CIV5000W: DISSERTATION FOR THE DEGREE OF MASTER OF SCIENCE IN ENGINEERING IN CIVIL ENGINEERING

An investigation of the pollution contribution of catchments surrounding the Knysna Estuary, with implications for stormwater management

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Abstract

The Knysna Estuary is ranked highest in South Africa for conservation importance and is a haven for endemic marine species. The ecosystem services provided by the estuary include significant biodiversity value and amenity value for residents and tourists. The economy of Knysna is reliant on tourism, which in turn is dependent on ecosystem services.

The health of the Knysna Estuary is currently threatened by poor water quality. If the water pollution can be addressed, ecosystems can be protected and significant social and economic costs of environmental degradation can be avoided. The pollution contribution of runoff from catchments to the estuary is imperfectly understood. Mitigation measures designed based on imperfect knowledge may be inappropriate or fail to address the pollution concerns. A poor understanding of the world views of stakeholders could lead to the design of socially unacceptable solutions. This study aimed to improve knowledge of the catchments surrounding the estuary, and stakeholders within these areas, to inform solutions.

Surface water sampling and testing and analysis of national and municipal databases were used to assess the pollutant contribution of catchment runoff. High nutrient concentrations were conducive to eutrophic or hypertrophic conditions at most sites. Total Inorganic Nitrogen (TIN) concentrations exceeded 5 mg/ℓ at 60% of the sites. Ammonium concentrations made up a disproportionate fraction of the TIN readings, with most fractions exceeding 20%, and many exceeding 70%. Student t tests indicated that TIN concentrations at the Bongani River were significantly higher than historical data. Total Suspended Solid (TSS) concentrations at some sites were lower than historical data. *E. coli* spikes of over 30,000 CFU/100 mℓ were measured at nine sites in October 2018. The Bongani River catchment was identified as a significant source of elevated nutrients and *E. coli*. Elevated nutrients and TSS were also recorded in the effluent from the Knysna Waste Water Treatment Works (WWTW) with mean values of 36 and 24 mg/ℓ for Total Ammonia Nitrogen (TAN) and TSS respectively. A Kendall correlation analysis indicated significant positive trends in TIN and TAN, and negative trends in Soluble Reactive Phosphorus.

A hydrological model was built for the Bongani Catchment. Data input to the model was obtained from site visits, literature, and a desktop study of available catchment information. The model was calibrated against observed data at two water level monitoring points. The model was used to estimate pollutant loads for large storms, and can be used to inform possible pollution mitigation strategies.

Further water management challenges and pollution sources were identified through stakeholder interviews. A decision support tool was used to understand how stakeholder world views and values can inform the selection of socially acceptable solutions. Stakeholder interviews identified sewage leaks as a water management concern. This corresponds well with the elevated nutrient and *E. coli* concentrations measured in many catchments. Other identified pollutants were litter and TSS.

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Definitions of acronyms

AHP	Analytical Hierarchy Process
ARC	Agricultural Research Council
BPA	Buffer Pervious Area
BMP	Best Management Practice
CBD	Central Business District
CFU	Colony Forming Units
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
DCIA	Directly Connected Impervious Area
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
E. coli	*Escherichia coli*
EC	Electrical Conductivity
EMC	Event Mean Concentrations
GDRP	Gross Domestic Product per Region
GIS	Geographical Information System
ICIA	Indirectly Connected Impervious Area
ICM	Integrated Catchment Management
ISE	Integrated Squared Error
ISP	Internal Strategic Perspective
I&APs	Interested & Affected Parties
KBP	Knysna Basin Project
LID	Low Impact Design
LiDAR	Light Detection And Ranging
mamsl	Meters Above Mean Sea Level
MAP	Mean Annual Precipitation
mg/ℓ	milligrams per litre
MMDMF	Mauri Model Decision Making Framework
mS/m	milli-Siemens per metre
MWTW	Municipal Water Treatment Works

NEMA	National Environmental Management Act
NEsMP	National Estuarine Monitoring Programme
NH_3	Ammonia
NH_4^+	Ammonium
NO_2	Nitrite
NO_2N	Nitrite expressed as mg/ℓ of Nitrogen
NO_3	Nitrate
NO_3N	Nitrate expressed as mg/ℓ of Nitrogen
NO_xN	Combined nitrate and nitrite expressed as mg/ℓ of Nitrogen
NRUGS	Natural Resource User Group
NSE	Nash-Sutcliffe Efficiency
NTU	Nephelometric Turbidity Units
RSA	Republic of South Africa
SANParks	South African National Parks
SAWS	South African Weather Service
SDG	Sustainable Development Goal
SPA	Standalone Pervious Area
SRP	Soluble Reactive Phosphorus
SRTC	Sensitivity-based Radio Tuning Calibration
SuDS	Sustainable Drainage Systems
TDS	Total Dissolved Solids
TAN	Total Ammonia Nitrogen
TIN	Total Inorganic Nitrogen
TIP	Total Inorganic Phosphorus
TSS	Total Suspended Solids
TP	Total Phosphorus
UCT	University of Cape Town
WESSA	Wildlife and Environment Society of South Africa
WSD	Water Sensitive Design
WWTW	Waste Water Treatment Works

1. Introduction

1.1 Background

The Knysna Estuary is ranked highest in South Africa in terms of conservation importance, provides habitat and a nursery for many marine species, including those endemic to the region, and is an important staging area for migratory birds (Turpie *et al.*, 2002). The estuary provides a wealth of additional ecosystem services, including recreational activities, food production, and jobs, and consequently any impacts to the estuary could result in significant impacts on a wide range of ecosystem services (Mander & Van Niekerk, 2013). The estuary also has significant educational and research value, and in 2018 alone the Knysna Basin Project formed collaborative research projects with five South African universities, and with researchers from Australia and America (KBP, 2018). The town of Knysna hosts the renowned Knysna Oyster Festival and many sporting and recreational events. Although no commercial oyster farms remain in the estuary, the festival and events are vital to the town's economy and local employment figures, with the Oyster Festival alone bringing over 70,000 visitors to Knysna, resulting in an estimated R124 million spend on the local economy (Pick n Pay Knysna Oyster Festival, 2016). The amenity and recreational value that the estuary provides is vital to the success of these events, and to the tourism industry in Knysna.

The health of the Knysna Estuary is being threatened by poor water quality. Various studies have indicated that elevated Total Suspended Solids (TSS) and nutrient concentrations could have significant impacts on natural ecosystems, whilst high *E. coli* are indicative of faecal pollution, and could have associated health impacts for those exposed to contaminated water. The catchments surrounding the estuary, and the Knynsa Waste Water Treatment Works (WWTW) are likely sources of pollution. Land use in the catchments surrounding the estuary includes formal and semi-formal urban development, the Knysna industrial area, commercial forestry, golf courses, parks and indigenous forests and fynbos. Historically Thesen Island was the site of a timber treatment plant but has subsequently been redeveloped into an urban settlement. Rivers on the northern and eastern shores of the estuary include the Bongani, Bigai and Salt rivers, which are currently degraded, provide few ecosystem services, and can be considered a burden on the estuary (Mander & Van Niekerk, 2013). The catchments to the south and west of the estuary are less developed and streams draining these catchments are in a better state to provide ecosystem services (*ibid*).

Various studies have raised concerns that elevated Total Suspended Solids (TSS) concentrations could have adverse impacts on the Knysna Estuary (Russel, 1996; Allanson *et al.*, 2000; Maree, 2000; Marker, 2003). Elevated TSS concentrations can reduce water clarity, thereby negatively impacting fish and reducing light penetration to plants, can have negative impacts on benthic communities, and can act as conveyors of other pollutants such as heavy metals (DWAF, 1996a; Allanson *et al.*, 2000; Monteiro *et al.*, 2000). Heavy metals are likely to originate from roads, urban areas, the WWTW or industrial areas. Multiple studies have found that although heavy metals are present in the estuary, the concentrations do not currently pose an environmental risk (Monteiro *et al.*, 2000; Allanson *et al.*, 2010; Armitage, 2018).

