in wetlands has been observed in several studies. A study undertaken by Toet et al. (2005) recorded pollutant removal values for different HRTs in Texel, Netherlands. They collected TN and TP removal data from a sewage treatment wetland with 4 different HRTs (0.3, 0.8, 2.3, and 9.3 days) (Table 2).

Table 2. 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
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

Pollutant removal can be expressed by a first-order decay function (Rossman and Huber, 2016). Equation 1 represents a first-order decay relationship between pollutant removal and HRT.

$$\frac{A}{A_o} = e^{-k \times \mathrm{HRT}} \quad (1)$$

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

Pollutant removal coefficients (k-values) in constructed wetlands are provided in Table 3.

There is enormous variability in hydrological conditions and their modelling at any specific location (Hallouin et al., 2018). For example, rainfall varies spatially and temporally, and no data collected from specific points in the catchment will be able to fully represent these variations in space and time (Smithers, 2012; Halloiun et al., 2018). Therefore, it is important that any model used to estimate the performance of a system be capable of dealing with this kind of uncertainty (Hughes, 2004; James, 2005).

Table 3. Pollutant removal constants (k-values) for total nitrogen (TN) and total phosphorus (TP) reductions with respect to hydraulic retention time (HRT) in constructed wetlands

TN *k*-value	Reference
0.0067	Tanner et al. (1995)
0.0025	Wittgren and Maehlum (1997)
0.0022	Gajewska et al. (2020)
TP *k*-value	**Reference**
0.0058	Tanner et al. (1995)
0.0117	Wittgren and Maehlum (1997)

Site description

The streams and rivers draining into the Knysna Estuary are under considerable anthropogenic stress (Winter et al., 2016). Harvey (2019) investigated the water quality of stormwater discharges along the north-eastern shores of the Knysna Estuary from the Salt Stream in the west to the Bigai Stream in the south (Fig. 1). She gathered data on the inorganic nutrients (ammonium, nitrites, and nitrates) which make up total inorganic nitrogen (TIN), soluble reactive phosphorus (SRP), sediments as total suspended solids (TSS), and *Escherichia coli* (*E. coli*) to identify which stormwater discharges were polluting the Knysna Estuary. The pollution problem is especially noticeable along the eastern coastline of the Knysna Estuary, particularly in the Ashmead Channel that separates Thesen Island from the mainland, where a recurring macro-algal 'green tide' primarily consisting of *Ulva lactuca* is causing concerns (Human et al., 2016; Claasens et al., 2020). This bloom is fed by high nutrient loads in surface water runoff from the Bongani River, contaminated municipal discharge from the Knysna Wastewater Treatment Works (WWTW), and benthic flux from the anoxic sediment in the Ashmead Channel (Adams et al., 2016; Human et al., 2016; Claasens et al., 2020) The Bongani River has 3 main tributaries – Old Place Stream, Bongani Stream, and Vigilance Canal – that combine and flow into the Ashmead Channel near the Knysna WWTW (Fig. 2).

METHOD

This research aimed to evaluate stormwater management interventions that could improve the water quality of the Bongani River. The steps taken in developing the continuous model included (Fig. 3): selecting an appropriate modelling software; collecting various data for the model; developing the hydrological and water quality models; and investigating the

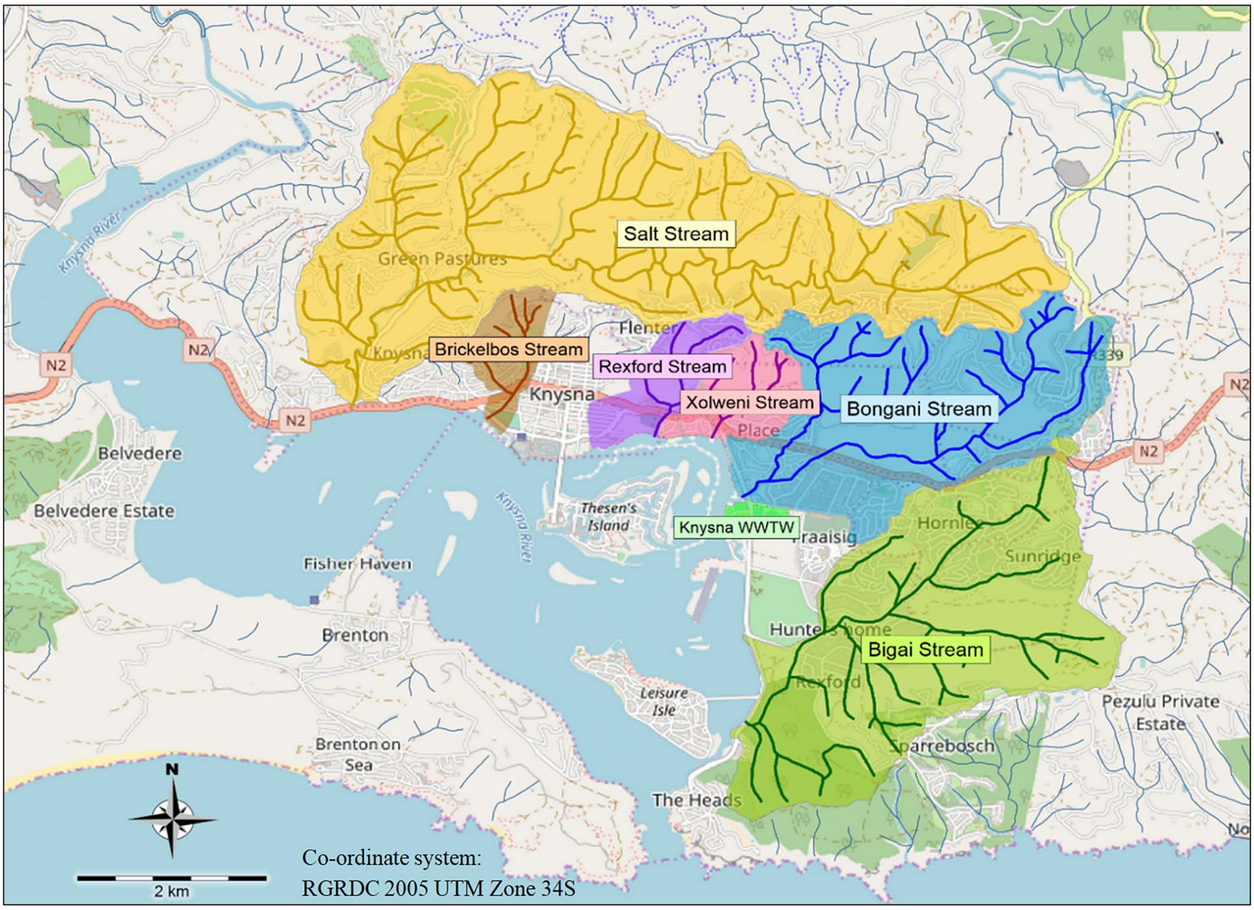

Figure 1. Knysna Estuary's north-eastern catchments (Bing map roads, n.d.; Knysna Municipality, n.d.)