Nutrient concentrations have been found to be problematic in the Knysna Estuary (Russel, 1996; Allanson *et al.*, 2000; Human *et al.*, 2016). High nutrient concentrations can lead to eutrophication, with associated algal blooms and a reduction in biodiversity. Algal blooms can include species such as cynobacteria, which can be toxic to both humans and animals. Human *et al.* (2016, p. 62) warned that if the state of nutrient enrichment persists in the Ashmead Channel (a shallow channel of the estuary) the '*functionality of the seagrass ecosystem and its associated services will cease*'. Multiple studies have indicated that the Knynsa WWTW effluent, and/ or the Bongani River, may be the source of the elevated nutrient levels (Russel, 1996; Allanson *et al.*, 2000; Allanson *et al.*, 2010; Human *et al.*, 2016).

E. coli concentrations have been cited as high in the Bongani, Bigai and Salt rivers, as well as in stormwater drains in the Knysna Central Business District (SSI, 2012). *E. coli* indicates the presence of faecal contamination which can lead to water-borne diseases in those exposed to the contaminated water, for example through recreational activities. Typical diseases that are associated with human faecal pollution are '*gastroenteritis, giardiasis, hepatitis, typhoid fever, cholera, salmonellosis, dysentery, and eye, ear, nose and skin infections*' (DWAF, 1996a, p. 33).

The presence of chlorine in discharge from the Knysna WWTW has been associated with chlorine bleaching, and therefore the absence of benthic microalgae, and reduced abundance of macro-benthic species at the Bongani outflow (Allanson *et al.,* 2010).

Historical studies of the pollution problem have primarily focused on determining pollution levels and impacts within the estuary. A number of studies have provided some data on the quality of surface water runoff originating in the surrounding catchments. In 1996 Russel documented physical and chemical aspects of water quality, including TSS, within selected streams draining to the estuary (Russel, 1996). TSS concentrations were also recorded for five streams through grab sampling methods between 1996 and 1999 (Allanson *et al.*, 2000). Monteiro *et al.* (2000) tested samples from ten effluent discharge sites to determine heavy metal concentrations. In 2010 heavy metal concentrations, as well as impacts on benthic communities, were also measured in the outflow from the Bongani Channel (Allanson *et al.*, 2010). In 2012 a study was commissioned by the Knysna Municipality found elevated *E. coli* concentrations within streams throughout Knysna (SSI, 2012). More recently researchers investigating the source of elevated nutrients in the Ashmead Channel found that nutrient levels in the Bongani River were very high (Human *et al.*, 2016).

Water quality data for streams has typically been limited in duration, spatial extent and the pollutants measured. Only the SSI (2012) study extensively covered surface water locations higher up in the catchments. Changes in catchment land use, development and business practices, and water management all impact the quality of surface water. Most of the historical water quality data is now between seven and twenty-three years old and it is therefore dated. Due to the dated data, and the data limits on spatial and temporal extent, it is difficult to get a clear understanding of the current state of surface water within the catchments to the Knysna Estuary. Which catchments contribute the most significant pollution concentrations to the estuary, what pollutants and at what concentrations? Can pollution sources within the catchments be isolated? How do catchment land uses and the flows in rivers impact pollutants and their conveyance to the estuary?

If the water pollution originating from catchments can be addressed, ecosystems can be protected and significant social and economic costs of environmental degradation can be avoided. An imperfect knowledge of the pollutant contribution of catchments could lead to the design of solutions that may be inappropriate, in the wrong locations, or technically fail to address the water quality concerns. Perhaps more significantly, an imperfect knowledge of the system could lead to inactivity, and therefore failure to implement any pollution minimisation or mitigation strategies.

Consultation with stakeholders can provide insight into possible pollution sources, water management challenges, and proposed solutions to address these challenges. An understanding of what stakeholders value, and how this is being impacted by pollution, can help to inform appropriate solutions or mitigation strategies. Conversely, a poor understanding of the world views and values of stakeholders could lead to the design of socially unacceptable solutions.

This study used water quality sampling, hydrological modelling and stakeholder engagement to improve knowledge of the catchments surrounding the estuary. The water quality sampling was undertaken in two phases, the first to identify catchments that are the source of high pollutant concentrations, and the second phase to further investigate possible pollutant sources within the catchments, the relative pollution contribution of different catchments, and how this contribution has changed over time. The hydrological model informed an understanding of the Bongani Catchment, and was used to estimate pollutant loads for large storms. Data input to the model was obtained from site visits, literature, and a desktop study of available catchment information. The model was calibrated against observed data. Stakeholder engagement and the application of a decision-making tool were also used to understand what stakeholders value, how this is currently being impacted by pollution, and how these values can impact the preference of solutions or mitigation measures.

1.2 Problem statement

The Knysna Estuary is key to the economic wellbeing of the town and surrounding communities, and provides vital ecosystem services for many species, including those endemic to the region. Literature shows that the health of the estuary is being threatened by water pollution. Multiple studies have investigated the impact of pollution on the estuary but there is limited data on the pollution contribution of runoff from the surrounding catchments. The system and pollution sources are therefore imperfectly understood. The development of solutions based on this imperfect knowledge risks the implementation of solutions that are inappropriate, socially unacceptable, or that technically fail to address the pollution problem. This study used water quality sampling, hydrological modelling, and stakeholder engagement to investigate surface water runoff in catchments surrounding the Knysna Estuary. The aim of the investigation was to determine how this runoff is contributing to pollution in the estuary, in order to inform possible solutions.

1.3 Aims and objectives

The aim of the project was to investigate how the catchments surrounding the estuary are contributing to pollution in the estuary. To do this the following objectives were established:

- Determine what pollutants are present in surface water (streams, rivers and stormwater) within the catchments to the Knysna Estuary, and at what concentrations
- Determine which catchments are contributing the highest pollutant levels
- Where possible assess how pollutant concentrations have changed over time
- Investigate the sources of pollutants within the catchments
- Build a hydrological model to provide water quantity information
- Estimate pollutant loads
- Obtain stakeholder insights on current water management concerns, possible pollutant sources, and proposed intervention measures

- Understand what stakeholders value and how this is being impacted by pollution
- Investigate how stakeholders’ values and world views impact on the acceptability of solutions

1.4 Dissertation layout

This dissertation consists of seven chapters. Additional information is contained in the appendices.

- **Chapter 1** introduces the project, details the aims, objectives and problem statement.
- **Chapter 2** presents a literature review of current water management challenges in South Africa and in Knysna, and a consideration of stakeholder engagement in a South African context.
- **Chapter 3** includes details of the study site. The study approach and the methods employed for water quality sampling and testing, hydrological modelling, stakeholder engagement and application of the selected decision support tool are described.
- **Chapter 4** describes the water quality sampling locations and discusses the results of the water quality testing. Assumptions and limitations of the water quality data are also presented.
- **Chapter 5** details the results and assumptions and limitations of the hydrological modelling.
- **Chapter 6** presents the findings of the stakeholder engagement sessions. The application of the selected decision-making tool to address water management challenges in Knysna is also discussed.
- **Chapter 7** discusses the project findings and presents recommendations for future research.

2. Literature review

2.1 Water management challenges in South Africa

Internationally there is an increasing focus on the ability of water resources to supply demand, both in terms of water quantity and quality (Carden & Armitage, 2012). An estimated 40% of the world's population is affected by water scarcity, with this number likely to increase due to the effects of climate change (UNDP, 2019). An estimated 80% of wastewater generated by anthropogenic activities is discharged to water bodies untreated (*ibid*), which places a burden on receiving ecosystems, affects the ability of water bodies to provide ecosystem services, and stresses scarce water resources.

South Africa is a water scarce country with a high demand on water resources. Gassert *et al.* (2013) give South Africa a water stress rating of 3.04, which ranks in the 'high stress' category, with an estimated 40-80% of available renewable water withdrawn annually. It is interesting to note that South Africa ranks far higher on the stress rating than neighbouring countries Namibia or Botswana. Rainfall across South Africa is highly spatially varied, with a maximum Mean Annual Precipitation (MAP) of 2004 mm recorded at Matiwa in the Limpopo Province and only 46 mm recorded for Alexander Bay in the Northern Cape (SAWS, 2018a). Settlement patterns do not correspond with MAP, or necessarily with water availability, which results in high water demand in parts of the country.