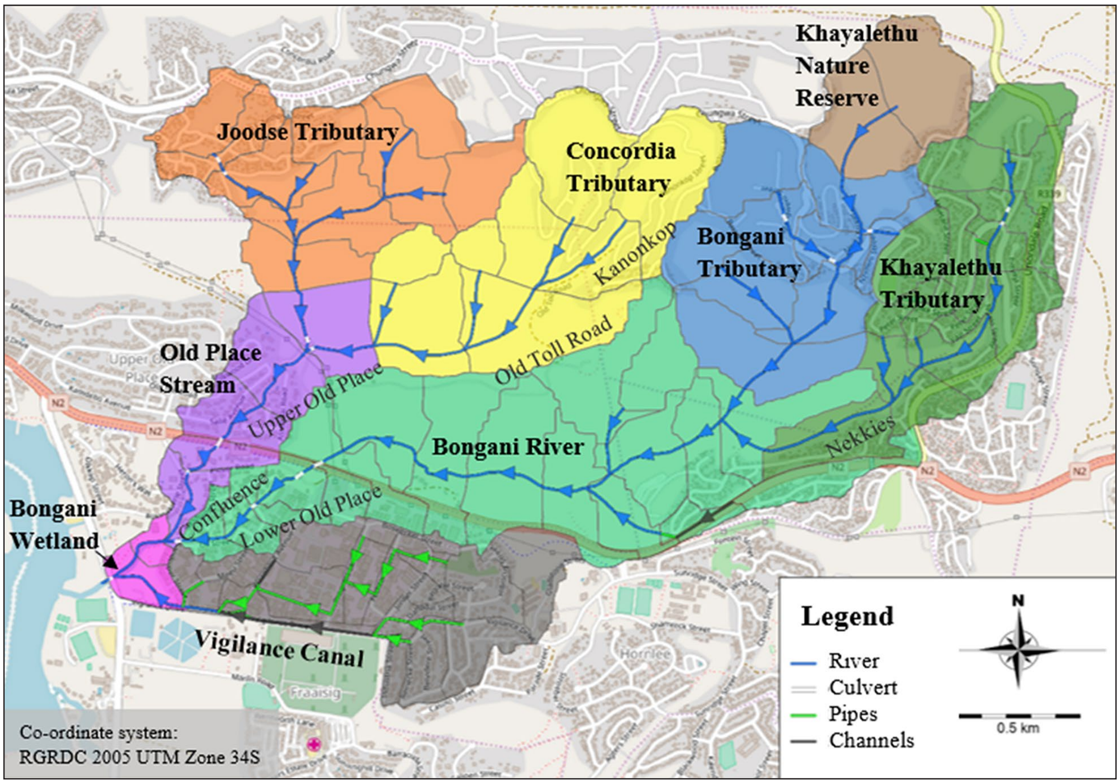

Figure 2. The tributaries of the Bongani River (Bing map roads, n.d.)

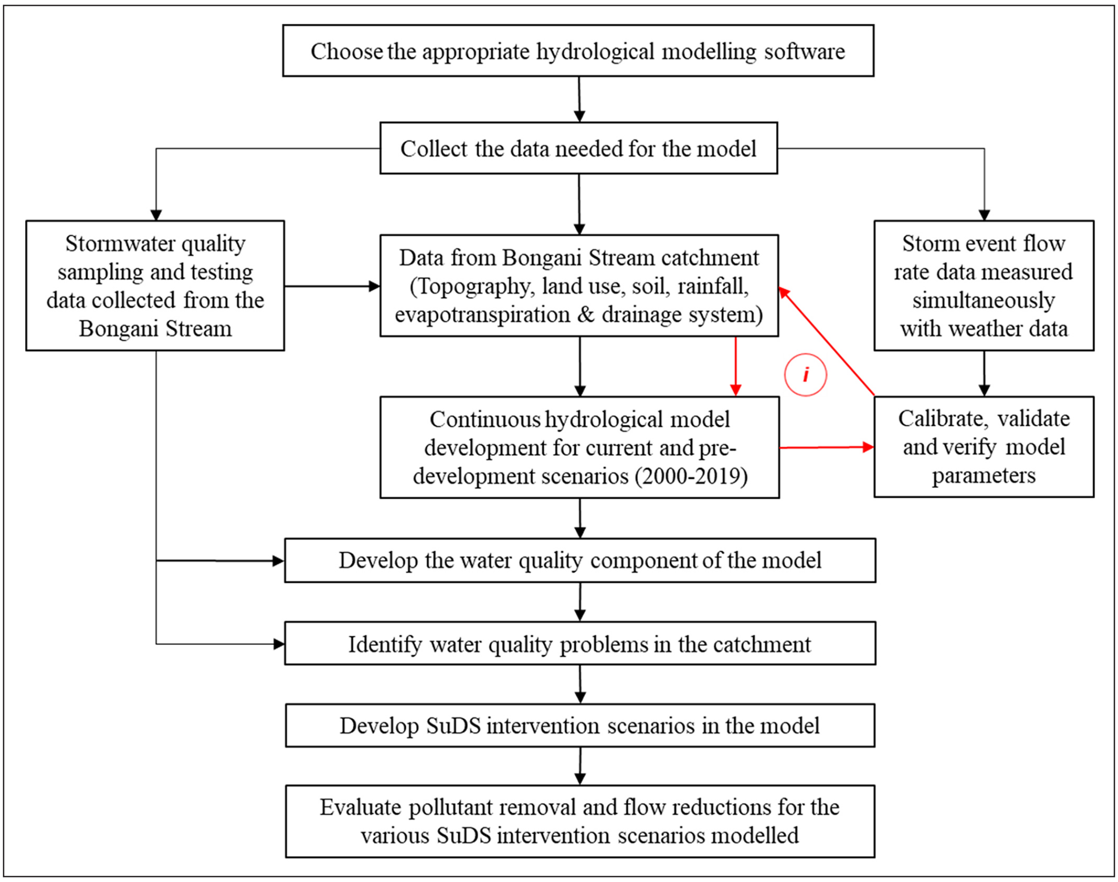

Figure 3. Research method

potential impact of various SuDS interventions by evaluating the theoretical reductions of pollutant loads in the Bongani River upon their introduction. Water quality data collected by Harvey (2019) identified that the Bongani River catchment has a problem regarding nutrients and *E. coli*. This investigation thus continued the research into stormwater pollution in the Bongani River by measuring water quality by the concentrations of nutrients and sediment and counts of *E. coli* at key points throughout the catchment. The water quality data were used to identify problem areas and provide input into the water quality model.

Several software alternatives were available for stormwater management and hydrological modelling applications. These were evaluated against various criteria, including cost, ease of use, technical support, and the ability to handle continuous flow data and water quality simulation reliably. Most pollutant modelling focuses on the removal of pollutants for specific pre-defined events. However, continuous modelling considers a more realistic range of flows from small to large, provided an appropriately long rainfall time series is available. PCSWMM was selected for the modelling as it is widely used for assessing stormwater management interventions and can run continuous simulations (Palla and Gnecco, 2015). It is supplied by Computational Hydraulics International (CHI) and uses an enhanced SWMM 5 engine, giving it good usability and functionality, together with a GIS that provides the tools for optimisation and comprehensive analysis of stormwater management applications and research (CHI, 2021). The SWMM engine is regarded as a robust software due to its long open-source history; it is continuously updated and universal, with many versions and a large user group (Hossain et al., 2019; Niazi et al. 2017). The model development was as follows:

- Setting up the initial hydrological/hydraulic flow model – including continuous rainfall, topography, land use, soil infiltration characteristics, and the existing stormwater drainage system.
- 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 that allows for storm event and continuous time series calibration of the sub-catchment and conduit parameters that 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.
- Adding the water quality component – focusing on the nutrient flux comprising various species of nitrogen (nitrites, nitrates, ammonia, and total Kjeldahl nitrogen (TKN)) and phosphorus (soluble reactive phosphorus (SRP) and total phosphorus (TP)). The wash-off event mean concentrations (EMCs) were measured for TN and TP for various rainfall events and compared with published EMCs to determine representative values.
- Once the model was calibrated and the water quality parameters estimated, the Current Scenario model was deemed complete. This was then used to investigate and interpret the impact of different SuDS interventions on the water quality of the model of the Bongani River.

Flow level and water quality data collection

Historical streamflow data from the Bongani River catchment were unavailable prior to the flow data collected by Harvey (2019) in 2018, which were used in the calibration of the hydrological model. Only two continuous flow level datasets were collected by Harvey (2019) – at the Bongani River at Uil Street (Bongani Stream Sensor), and beneath a culvert along the Vigilance Canal (Old Vigilance Canal Sensor) – both of which were used to calibrate the hydrological model developed in this research (Fig. 4).

The sampling and testing across the Bongani River catchment were undertaken in collaboration with the Knysna Basin Project (KBP) – a local NGO that helped with sampling and testing and provided a laboratory for testing. The monthly sampling and testing included 12 sites along Bongani River, the Knysna WWTW effluent, and 7 sites along the Bigai Stream. This study focused on the results from the sites in the Bongani River catchment (Fig. 5). Initially, 12 specific site locations were selected for sampling and testing in the Bongani River catchment. After 6 months of data collection from these sites, however, 6 of the sites were replaced by new sites to acquire data from the tributaries of the Bongani River not covered in the first 6-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.

The water quality measurements for the Bongani River included nutrients and *E. coli*. A map of the sample sites with the mean SRP concentrations and the mean *E. coli* counts for each site are provided in Fig. 6 and Fig. 7, respectively.

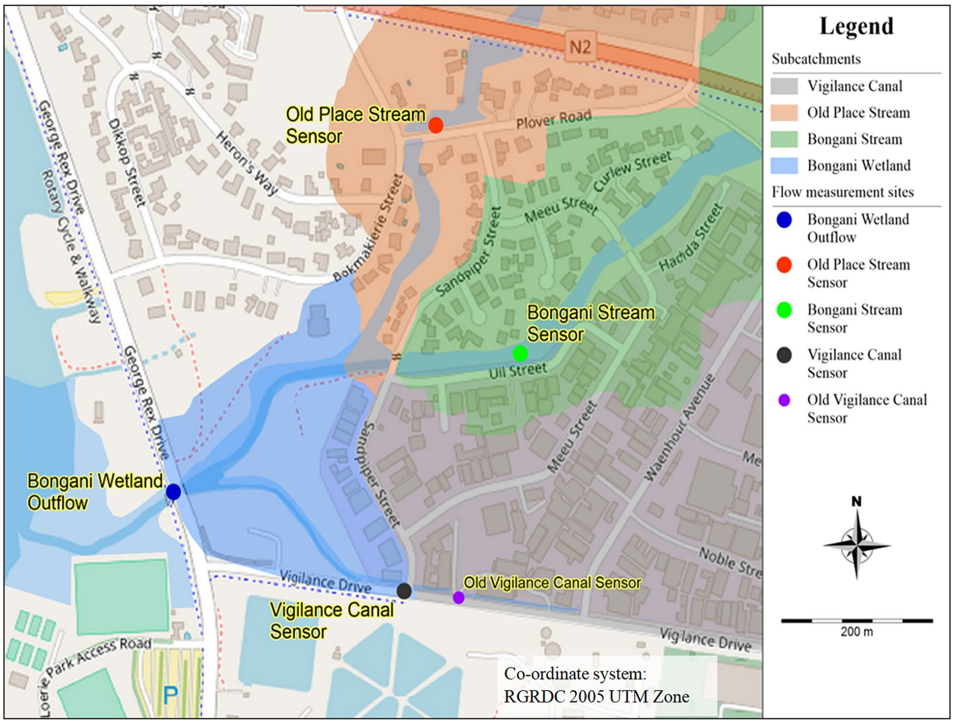

Figure 4. The flow measurement sites (Open Street Map Roads, n.d.)

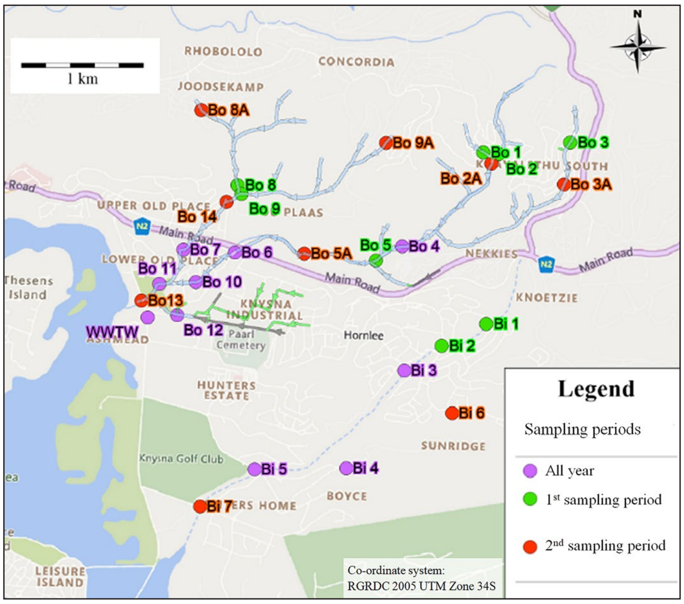

Figure 5. Sampling sites and their sampling periods (Bing map roads, n.d.)

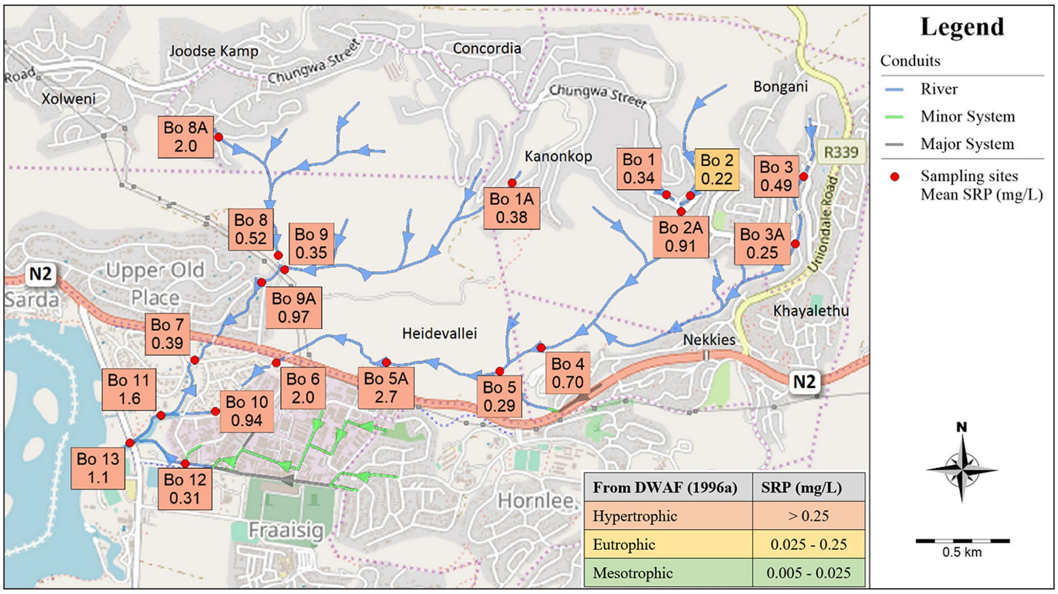

Figure 6. Mean soluble reactive phosphorus (SRP) results across the Bongani Catchment (Open Street Map, n.d.)