South Africa has additional water challenges as a developing country; with the legacy of apartheid still very evident in the wealth inequality that divides the country, including unequal access to water and sanitation. In 2015, 14% of South African households did not have access to municipal water (although 92.5% of all households had access to 'improved drinking water resources') and 20% of households still required access to improved sanitation (Statistics South Africa, 2016). Rapid urbanisation has placed additional demands on scarce resources, and on the ability of cities to provide basic services (Carden & Armitage, 2012). In addition, an adequate supply of acceptable quality water for the agricultural industry is vital for food security.

Water bodies are resources and provide essential ecosystem services such as water supply, waste assimilation and waste dilution, as well as providing recreational services (Mander & Van Niekerk, 2013). Additional services can include preservation of biodiversity, amenity value, tourism opportunities which in turn provide economic opportunities and employment, and the provision of healthy living environments. Urbanisation places demands on these resources and also degrades amenity, biodiversity, and aquatic ecosystem services as well as posing potential health risks (City of Cape Town, 2009). '*Water resources are further stressed by the increasing pollutants, which include industrial effluents, domestic and commercial sewage, acid mine drainage, agricultural runoff, and litter*' (DEAT, 2008, p. 64). In various parts of the country increasing nutrient levels in water bodies are being associated with non-compliant effluent discharge from sewage Waste Water Treatment Works (WWTW) or agricultural practices (Dabrowski & de Klerk, 2013; Lemley *et al.*, 2014). The degradation and poor management of sewage infrastructure has led to significant environmental pollution and human health risks in some locations, with the national army being deployed to assist in addressing these issues (Mailovich, 2018).

South Africa has a progressive legal framework which regulates the water industry, but a lack of technical skills and capacity has hampered effective water management at a national and local level (Carden & Armitage, 2012). Several pieces of legislation govern environmental and water management in South

Africa, including the National Environmental Management Act (NEMA), the National Water Act (NWA) and the Marine Living Resources Act. The range of regulatory authorities involved can lead to a fragmented approach to environmental protection and water management, even within departments. Fisher-Jeffes *et al.* (2012) describe how lack of integration between the stormwater, and water and sanitation portfolios led to confusion and under-funding of the stormwater portfolios in four major metros in South Africa.

Unless current management practices are re-assessed, water crises are likely to occur more frequently. The 2018 water crisis in the Western Cape of South Africa highlighted the need to manage water in a more holistic manner. The crisis has served to highlight to all South Africans that water is not an infinite resource and that it must be valued and protected.

2.2 Ecosystem services provided by the Knysna Estuary

Estuaries are important to biodiversity, form habitat for many species (including endemic species), are nurseries for marine fish and provide staging areas for migratory birds (Turpie *et al.*, 2002). In this same study, the Knysna Estuary was ranked highest in South Africa in terms of conservation importance. The ranking is based on weighted size, habitat, zonal type rarity and biodiversity scores. The study also ranks Knysna third in South Africa for botanical importance and eighth for fish importance. The authors assessed the number of estuarine protected areas, '*estuaries which are fully or partly protected as national parks, nature reserves etc.*' that would be required to provide habitat for all of the species assessed during the study (Turpie *et al.*, 2002, p. 192). Knysna has protected status under the National Environmental Management Protected Areas Act (RSA, 2004). Turpie *et al.* (2002) strongly recommend that the protected status of these estuaries be strengthened, and that the Knysna Estuary forms part of a network of protected estuaries to preserve biodiversity.

The value of South Africa's biodiversity for economic growth and development is recognised in the South African National Framework for Sustainable Development (DEAT, 2008). The framework recognises the importance of biodiversity and particularly relevant to Knysna is recognition of:

- Healthy aquatic ecosystems support industrial and subsistence fishing;
- Wildlife which supports tourism; and
- Indigenous plants for the medicinal industry.

In addition to significant biodiversity value, the Knysna Estuary supplies a host of ecosystem services. Ecosystem services are environmental services that directly benefit the lives of people, whether residents or the wider community. The quality and quantity of water in ecosystems, as well as the condition of the system, affect the ability of natural resources to supply ecosystem services, and the value of these services (DWS, 2017). In 2013 a group of specialists and selected stakeholders determined that the Knysna Estuary is able to supply 70% of identified ecosystem services, ranging from recreational activities to jobs and conservation of endemic species (Mander & Van Niekerk, 2013). The same study found that forests, the estuary and riparian vegetation scored highest in the supply of services per hectare, and that any impacts on these systems could therefore translate into a significant loss of ecosystem services.

The value of the ecosystem services that the Knysna Estuary provides is evident in the impact of the estuary on the local economy. The estuary is vital to the town's economy and employment through fisheries and tourism. The estuary and beautiful surroundings attract both domestic and international tourism. The largest employment sector in the Knysna area is ‘wholesale and retail trade, catering and accommodation’, with 26% of all jobs classified in this category (WCG, 2017, p. 25). According to the official Knysna Oyster Festival webpage the ten day festival brought over 70,000 visitors to Knysna in 2016, resulting in an estimated R124 million spend on the local economy and raising over R3 million for charitable organisations (Pick n Pay Knysna Oyster Festival, 2016). The health of the estuary and surrounding environment is key to ensuring the sustainability of the festival and the nature-based activities included in the programme (such as the Momentum Featherbed trail run, Forest Marathon and the Big Five pentathlon). Business Live (Phakati, 2017) notes that the tourism spend in Knysna for 2016 is estimated to have been in excess of R2 billion and quotes Western Cape economic opportunities MEC Alan Winde as stating that the Oyster Festival alone generates over 2000 jobs in the region. Any risks to the health of the estuary could therefore have a significant impact on the local economy and the communities who depend on it as a source of income.

The Knysna Estuary is also important for research and education due to its high degree of biodiversity. The Knysna Basin Project (KBP) supports research initiatives in the area and the value of the estuary to researchers is evident in the 18 academic publications listed on the KBP website since 2013. In 2018 the KBP developed collaborative projects with five South African Universities, as well as researchers from Australia and America (KBP, 2018). The KBP is also involved in education through local schools’ programmes and community engagement through citizen science (*ibid*).

2.3 Water management of the Knysna Estuary and catchments

Urbanisation places increased demands on water resources, both for water supply and a host of additional ecosystem services. Growth estimates for the Knysna Municipality are currently 4.8% per year until 2023 (WCG, 2017). The same report notes that of the current population, 3.4% still require access to water, and 7.5% still require access to sewage. In an ecosystem services assessment in 2013, the impact on ecosystem services of four growth scenarios were assessed (Mander & Van Niekerk, 2013). The study found that a growth scenario with a focus on investment in ecological infrastructure would result in an estimated 13% increase in ecosystem services. The three growth scenarios that neglected investment in this infrastructure resulted in estimated declines of ecosystem services of between 30 and 35% (Mander & Van Niekerk, 2013). It is clear that unsustainable development could have significant negative impacts on water resources, with a resultant decline in ecosystem services.

Pollution can place additional strain on already over-burdened water resources. The Knysna Waste Water Treatment Works (WWTW) has been identified as a possible source of point-source pollution to the estuary (Russel, 1996; Allanson *et al.*, 2000; Human *et al.*, 2016). In 2004 the Internal Strategic Perspective (ISP) recommended that the Knysna WWTW desist discharging effluent directly into the estuary, and rather discharge into a river further upstream to facilitate dilution (DWAF, 2004). The WWTW continues to discharge effluent directly to the Knysna Estuary. In 2014 the WWTW was identified as the key stress on the estuary (Van Niekerk *et al.*, 2012), and the nutrient loading originating from the WWTW was rated third highest in the Gouritz Water Management Area for nitrogen loading, and fourth for phosphorus loading (Lemley *et al.*, 2014). In addition, runoff from the surrounding catchments is a source of pollution to the estuary. The Bongani, Salt and Bigai Rivers, as well as smaller streams in the CBD, are in a degraded state, with a low ability to provide ecosystems services, and these rivers negatively impact the estuary (Mander & Van Niekerk, 2013). Pollution concerns for these rivers and the estuary are discussed in more detail in Section 2.4.