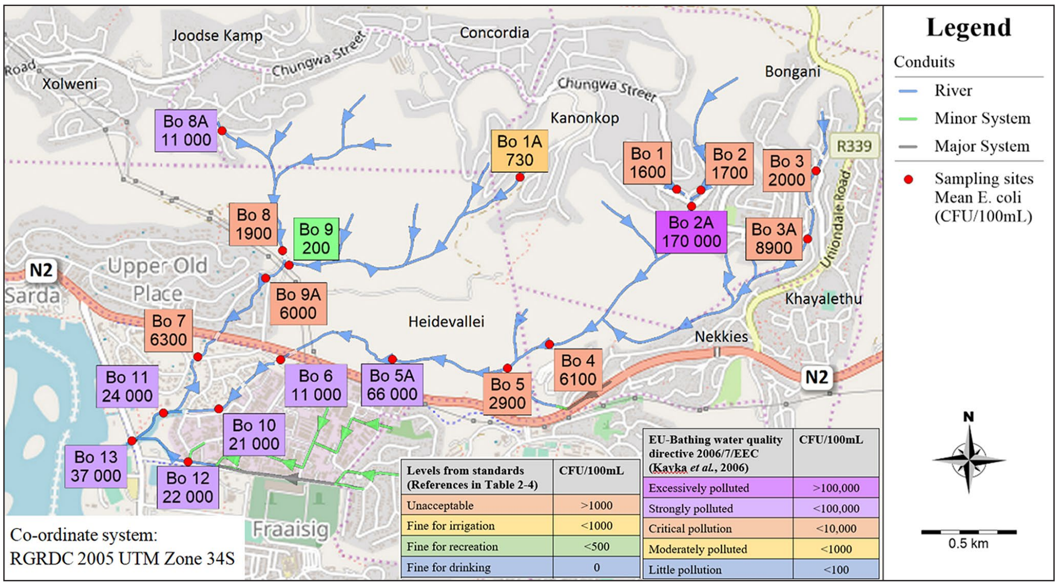

Figure 7. Mean *E. coli* counts across the Bongani Catchment (Open Street Map, n.d.)

Flow model component

The PCSWMM model setup is described in Fig. 8. Other tools used in the development of the model included:

- Microsoft Excel was used to convert data to the correct formats for PCSWMM and for data analysis purposes.
- The LEED v4.1 Rainfall Events Calculator, an Excel spreadsheet tool created by the Green Building Council (2021), was used to calculate percentile rainfall depths from the Knysna (TNK) rainfall time series.
- The software NetStorm was used to disaggregate rainfall data where required.

Flow model calibration

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 Fig. 5). The model was calibrated using a group of 5 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 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.

Water quality model component

The monthly water quality data were 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.

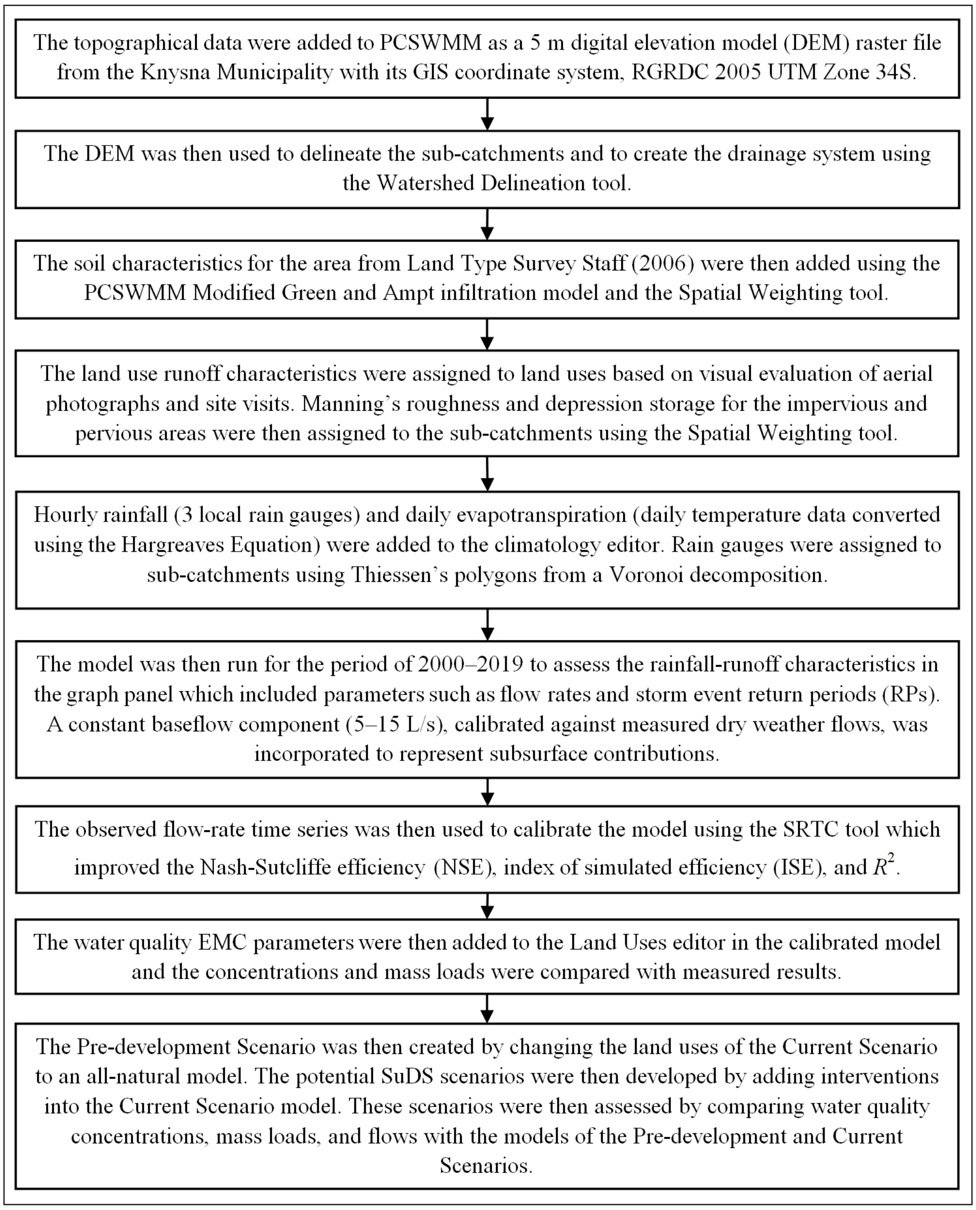

Figure 8. Process followed in setting up the PCSWMM model

Build-up coefficients were not readily available locally – neither for Knysna nor South Africa – and their use would add 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 thus needed to be estimated for the water quality component of the model. Since these were not available for Knysna, published EMC wash-off parameter coefficients for other parts of the world were used to establish a baseline that could be adjusted upon comparison with the values measured on site for various land uses and pollutants.

More than 12 months of nutrient data were collected across the Bongani River catchment for TN and TP. These allowed the estimation of EMCs that could then be compared with published values. As can be seen in Table 4, they were much higher than the published values, except for the pervious land use group.

The water quality model developed for the Bongani River catchment assumed constant EMC wash-off rates. This is an evident simplification as storm events at the beginning of the rainy season would likely remove the bulk of the pollutants resulting in a decreasing concentration through the remainder of the rainy season. Also, pollutant concentrations change continuously through a storm. Furthermore, of particular relevance in the Bongani River catchment, pollutant concentrations spike from sewerage failures which happen sporadically through the rainy season. Since no model capable of taking the variability of pollutant concentration in the Bongani River into account was available, adoption of the constant EMC wash-off approach was determined to be the most appropriate method for representing the pollutant concentrations in the model.

SuDS scenarios

Once the Current and Pre-development Scenarios had been created in the model, various site characteristics, such as available open space and water quality, were used to guide appropriate SuDS interventions for improving the Bongani River's water quality. The key water quality problems identified during the research project included the following:

- Point pollution sources, e.g., sewage overflows at points where the sewer changes gradient at a manhole (Fig. 9 left), and at sewage pump stations.
- Diffuse pollution sources such as the litter and nutrients in the stormwater (Fig. 9 right); wash-off from impervious surfaces such as the N2 highway and the Knysna industrial area; and faecal pollution from sub-serviced settlements and livestock.

Current Scenario

The Current Scenario was based on a 20-year time series, the hydraulic network as of 2020, and water quality components that were incorporated from measurements taken from the Bongani River between 2019 and 2020. The final model included 78 sub-catchments, connected by a dendritic network of 110 junctions, 3 storages, and 116 conduits draining into the Ashmead Channel (Fig. 10).

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, and served as an idealised best-case situation for comparison with the current and proposed scenarios. It was modelled by replacing the hydraulic and water quality parameters in the Current Scenario with those indicative of natural vegetation and channel types.