Effective management of the estuary requires an integrated approach to addressing pollution concerns, both spatially and between role players. The Knysna Municipality is responsible for stormwater, potable water and sewage management in the surrounding catchments, whilst SANParks is responsible for the management of the estuary, wetlands, and river riparian zones. In 2013, the need for greater co-ordination on a catchment level in Knysna was identified (Mander & Van Niekerk, 2013). The Knysna Catchment Management Forum meets regularly to discuss catchment wide issues, and includes representatives from the municipality, SANParks, environmental organisations, the Knysna Farmers' Association and the Knysna Ratepayers' Association. The Knysna Pollution Committee was established in response to pollution issues, and meetings are attended by representatives of the municipality, SANParks, the Knysna Ratepayers' Association and environmental organisations. There are a number of environmental organisations concerned with the welfare of ecosystems within the Knysna area, including the KBP, SANParks, Cape Nature, WESSA and Biowise. The Knysna Environmental Forum also meets to discuss environmental issues within the Knysna area, whilst the newly established Garden Route Environmental Forum has the objective of co-ordinating more regional conservation efforts. The Natural Resource User Group (NRUGS) comprises of traditional healers, initiation schools and members of the Rastafarian community, and the group works with SANParks and Cape Nature to ensure sustainable harvesting of natural resources for cultural purposes. It is clear from this diverse array of forums and organisations that environmental protection is a key priority for many stakeholders in Knysna. It is possible, however, that the sheer number of organisations and forums could lead to a fragmented management approach if efforts are not well co-ordinated, with an over-arching vision. Implementation of management strategies is also ultimately the responsibility of the managing authorities, SANParks and the Knysna Municipality.

International best practice is moving towards Integrated Catchment Management (ICM). ICM recognizes that to address impacts at a river and estuary level, cumulative effects from the entire catchment must be considered. ICM therefore identifies the catchment as the appropriate management unit, even though this unit may cross regional and jurisdictional boundaries and will require cross-disciplinary engagement (Fenemor *et al.*, 2011). This is also encapsulated in the 'source to sea' concept, which considers the inter-relationships between water bodies, from their source to outflows to the sea (Cilliers & Adams, 2016).

In order to effectively manage water at a catchment level, water quality and quantity monitoring is required. The National Water Act (Act 36 of 1998) requires the establishment of national water monitoring programmes to provide data to guide the management and sustainable use of water (RSA, 1998a). Subsequently, the National Estuarine Management Protocol standards require that estuarine management be based on scientific principles (Cilliers & Adams, 2016), and it therefore follows that these actions should be informed by scientific data. The Department of Water and Sanitation (DWS) has extensive resource monitoring programmes designed to produce this scientific data to inform monitoring decisions (Cilliers & Adams, 2016). The National Chemical Monitoring Programme contains a database of water quality data (DWS, 2018a). For the Knysna area the database includes historical data for six estuary monitoring sites, and thirteen sites at the outflows of rivers or drains to the estuary, with varying durations and frequency of data collection. Whilst the most recent data for the estuary monitoring points is for August 2018, the river monitoring points were last sampled in 2013.

The DWS also provides flow data for river monitoring points across the country (DWS, 2018b). Monitoring at the Gouna River site ceased in 1984 but flow in the Knysna River is still monitored at the Charlesford Weir (Figure 2-1), and very high up in the catchment, at Milwood forest. No hydrological data is available for the smaller rivers draining to the Knysna Estuary. The National Eutrophication Monitoring Programme provides measures of eutrophication for the nearby Swartvlei Estuary, but no data is available for the Knysna Estuary (DWS, 2018c). The national River Ecosystem Monitoring Programme provides information on the ecological condition of South Africa's rivers but the most recent document is for 2011, and the 'State of Rivers' report for the Gouritz area is now twelve years out of date. The National Estuarine Monitoring Programme (NEsMP) is currently active, with SANParks assisting the DWS in collecting water samples in the Knysna Estuary. All of this data provides valuable information to assist in informing water management in Knysna, however the decline in data collection in recent years could have negative implications on the proactive management of the estuary. The estuary has been the focus of intensive research for many years, and in Section 2.4 the available literature is analysed to determine the current state of the estuary, and the pollutants of concern.

2.4 Water quality: pollutants affecting the Knysna Estuary

'*The future health and productivity of South Africa's approximately 250 estuaries is dependent on two main factors: management and freshwater inputs*' (Turpie *et al.*, 2002, p. 191). This is relevant to the Knysna Estuary, where stakeholders, researchers and Interested & Affected Parties (I&APs) are increasingly concerned about the health of the estuary.

The Knysna Estuary is highly acclaimed for its biodiversity value and has been the focus of several research projects. Detailed studies have primarily been focused on the estuary itself, with less data available for the surrounding catchments. The literature review discussed in this section encompasses the study of pollutants both within the Knysna Estuary, and in rivers and stormwater systems that drain the catchments surrounding the estuary. Study of the literature data provided information on the state of the estuary, possible pollutant sources, and pollutants of concern. This information was used to inform the selection of water quality monitoring points, and the range of pollutants measured as part of this study.

2.4.1 Total Suspended Solids

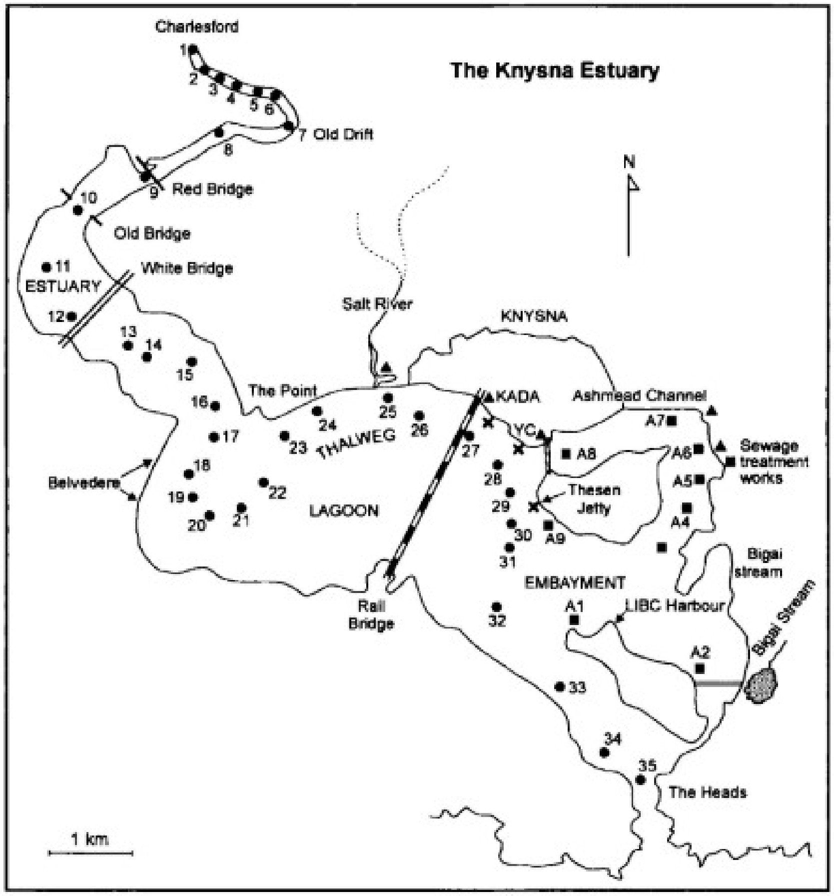
Total Suspended Solids (TSS) comprise of both inorganic solids (for example sediment) and organic matter. Elevated TSS concentrations can have direct impacts on aquatic life, and can also serve as transporters of other pollutants. For example, high TSS concentrations reduce water clarity, which in turn impacts the hunting ability of predatory species and can reduce the ability of aquatic plants to photosynthesise, with potential impacts for the entire food chain (DWAF, 1996a). The same report notes that suspended solids can also affect the gills of fish and impact fish growth. Suspended solids that settle out of the water column can smother benthic animals and plants (*ibid*) that survive in the lower portion of the water column and upper portion of deposited sediments. In the Knysna Estuary, Allanson *et al.* (2000, p. 152) noted that excessive deposition of the cohesive fraction of suspended solids could lead to '*irreversible changes to benthic habitats*'. Cohesive particles are also potential transporters of trace metals and organic toxic pollutants (Monteiro *et al.*, 2000). If the fine fraction of sediments contains a high organic content then decomposition can lead to nutrients becoming available in the aquatic environment (Allanson *et al.*, 2010). The impacts of excessive nutrients are discussed in Section 2.4.2.

In 2003 Marker studied the geomorphology of the Knysna Basin and the impacts of landscape sensitivity on the Knysna Estuary (Marker, 2003). Based on an extensive categorization of the geomorphology in the basin, Marker (2003, p. 41) concluded that landscape sensitivity in the catchments to the estuary is high and that '*thresholds are easily exceeded, leading to rapid and irreversible change*'. This is attributed to transported (aeolian) cover sands which are up to 15 m thick in places and which overlie clays (*ibid*). These sand deposits are sensitive to land changes such a reshaping or removal of vegetation cover. Marker cites two case studies where reshaping activities, and the removal of indigenous vegetation, at two golf courses led to mass mobilization of sediment. Sediment was thus identified as a pollutant of concern to the estuary, although no attempt was made to quantify sediment loads as part of her study.

Earlier studies also express concerns regarding sediment loads to the estuary (Russel, 1996). Whilst Marker (2003) focused on the potential of the catchment to generate sediment, Russel documented physical and chemical aspects of water quality within the estuary and selected streams draining to the estuary. Samples from the estuary were collected monthly for a period of four years but sampling from streams was collected on an *ad hoc* basis. *Ad hoc* grab sampling does not provide representative mean or extreme values, nevertheless values that exceed water quality standards are still an indicator of issues within the catchments. Some inflows to the estuary were found to have high TTSS (over 1000 mg/ℓ) and high turbidity (over 2000 NTU) values, indicative of high sediment loads. TSS values in this range are an order of magnitude higher than the recommended TSS limit from the South African Guidelines for Aquatic Ecosystems (DWAF, 1996a).

Water quality sampling locations determined by Allanson *et al.* (2000) are shown in Figure 2-1. The researchers found TSS concentrations in excess of the DWAF aquatic ecosystem limit (100 mg/ℓ) in 82% of samples taken at the Salt River and Long Street Drain in 1996/1997. The mean TSS values for the two streams for the sampling period were 1993 and 382 mg/ℓ for the Salt River and Long Street Drain sampling points respectively. Only two of the ten samples at the KADA Drain, in the Knysna CBD, exceeded the DWAF limit. The authors also cite the test results of sampling undertaken by Mr R. Milne in 1998 and 1999. The sampling at points entering the estuary was undertaken at the Salt River at the N2 crossing, the railway bridge, the 'site of old swimming bath', KADA Drain, Long Street Drain and at the industrial area drain. Of these sites the highest mean TSS values were recorded at the Salt River (916 mg/ℓ) and industrial area drains (522 mg/ℓ), with the maximum TSS (3960 mg/ℓ) recorded at the Salt River. Despite these relatively high TSS values, of 113 samples collected in the estuary only three showed TSS values in excess of the DWAF aquatic ecosystems limit during the heavy flood of 1996, and one in 1997. Mean values were 24, 18 and 29 mg/ℓ for the Thesen Jetty, Yacht Club and KADA sites respectively (Allanson *et al.*, 2000). Maree (2000) noted impacts on eelgrass beds due to deposition of fine sediments conveyed from the Salt River and stormwater drains, and observed that the eelgrass beds took a considerable time to recover.

Reddering (1994), as cited by Russel (1996), found very little change in sediment body sizes or localities between 1936 and 1990. Reddering (1994) therefore concluded that sedimentation from external sources was negligible. This conflicts with the findings of Russel (1996) and Allanson *et al.* (2000), but as noted previously the catchments surrounding the estuary are constantly undergoing changes and water quality will vary accordingly. The study conducted by Reddering (1994) also pre-dates the two case studies of mass mobilisation of sediment discussed by Russel (1996).



(●) along the thalweg 1–35.
(x) sampling sites at KADA, Yacht Club and Thesen jetty.
(■) sampling sites in the Ashmead Channel and downstream Thesen jetty.
(▲) stormwater drains.

Figure 2-1: Testing locations discussed by Allanson *et al.* (2000)

In 2000 water clarity in the estuary was high, with mean Secchi disk depths of 1.86 m (Allanson *et al.*, 2000). Although the authors conclude that clarity reductions in summer are likely attributable to elevated TSS in summer stormwater flows, it is possible that other factors also affect this seasonal impact. The mean of the Secchi disk depth measurements was not significantly different to data collected by Day (1967) as cited by Allanson *et al.* (2000), indicating that, catchment development had not significantly affected water clarity in the estuary in the intervening years. The authors note that light penetration is sufficient for the tidal wetland eelgrasses based on the measured Secchi disk depths. Should water transparency significantly decrease, for example due to sediment loading, eelgrasses will not be able to grow in these areas (Allanson *et al.*, 2000), with corresponding impacts on other species.

Based on these studies it is not conclusive whether sediment is currently problematic in the estuary. TSS levels measured in the estuary were not excessive, and water clarity was high (Allanson *et al.*, 2000). However, the high capability of the catchment to generate sediment, and elevated TSS and/or turbidity measured by Russel (1996), Allanson *et al.* (2000) and Mr Milne (cited by Allanson *et al.*, 2000) in streams flowing to the estuary, make this a pollutant of concern.

2.4.2 Nutrients

Nitrogen and phosphorus are collectively referred to as nutrients, and both are required to promote plant growth. Total Inorganic Nitrogen (TIN) includes nitrites, nitrates, and Total Ammonia Nitrogen (TAN), all of which can be present in water and are readily converted between the different forms. TAN includes measurement of both the ammonium ion (NH_4^+) and un-ionized ammonia (NH_3). At higher pH and temperatures the ammonium ions are converted to un-ionized ammonia (DWAF, 1996a). Un-ionized ammonia can be toxic to fish, with the DWAF (1996a, Ammonia/Ammonium p. 3) noting that '*acute toxicity to fish may cause a loss of equilibrium, hyper-excitability, an increased breathing rate, an increased cardiac output and oxygen intake, and in extreme cases convulsions, coma and death*'. Where fish are chronically exposed to lower un-ionized ammonia concentrations, this pollutant can reduce hatching rates, impact growth, and affect the gills and vital organs such as the liver and kidneys (DWAF, 1996a).

At lower pH values and temperatures, TAN concentrations are typically dominated by the ammonium ion, which is not toxic to aquatic life. Ammonium, nitrates, nitrites and phosphorus all impact the trophic state of a water body. If either nitrogen or phosphorus is available only in low concentrations, plant growth is limited and the system is considered to be oligotrophic. If both nutrients are present in high concentrations plant and algal growth is not limited and the system is said to be eutrophic, or in extreme cases, hypertrophic. Eutrophic conditions are typically characterized by algal blooms and low species diversity, whilst hypertrophic conditions are characterized by very low species diversity and significant algal blooms (DWAF, 1996a). In both cases the algal blooms can include species such as cynobacteria (also called blue-green algae), which can be toxic to animals and humans (*ibid*).