SuDS interventions

Identifying the areas of the Bongani River catchment that contributed significant amounts of pollution was an important aspect of the study. Figure 11 shows some of the problem areas identified in the catchment and selected locations where there was open space available for SuDS.

Table 4. Estimated site wash-off EMCs compared to mean of published values

Land use group	Estimated site EMC-TN (mg/L)	Published mean EMC-TN (mg/L)*	Estimated site EMC-TP (mg/L)	Published mean EMC-TP (mg/L)*
Urban	5.6	2.84	2.1	0.47
Suburban	6.6	2.92	2.8	0.49
Peri-urban	17.4	4.33	5.5	0.54
Bare earth	6.7	3.14	1.3	0.41
Green space	3.5	1.89	0.90	0.22
Pervious	0.5	0.50	0.13	0.13

*(USEPA, 1983; Maestre and Pitt, 2005; DDE, 2014; Järveläinen et al., 2017)

Figure 9. Example of point-source pollution (left) and diffuse-source pollution (right)

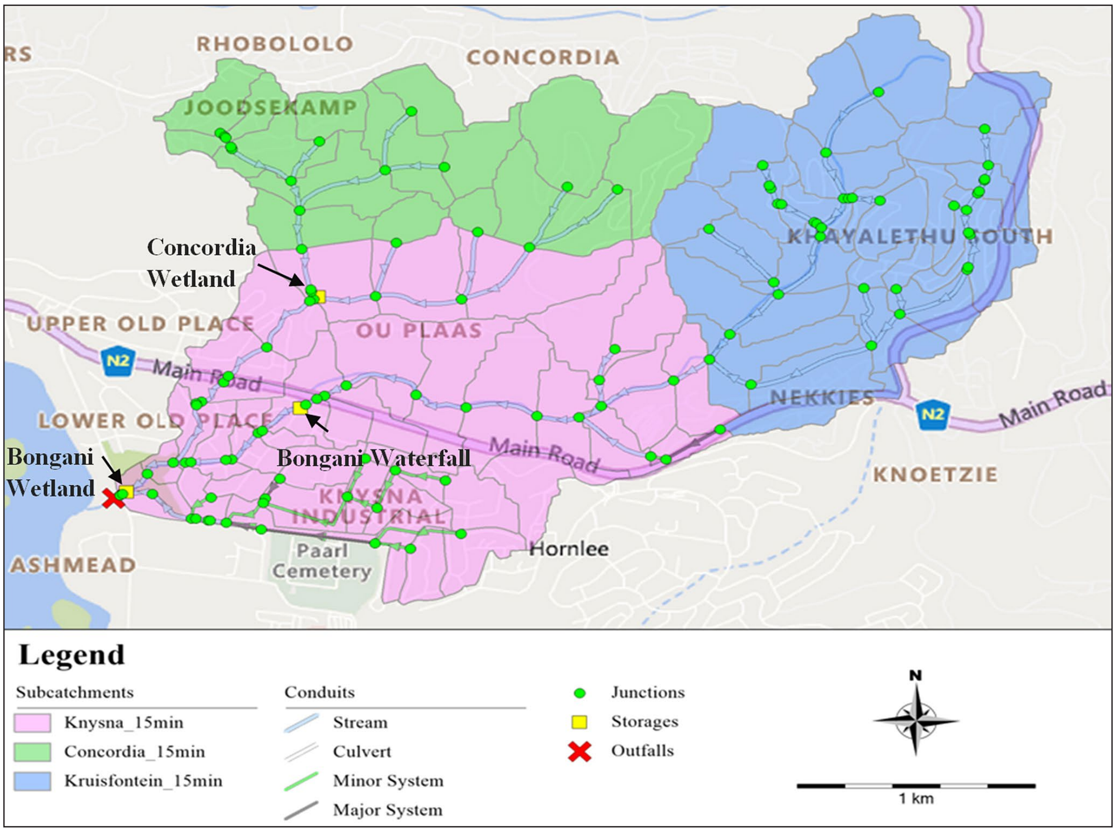

Figure 10. Hydrological model of the Bongani River's Current Scenario (Bing Map Roads, n.d.)

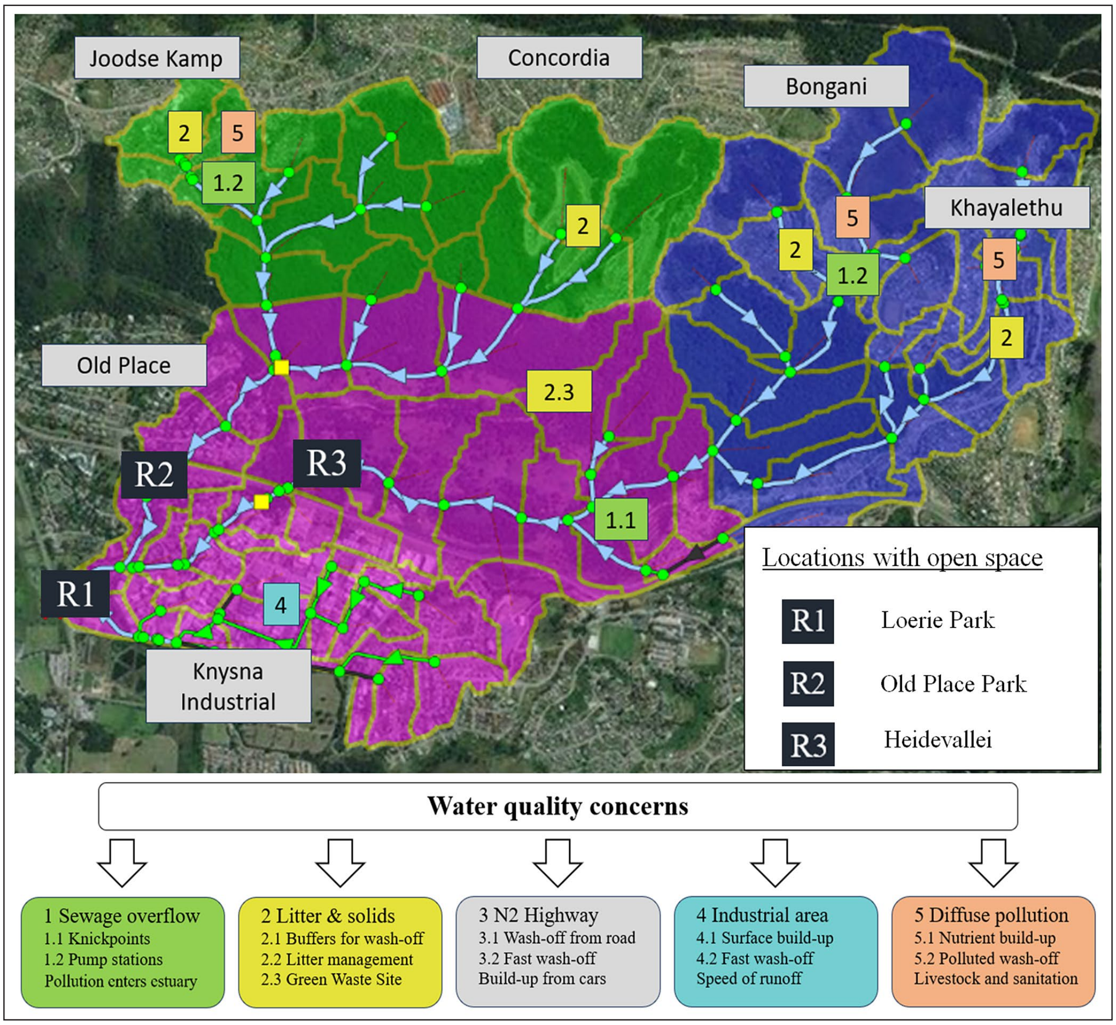

Figure 11. Water quality concerns and open spaces in the Bongani Catchment (Bing Map Satellite, n.d.)

Settlement Upgrade Scenario

The Settlement Upgrade Scenario represented an improvement to the management of stormwater, sewage, and solid waste in the Bongani Catchment. Examples of water quality issues include: the inadequate provision of sanitation which leads to informal sewage discharges; the presence of abundant livestock within informal settlements that contaminate stormwater; and the mismanagement of byproducts from automotive and other industries which discharge cleaning products, vehicle-related contaminants, and heavy metals directly into the stormwater system. If the municipality addresses these issues at a household and industry level, then this should greatly improve the quality of water coming from peri-urban areas. The Settlement Upgrade Scenario thus involved the conversion of peri-urban to suburban land use to show the achievable water quality improvement if settlements are effectively managed. Likely upper and lower range limits for flow and pollutant removal values of the Settlement Upgrade Scenario were modelled using two scenarios as described below:

- Settlement Upgrade Scenario 1 involved pollutant wash-off parameter coefficients for the peri-urban land use converted to the suburban land use, but with the same runoff parameters (Manning's roughness and depression storage) as the original peri-urban land use.
- Settlement Upgrade Scenario 2 involved pollutant wash-off parameter coefficients for the peri-urban land use converted to the suburban land use, but with the runoff parameters (Manning's roughness and depression storage) for suburban land use.

Tributary Management Scenario

This scenario encompassed the development of constructed wetlands on the two streams that drain from the headwaters of the catchment, namely, the Old Place Stream and the Bongani River (Fig. 12).

Bongani Wetland Upgrade Scenario

The Bongani Wetland Upgrade Scenario (Fig. 13) involved a retrofit of the current Bongani Wetland. This involved modelling 2 sediment forebays –small ponds designed to slow stormwater to allow sedimentation, which removes various pollutants from the influent stormwater and helps to prevent siltation of the Bongani Wetland (Fig. 12). These then spill into the constructed wetland downstream. A storm exceedance channel directs large flows away from the wetland to reduce the risk of damage to it.

Sizing of the structures

In the design of stormwater management facilities, there is a trade-off between size (which relates to cost) and treatment. Larger, more expensive facilities offer better treatment; however, the benefits of these systems are often not in proportion with the mounting costs of their construction. The 6-month return period (RP) storm is suggested by several guidelines to be a reasonably optimal event for use in the sizing of the treatment volumes for SuDS (Woods Ballard et al., 2015; Armitage et al., 2013). The continuous simulation approach adopted in this study was designed to model the facility performance across the full spectrum of actual rainfall conditions and corresponding hydraulic retention times, rather than optimizing for a single event size. It did not explicitly evaluate whether the 6-month RP storm represents the optimal sizing event for pollutant removal efficiency. Historic storm events were ranked using the RP generator available in PCSWMM, as well as by graphing the long-term rainfall time series in Microsoft Excel. A storm event that occurred on 23 July 2006 was deemed to be the representative storm event for the determination of the water quality volumes, as it had both a rainfall intensity and maximum runoff rate of a 6-month RP storm event.

RESULTS AND DISCUSSION

Flow reduction

Figure 14 presents the modelled total outflow hydrographs for the various scenarios. Although the graphs presented are theoretical, they show the likely relative impact of the different scenarios on pollutant transport from the Bongani River into the Ashmead Channel. The figure shows:

- The Current and the Settlement Upgrade 1 Scenarios had the highest peak flows through the outfall.
- The Tributary Management and the Settlement Upgrade 2 Scenarios had the next highest flows through the outfall, followed by the Bongani Wetland Upgrade Scenario where the peak was delayed because of retention within the system for longer than the other scenarios.
- The Pre-development Scenario had the lowest total outflow due to the large change in the impervious percentage area in this scenario of the catchment.