Russel(1996), who measured high DO concentrations in the Knysna Estuary, cited historical studies that recorded particularly high dissolved oxygen (DO) concentrations in the Ashmead Channel, a shallow portion of the estuary that extends around Thesen Island. The Ashmead Channel separates the island from the Knysna CBD, and stormwater runoff from the CBD, its eastern extensions, and the Bongani River, all discharge to the channel (Figure 2-1). These historical studies attributed the high DO to high photosynthetic activity (which would be driven by high nutrient concentrations) (Russel, 1996). The proximity to the outfall of the Waste Water Treatment Works (WWTW), could point to the WWTW as the possible source of the elevated nutrient levels. The credibility of these high DO concentrations in the Ashmead Channel is supported by the findings of two previous studies, as cited by Russel (1996), and a later study by Allanson *et al.* (2000).

In a study of the nutrient characterization of rivers in the larger Gouritz area, it was found that the Knysna WWTW contributes significant Total Inorganic Nitrogen (TIN) and Soluble Reactive Phosphorus (SRP) loads to the Knysna Estuary (Lemley *et al.*, 2014). Nine WWTW were assessed in the Gouritz area, of which the Knysna WWTW was found to contribute the third highest TIN load, and the fourth highest SRP load. The study also assessed nutrient concentrations and loads in the Knysna River. The gauging site for the Knysna River was unfortunately located high up in the Knysna catchment, with a catchment area that comprises approximately 40% of the catchment of the Knysna River. It is still telling that the Knysna WWTW contributes 7.3 times the TIN loading, and 11.5 times the SRP loading of this gauging site (as calculated from data provided in Lemley *et al.* (2014)). The study also noted a significant increase in SRP concentrations over time at the gauging site.

Allanson *et al.* (2000) also undertook sampling along the thalweg of the estuary and tested for NO_xN (combined nitrate and nitrate concentrations expressed as mg/ℓ of Nitrogen) and TAN (ammonia and ammonium concentrations expressed as mg/ℓ of Nitrogen). Based on the plotting of the measured NO_xN and salinity concentrations against a theoretical dilution line, the authors concluded that the estuary must have a nutrient source and hypothesised that this could be the sewage treatment works. Elevated NO_xN during the wet summer of 1996/1997 was attributed to agricultural activities, although this hypothesis was not substantiated.

The same study found significant reductions in SRP and TAN when compared to 1977 data. NO_xN and SRP concentrations in the Ashmead Channel were found to be significantly higher than in the main estuary but TAN could not be statistically differentiated (Allanson *et al.*, 2000). With the exception of nitrate, the Ashmead Channel nutrient levels were found to be significantly lower than values reported by Grindley & Snow in 1983 (*ibid*). In 1983 one end of the Ashmead Channel was blocked and therefore through-flushing of the channel was not possible, which could explain the discrepancy. Allanson *et al.* (2000) found the estuary was oligotrophic (nutrient concentrations were low, leading to low chlorophyll concentrations). Low nutrient concentrations limit plant and algal growth under oligotrophic conditions, which can lead to moderate species diversity with high nutrient cycling (DWAF, 1996a). Allanson *et al.* (2000) also warned that although tidal flushing and dilution were preventing the system from becoming eutrophic, the increased nutrient loads in areas of long residence time (such as those found in the Ashmead Channel) could become problematic.

This warning was apt, as a study in 2010 found the presence of microalgae and cynobacteria in the Ashmead Channel in bloom proportions (Allanson *et al.*, 2010). Algal blooms are generally an indicator of high nutrient contents. A more recent study was undertaken in 2016 to investigate the cause of a macroalgal bloom (Figure 2-2) in the Ashmead Channel (Human *et al.*, 2016). The researchers found that nutrient levels in the Bongani River, which discharges to the Ashmead Channel, were very high, and that sites in the estuary close to this outlet had significantly higher nutrient concentrations than estuary sites further away. It is interesting to note that this study found concentrations of TAN in the water column that were several orders of magnitude higher than a study of the Ashmead Channel undertaken in 2003.

Figure 2-2: macroalgal bloom in the Ashmead Channel (Claassens & Smith, 2018)

As opportunistic macroalgae replace other primary producers during an algal bloom, sediments can become unstable and water turbidity increases (McGlathery *et al.* (2007); Qiuying & Dongyan (2014) as cited by Human *et al.* (2016)). This was found to be the case in the Ashmead Channel. Human *et al.* (2016) deployed benthic chambers, acrylic chambers partially inserted into the estuary sediments to measure the flux of nutrients across the sediment-water boundary. Periodic sampling of the water in the chambers showed nutrient fluxes, indicating the release of nutrients to the water column from settled sediments (*ibid*). The study notes that a fault at the WWTW in 2011 led to the release of a significant amount of nutrient-laden sludge to the channel. Fluxes in benthic sediment would lead to the release of these nutrients into the water column, helping to sustain the algal bloom (*ibid*). In addition, and because of the algal bloom, DO concentrations from this study were very low, which favours the release of nutrients from sediments. The nutrient contents found in macroalgal tissue were very high and on decomposition these nutrients would become available to fuel new algal growth (Human *et al.*, 2016). The same authors noted that an algal bloom increases turbidity and therefore reduces the amount of light able to penetrate to submerged plants and benthic microalgae, and that the bloom had a negative impact on intertidal plants around the Ashmead Channel. Human *et al.* (2016, pp 61-62) conclude that '*It's clear that if the conditions of anoxia and waste water input persist, green tides will become a permanent feature in the estuary and the functionality of the seagrass ecosystem and its associated services will cease*.'

Studies of the Ashmead Channel point to the Bongani River, and the WWTW in particular, as the likely source of elevated nutrient levels in the Ashmead Channel (Russel, 1996; Allanson, *et al.*, 2000; Human *et al.*, 2016). That the source of elevated nutrients is anthropogenic was supported by isotope testing of nitrogen from samples collected in the channel (Human *et al.*, 2016). Both historical and current impacts from the WWTW could be influencing nutrient levels. From the cited studies it is clear that nutrients (nitrogen and phosphorus) are contaminants of concern in the Knysna Estuary, and are having a negative impact on the Ashmead Channel.

2.4.3 Coliform bacteria

A variety of water-borne diseases are transmitted by the faecal-oral route through drinking water, exposure to water during recreational activities, or consumption of food which has been exposed to contaminated water (DWAF, 1996b). Common water-borne diseases include '*gastroenteritis, giardiasis, hepatitis, typhoid fever, cholera, salmonellosis, dysentery, and eye, ear, nose and skin infections*' (DWAF, 1996a, p. 33). Some infections and diseases can be particularly dangerous in young children or those with immune compromised systems. Since it is not practically possible to test for all possible viruses and bacteria that may lead to diseases and infections, certain indicator species are measured such as *E. coli* which is a faecal coliform that is a specific indicator of faecal contamination from humans or warm blooded animals (DWAF, 1996b).

Literature information indicates that faecal contamination has been a concern in Knysna for many years. Articles in the local press in 2014, 2016 and 2018 all raise concerns about elevated *E. coli* levels reported by the Knysna Municipality (Stander, 2014; Knysna-Plett Herald, 2016; Gaffer, 2018), and in 2016 a national newspaper sought to reassure visitors that swimming areas within the estuary were safe for recreational use (CNS reporter, 2016).

Marker (2003) notes that runoff generated in the Knysna Central Business District (CBD), and the eastern shores of the estuary had low water clarity and elevated *E. coli* levels, but does not provide substantiation. In early 2012 the Knysna pollution committee was set up partially in response to unacceptably high *E. coli* levels in stormwater drains and streams draining to the estuary (SSI, 2012). Water sampling, and testing for *E. coli*, was conducted by SSI in 2012. The results showed significant contamination in the Bongani, Bigai and Knysna CBD catchments, although *E. coli* testing in the lower Bigai showed a substantial improvement below the reed beds (SSI, 2012). The authors noted 229 reports of sewage related problems in the first four months of 2012, with 53% of complaints registered in the CBD and Hornlee (Bigai Catchment) areas.

2.4.4 Heavy metals

Heavy metals can be toxic to animals, plants and microorganisms and can be particularly hazardous as some heavy metals bio-accumulate in the food chain. Mercury, lead and cadmium are particularly toxic to higher animals, while copper, nickel and cobalt are more toxic to plants (McBride (1994) as cited by Monteiro *et al.* (2000)).