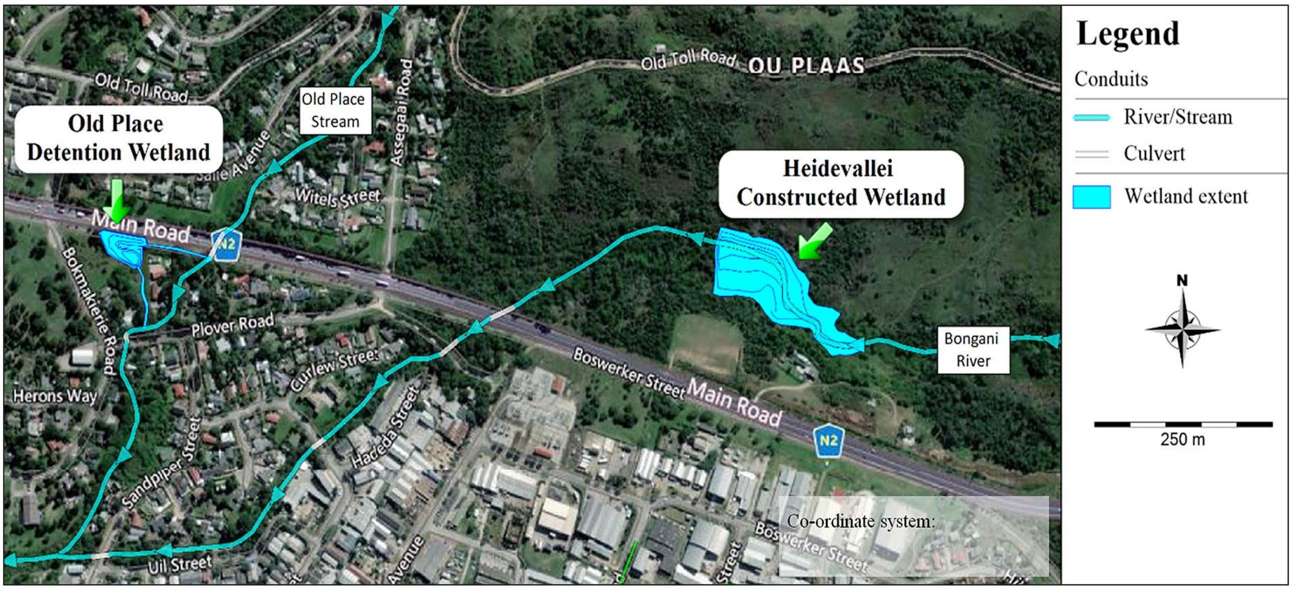

Figure 12. Wetlands modelled for the Tributary Management Scenario

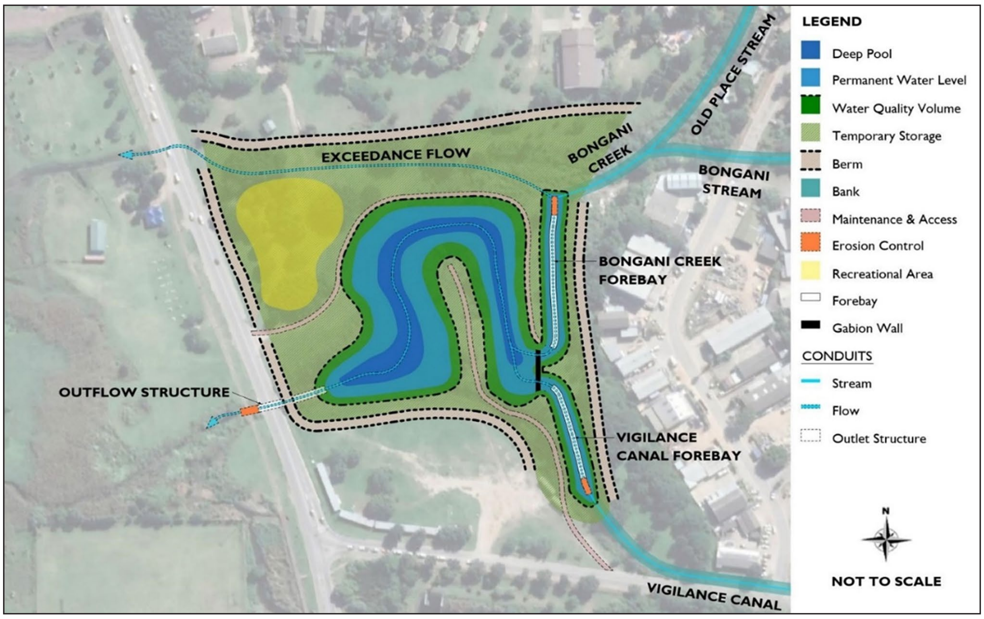

Figure 13. Proposed Bongani Wetland Upgrade Scenario

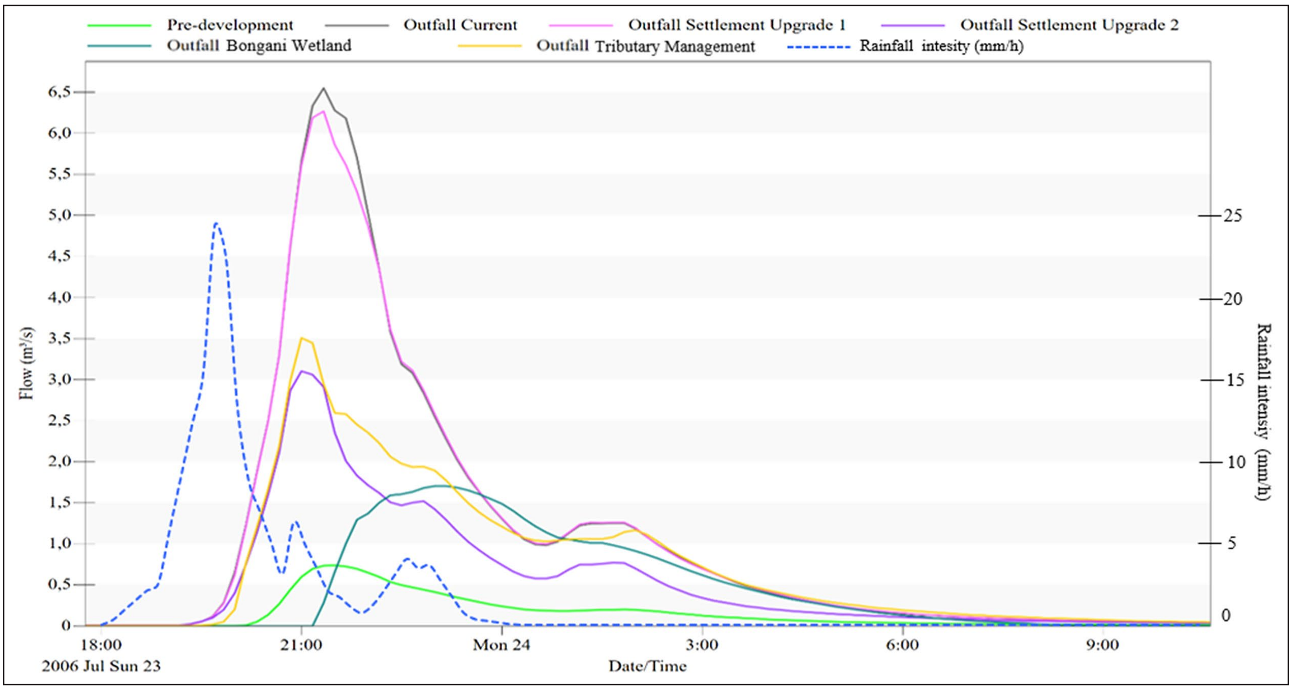

Figure 14. Modelled outflow for each scenario for the representative 6-month RP storm event

Table 5. Total volume and maximum flow rates for all scenarios modelled (2000–2019)

Scenario	Model output			
	Total volume		Maximum flow rate	
	million m³	% reduction	m³/s	% reduction
Current	29 000	-	32	-
Pre-development	2 700	91	20	37
Settlement Upgrade	16 000	45	23	28
Bongani Wetland Upgrade	6 800	77	9.3	71
Tributary Management	19 000	35	23	27

The total volume and maximum flow rates modelled for each of the five scenarios for the full 20-year time series are presented in Table 5.

The volume reduction in these scenarios is attributed to increased evapotranspiration from expanded wetland vegetation, enhanced infiltration to groundwater, and storage within the expanded wetland system. The permanently increased wetted area created by the modelled wetlands can thus significantly elevate evapotranspiration and infiltration.

Pollution reduction

The pollutant concentration values of the representative 6-month RP storm event that occurred on 23 July 2006 are shown in the pollutographs Fig. 15 (for TN) and Fig. 16 (for TP). The large difference between the Current and Pre-development Scenarios shows the need for urgent interventions in the Bongani River catchment. The Settlement Upgrade Scenario values were closest to the Pre-development Scenario with the lowest spike in nutrients of all the scenarios. The nutrient concentrations between the Bongani Wetland Upgrade Scenario and the Tributary Management Scenario in Fig. 15 and Fig. 16 are similar, besides the former having a delayed rising limb due to initial storage in the Bongani Wetland modelled, a less smooth appearance due to the Bongani Wetland modelled being so near to the outflow, and a higher nutrient concentration on the receding limb due to the difference in the two scenarios' hydraulic response times. Because of the impact of the lower total outflow of the Bongani Wetland Upgrade Scenario, it has a lower nutrient load in comparison with the Tributary Management Scenario. Although TN and TP removal have been modelled here in similar ways, albeit using different coefficients based on measured data, it is important to note that phosphorus removal in wetland systems is fundamentally different from nitrogen removal. Phosphorus is not lost through biological processes like denitrification but requires physical removal through sedimentation, plant uptake followed by biomass harvesting, or chemical adsorption onto media.

Figure 17 compares the pollutant load reductions for TN and TP with those of the Current Scenario for the 10 years between 2010/01/01 and 2019/12/31.

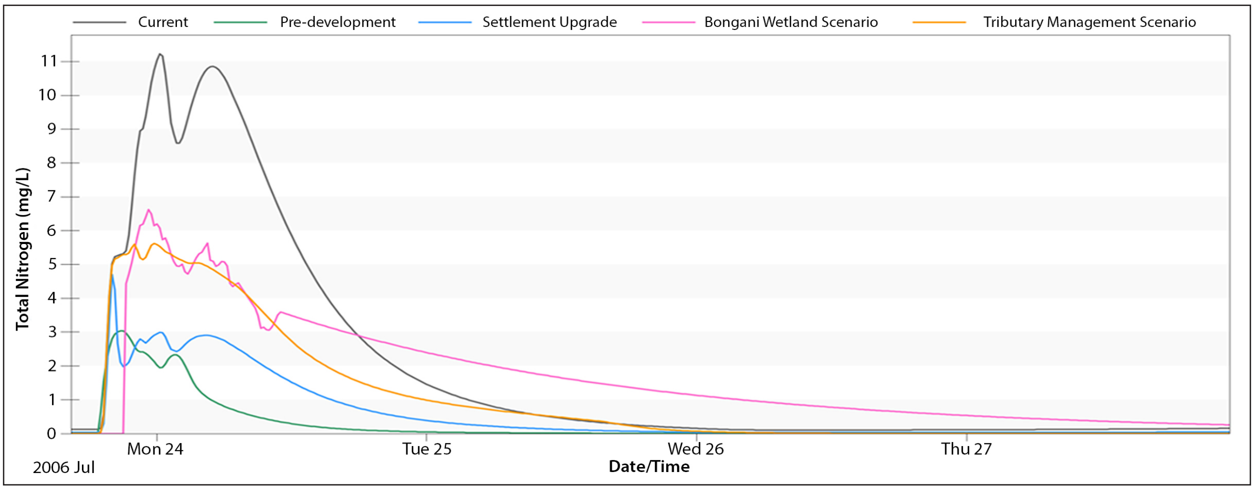

Figure 15. TN variation across the scenarios for the 6-month RP storm event

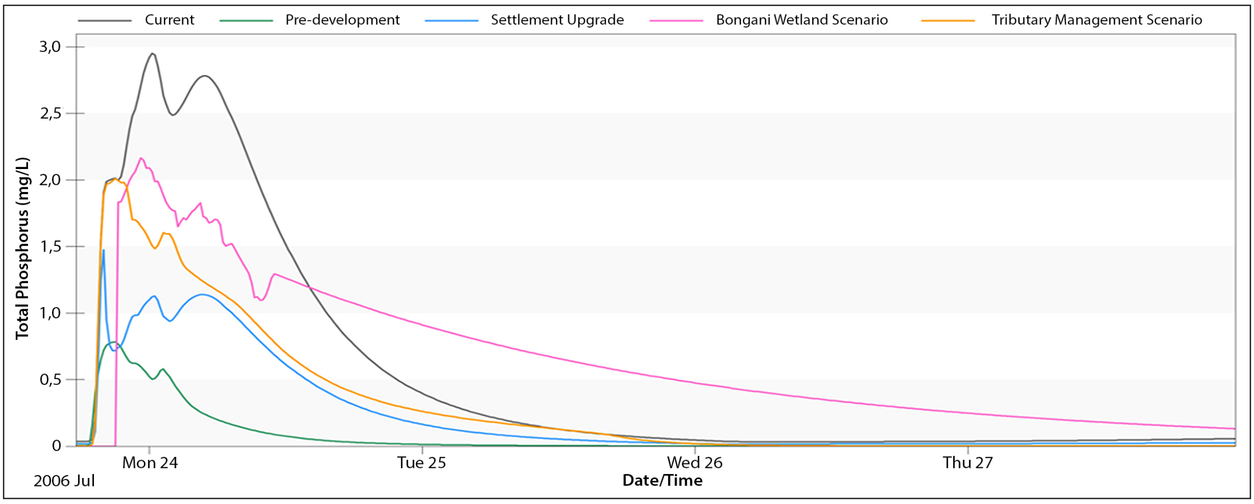

Figure 16. Total phosphorus (TP) variation across the scenarios for the 6-month RP storm event

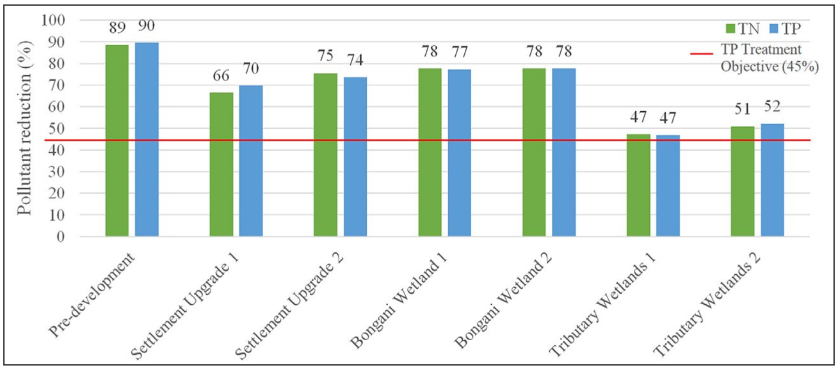

Figure 17. Modelled total nitrogen (TN) and total phosphorus (TP) reduction for the period between 2010 and 2020

CONCLUSIONS

The following conclusions can be drawn based on the results of this study:

- The Pre-development Scenario indicated reductions of 91% in the flow volume, 37% in the peak flow rate, 90% in the TN load, and 90% in the TP load compared with the Current Scenario. This shows how much larger the flow volume and nutrient loads currently are, in comparison with the natural system.
- The Bongani Wetland Upgrade Scenario was the best performer of any option in isolation. The upgrade of the Bongani Wetland captured the inflow of the whole catchment and has sufficient space and capacity to slow down the influent stormwater runoff, aiding with both flow reduction and nutrient removal.
- The Settlement Upgrade Scenario was the second best-performing scenario. The reduction of nutrients from the model in this scenario shows how important improving the state of pollution management of the settlements in the headwaters of the Bongani River catchment would be, with the nutrient reduction being equivalent to that of a large wetland at the bottom of the system, such as in the Bongani Wetland Upgrade Scenario.
- The Tributary Management Scenario was the worst performer; however, it still removed almost half of the nutrients of the Current Scenario, showing how valuable developing stormwater management interventions on each of the tributaries of the Bongani River catchment could be.
- The difference between the coefficients (Table 3) used in the wetland pollutant removal functions shown by Eq. 1 was observed to have a relatively small impact on nutrient reduction. The 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 Upgrade Scenario.

Combinations of the scenarios developed in the model could have shown improved performance over any one of them in isolation; however, at this juncture of our research the focus was primarily on assessing the performance of individual scenarios in a continuous simulation, given the complexity of the catchment and the need for a thorough understanding of each scenario's impact. The impact of combinations of interventions should be investigated prior to any future design.

Uncertainty and limitations

The principal sources of uncertainties in the study are provided in Table 6.

RECOMMENDATIONS

Future studies should aim to acquire higher-resolution and more accurate input data than what was available in this study to improve the performance of the hydrological model. Specifically:

- A higher-resolution digital elevation model (DEM) with finer spatial resolution could better capture the topographic details of the catchment, leading to more accurate delineation of drainage patterns and flow paths.
- Rainfall data with a finer temporal resolution and longer duration (e.g., 5-minute data from within the catchment over several years) would better represent the variability of precipitation events which is crucial for runoff and pollutant transport simulation than the more common available hourly or daily data.
- The collection of accurate flow rate data is essential for the calibration process of the model. Ideally, a substantial number of storm events captured over a long period would provide a more representative sample. This requires flow sensors with a reliable power supply.
- It is important to gather ample water quality data from the catchment area under study for the construction of a robust water quality component for a hydrological model. This implies the strategic selection of sampling locations downstream of distinct land-use areas to allow determination of the water quality associated with each specific land-use.
- There is a pressing need for better stormwater quality models. The impact of various SuDS interventions, e.g., the impact of wet ponds, is poorly understood.

Table 6. Sources of uncertainty in the study design and results

Data collection
• The collection of water quality data: A grab sample is a single sample of the stream's flow. Although there were 12 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 were retrieved using ultrasonic flow-level sensors. 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 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 parameters used in the calculation had inherent uncertainty, for example Manning's roughness which can vary during smaller and larger flow events.
• The challenge of measuring water quality in a stream where sewage is entering the stormwater system was a limitation.
PCSWMM modelling
• The rainfall data used in the model and its spatial and temporal variation. The Knysna area has a variable topography with steep hillsides which likely affects the distribution of rainfall intensity in time and space.
• The modelling parameters used for the sub-catchment and conduit network are estimates from literature and were not measured locally.
• The soil parameters and their infiltration rates were selected using published local soil types and local testing was not undertaken.
• The water quality component and the estimates of the EMC wash-off parameters came from tests in the field but will vary with different storm events and antecedent moisture conditions.
• The model may have overestimated long-term phosphorus removal efficiency as the modelling approach did not account for the persistent nature of phosphorus in biological systems, which requires active management strategies such as periodic biomass harvesting or specialized adsorption media for sustained removal.
• *E. coli* was not modelled in PCSWMM as a water quality component. This was because few data were available and because it represents living organisms that are not amenable to modelling via an EMC loading rate.

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AUTHOR CONTRIBUTIONS

Calvin van der Merwe was responsible for the collection of the data, the construction and running of the various models, the analysis of the model outputs, and the writing of the draft paper. Neil Armitage was responsible for the conceptualisation of the project, critical intellectual input during the research, and the final editing of the paper.

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