Numerous studies have shown that heavy metals are generally present in stormwater runoff from heavily trafficked roads. Andrés-Doménech *et al.* (2018) found that Zn, Cu, Pb and Ni Event Mean Concentrations (EMC) from runoff from a small portion of heavily trafficked road were all more than regulatory limits. These findings are supported by a study in Greece which found elevated concentrations of the same heavy metals in runoff from a highway (Terzakis *et al.,* 2008). In South Africa, a study of runoff from the R300 highway in Cape Town found elevated concentrations of Zn, Cu, Pb, Mg, and Al (Robertson, 2017). Runoff from the N2 highway flows to streams and stormwater channels that ultimately discharge to the Knysna Estuary, and may conceivably convey heavy metals to the estuary. Additional sources of heavy metals could include industrial activities within the catchments, and the WWTW.

Monteiro *et al.* (2000) tested samples from ten sites that discharged effluent to the estuary, and showed that only copper and zinc had dissolved concentrations above detection limits. Copper concentrations were in excess of the South African Marine Water Quality Guidelines at only one location, while non-compliance for zinc was found at four locations. Elevated particulate phase concentrations of chromium and lead were highlighted as of concern for several locations (*ibid*). Effluent from the industrial areas was not tested, as there was no flow from this area at the time of testing.

No significant contamination of heavy or trace metals was identified during testing of sediment and oyster samples in the Knysna Estuary in 2000 (Monteiro *et al.,* 2000). The study found that trace metal concentrations in oyster samples were all lower than the required legal standard. Pb, Cd, Ni and Sn concentrations in sediments were below analytical detection limits, and Cr, Cu, Zn, As and Hg concentrations in sediments were below the London Dumping Convention trace levels (*ibid*). The authors noted that the distribution of zinc and copper, in particular, indicated that the source of these metals was likely to be of urban or industrial origin. This was further substantiated by findings of high geochemical ratios of zinc and chromium relative to aluminium in the Ashmead Channel. The authors stated that higher ratios were indicative of urban-industrial influences and these trace metals, '*if shifted out of equilibrium by re-suspension or deposition could become bio-available*' (Monteiro *et al.*, 2000).

The data reported by Monteiro *et al.* (2000) 18 years ago found mean concentrations of trace metals reported in sediments were comparable to past measurements reported in 1982 and 1998 (Watling & Watling (1982); Calvo-Ugarteburu (1998) as cited by Monteiro *et al.* (2000)). Monteiro *et al.* (2000) found that leachate generated from wood treatment plant waste on Thesen Island could be a significant pollutant contributor to the Estuary. This activity has ceased, and the Island has been rehabilitated into an up market housing estate. In 2010 water and sediment samples were collected in the Bongani River outflow to the estuary, downstream of the WWTW effluent discharge site, as well as in the Ashmead Channel upstream and downstream of the Bongani River Outflow (Allanson *et al.*, 2010). The samples were tested for Cd, Cr, Cu, As, Pb and Hg. The sediment concentrations were all low, and those with slightly higher concentrations were found to be comparable to those measured by Watling & Watling (1982) (Allanson *et al.*, 2010). Comparison with the concentrations reported in the national action list (RSA, 2012), showed that Cd, Cr, Cu, As and Pb concentrations reported for all three sites were well below warning levels, but Hg concentrations for the Bongani outlet were above warning levels but below action levels. The heavy metal concentrations in the water samples were found to be extremely low or non-detectable for all except Cu, which was found to be comparable to results reported by Watling & Watling (1982) (Allanson *et al.*, 2010).

In 2018 sediment samples were collected in the Ashmead Channel, and at the Salt River mouth (Armitage, 2018). Concentrations of Zn, Cu, Pb and Cr were all below the London Dumping Convention trace levels (*ibid*), mirroring the findings of low concentrations reported by Monteiro *et al.* (2000) and Allanson *et al.* (2010). Mn concentrations were found to be well below the natural range that the World Health Organisation reports for intertidal mud flats (Armitage, 2018). The researcher found increases in the mean concentrations of Zn, Cu, Pb and Cr across all sites, when compared to the Monteiro *et al.* (2000) study, although the test sites in the two studies did not correspond, making it difficult to draw conclusions. Both studies had monitoring site locations near the Bongani River outflow, and Armitage (2018) found increases in Zn, Cu, Pb and Cr at these sites when compared to the 2000 study. The Cu, Pb and Cr results for this site reported by Armitage (2018) are also one to two orders of magnitude higher than those reported by Allanson *et al.* (2010).

In a recent study, researchers found relatively low concentrations of Zn, Cu, Pb and Cd in the tissue of algae in the Ashmead Channel, and extraction of the algae for use as fertilizers or compost was deemed to be safe (Human *et al.*, 2016). It was not possible for the researchers to determine the source of these heavy metals but the Knysna industrial zone and the WWTW discharge were identified as possible sources.

The studies assessed all indicate that while there is heavy metal contamination in the Knysna Estuary, the concentrations of these heavy metals are not currently at levels that could have significant impacts on aquatic ecosystems or human health. The increases in heavy metal concentrations measured by Armitage (2018) may indicate a upward trend, but further data would be required to confirm these findings.

2.4.5 Hydrocarbons

Runoff from roads may be a source of Polycyclic Aromatic Hydrocarbons (PAHs), (Terzakis *et al.*, 2008; Robertson *et al.*, 2017). PAHs may be of concern due to the proximity of the N2 to the estuary, industrial areas in the catchments, and boating activities in the estuary. Testing of ten effluent discharge sites for hydrocarbon compounds in 2000 showed an absence of PAHs in all but the Salt River (Monteiro *et al.*, 2000). The authors noted the presence of PAHs in the river and postulated that the source could be equipment used in the agricultural industry. The same study found traces of hydrocarbon concentrations at all ten sites, and linked these to runoff from roads and fuel stations. Effluent from the industrial areas was not tested (*ibid*). Hydrocarbon concentrations detected in sediment samples were all below levels that could pose a risk to human and ecological health (Monteiro *et al.*, 2000). The authors suggested wood treatment plants and light motor fuels as the most likely sources of the hydrocarbons.

2.4.6 Chlorine

In a study in 2010 the impact of chlorine on eco the Bongani River outflow was assessed (Allanson *et al.* 2010). Chlorine is used as part of the treatment regime at the WWTW. The benthic zone is the area at the bottom of the water column, and the upper layers of the sediments. The invertebrate species that survive in this zone and are visible to the naked eye are called the macro-benthic community, and the abundance and diversity of these species can be an indication of the health of the system. The presence and diversity of macro-benthic life was assessed in core samples collected at the Bongani River outflow and at a nearby outflow from Kathy Park (Allanson *et al.*, 2010). The species diversity was similar at the two sites but the number of macro-invertebrates was orders of magnitude lower at the Bongani River Site (*ibid*). The authors conclude that the combined flow from the Bongani River and the WWTW effluent has created a toxic environment at the Bongani River outflow, and link toxicity with pollution loads, and specifically with chlorine (Allanson *et al.*, 2010). The same study compared the growth of benthic microalgae at the Bongani River outflow to growth at the Kathy Park outflow. The researchers found that growth of benthic microalgae at the Bongani River Site was prevented due to chlorine bleaching of the benthic zone, to a depth of 30 cm into the sediments (Allanson *et al.*, 2010). Growth of benthic microalgae was high at the Kathy Park site.

2.4.7 Summary of pollutants of concern

Studies have indicated that TSS levels in the estuary are acceptable, and water clarity is high (Allanson *et al.*, 2000) however, the Knysna Basin has significant capacity to generate sediment (Marker, 2003). High TSS concentrations and turbidity have historically been measured in rivers flowing to the estuary, and therefore sediment loads should be managed to prevent ecological harm in receiving environments.

Both recent and historical studies have found nutrients to be problematic in the Knysna Estuary, and in particular in the Ashmead Channel. Multiple studies have indicated that the WWTW effluent, and / or the Bongani River, may be the source of the elevated nutrient levels (Russel, 1996; Allanson *et al.*, 2000; Allanson *et al.*, 2010; Human *et al.*, 2016). Elevated nutrients can lead to eutrophic or hypertrophic conditions, with associated algal blooms and a loss of biodiversity. Algal blooms can include species toxic to animals and humans. The algal bloom that settled in the Ashmead Channel in 2014 could lead to a loss of functionality in the seagrass ecosystem (Human *et al.*, 2016).

Elevated *E. coli* concentrations have been measured in the Salt, Bigai, Knysna CBD and Bongani Catchments. *E. coli* indicates the presence of faecal contamination and can lead to water-borne diseases in those exposed to the contaminated water.

Although multiple studies have found low concentrations of heavy metals in the estuary, these contaminants remain of concern, given the proximity of the N2 highway and Knysna industrial areas. Heavy metals can be toxic to both flora and fauna, and can bioaccumulate, and thus pass up the food chain.

Limited testing for PAHs was found in the literature studied. Testing of river and stormwater flows showed elevated PAHs at the Salt River outflow (Monteiro *et al.*, 2000). These remain contaminants of concern due to the proximity of the N2 highway, and other possible contamination sources.

The presence of chlorine in the WWTW effluent has been associated with the absence of benthic microalgae, and reduced abundance of macro-benthic species at the Bongani outflow (Allanson *et al.*, 2010).

There is a wealth of data documenting the health of the Knysna Estuary, and how it has been impacted by pollution over time. Some of the studies have included data on pollutants originating from the surrounding catchments, but most of this data is limited in both duration and spatial extent, and is now dated. Various studies have identified the WWTW and the Bongani River as pollution sources, particularly for elevated nutrients.

2.5 Stakeholder engagement and decision making in South Africa

'*There is a need to address the relationship between man and nature. The South American countries have become leaders in reminding the world of the interconnectedness between man and nature. This corresponds with African tribal ideologies and should be pursued in the South African context*' (Mosdell, n.d.). Indigenous beliefs from other parts of the world such as New Zealand also recognise the connectedness of people to land and the environment.

The relationship between indigenous South African people and the environment is poorly documented (Cocks & Dold, 2012) but is vital to the sustainability and acceptability of projects to stakeholders within communities. Engagements with indigenous communities also offers an opportunity for learning and for incorporating indigenous knowledge into engineering solutions.

The South African National Water Act (1998) also strongly promotes participatory processes through which communities can participate in '*the protection, use, development, conservation, management and control of the water resources in its water management area*' (RSA, 1998a, 80e). Given South Africa's complex history, engagement should involve all local communities who are interested in, and affected by water management. Knysna has a history of stakeholder engagement which has been used to access the skills and knowledge of local stakeholders in the social and environmental spheres (Winter *et al.*, 2016), and this local knowledge can assist in informing the selection of appropriate pollution mitigation measures or solutions.

In the context of the 'Blue Economy' (the sustainable use of marine resources), the World Bank and United Nations note that '*(r)ealizing the full potential of the blue economy also requires the effective inclusion and active participation of all societal groups, especially women, young people, local communities, indigenous peoples, and marginalized or underrepresented groups. In this context, traditional knowledge and practices can also provide culturally appropriate approaches for supporting improved governance.*' (World Bank/UN, 2017, p. x).

The array of very diverse stakeholders who must be consulted as part of decision-making processes in seeking a common vision and an over-arching water management strategy, can be challenging. Given South Africa's history of migration, indentured labour and colonisation, stakeholders are likely to have very diverse cultural and socio-economic backgrounds, and consequently very different values and priorities.

Many decision support tools have been applied in the water management sector to inform decision making processes. Lankford *et al.* (2011) describe the use of a custom Microsoft Excel-based tool to assess the economic value of ecosystem services on the Pongola Floodplain (South Africa). The tool is used to assess different management approaches for the Pongolapoort Dam and consequently the floodplain. The model used stakeholder engagement to understand the interests and viewpoints of I&APs. The economic evaluation of ecosystem services is in line with the Millenium Ecosystem Assessment (MEA), although Lankford *et al.* (2011) primarily assess provisioning services. The tool used is useful in helping to address inequality by providing an assessment of the impact of decisions on the poorest sector of the community.

There is inherent difficulty in using a cost-benefit type of approach to ecosystem services as the impacts of these services are diverse and complicated, often not fully understood and difficult to quantify. Supporting, regulating and cultural services may be under-valued if studies only consider provisioning services. As the authors themselves caution, the preferred solution from the decision-making tool may be the most beneficial in the short-term but the consequent degradation of the flood plain could have significant longer-term impacts which are not accounted for in the model (Lankford *et al.*, 2011).

An alternative tool that has also been applied in the water management sector to inform decision making is the SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis. Nagara *et al.* (2015) describe the use of this technique, with a Delphi type method of specialist input, for assessing alternative water provisioning solutions for Asia and Africa. This study demonstrates that the technique can provide clear, succinct analysis of the current narrative in academic or specialist circles and has the advantage of helping to identify possible future threats or opportunities. The technique is thus a powerful aid to decision makers, but is not well suited to inclusive stakeholder engagement, which could lead to a technically optimal solution that still fails to be acceptable to I&APs.

Carden & Armitage (2012, p. 346) describe the development of a South African tool to '*create an understanding of, and measure the potential for, sustainability in an urban water context*'. The researchers note that an agreement on a shared vision of sustainability is a key starting point which requires a participatory process. The resultant model, the Sustainability Index for Integrated Urban Water Management (SIUWM), shares many parallels with the New Zealand based tool, the Mauri Model. Both models use participatory processes in the selection of appropriate indicators (or performance measures) in four components. The four components in SIUWM are economic, social, environmental and institutional, whilst the Mauri Model substitutes cultural values for institutional components. Each model reduces complex assessments of indicators to a simple numerical scale and then aggregates these scores by sector and gives an equally weighted final score. An interesting facet of the Mauri Model, which differentiates it from similar decision support tools, is the use of an analytical hierarchy process to try to gain an understanding of world views. These world views can help decision makers to better understand how alternative solutions are perceived by different stakeholders. This is described in more detail in Sections 2.6 and **Error! Reference source not found.**.

2.6 Use of the Mauri Model

The Mauri Model Decision Making Framework (MMDMF) is an '*expert-weighted decision matrix that provides a culturally based template within which indigenous values are explicitly empowered alongside 'western' thinking*' (Morgan, 2006, p. 174). The model uses the Māori concept of mauri as the measure of sustainability. Mauri has been variously described as '*bonding element creating unity in diversity*' (Marsden, 1992, p. 7); uniting the physical and spiritual (Morgan, 2006); and the life supporting capacity of air, water or soil (Morgan *et al.*, 2013).

The model was developed in New Zealand, where the use of a quadruple bottom line (environmental, social, economic and cultural considerations) is supported by the Resource Management Act (Ministry for the Environment – New Zealand, 1991). In a South African context, a triple bottom line (environmental, social and economic considerations) is enshrined in the National Environmental Management Act (NEMA). Sustainable development is defined in the Act as '*the integration of social, economic and environmental* *factors into planning, implementation and decision making so as to ensure that development serves present and future generations*' (RSA, 1998b, p. 15).

A triple bottom line approach does not distinguish between social and cultural values. NEMA does recognise the importance of cultural values: '*the general objective of integrated environmental management is to… identify, predict and evaluate the actual and potential impact on the environment, socio-economic and cultural heritage…*'(RSA, 1998b, 23(2)(b)). The NEMA amendment bill passed in 2017 also notes that reports may require an assessment of cultural impacts of an activity (RSA, 2017). Use of an explicit measure of cultural value could hold the key to more inclusive development, learnings from indigenous and local knowledge, and participatory environmental protection which preserves the environment and water resources for future generations.

The MMDMF takes equal cognisance of four well-beings (economic, environmental, social and cultural). In the New Zealand context, the cultural well-being refers to the values and aspirations of the indigenous people of Aotearoa. South Africa has a more complex history of colonisation, indentured labour and migration patterns and the definition of cultural well-being is necessarily broader.

Application of an Analytical Hierarchy Process to assess the values and world-views of diverse stakeholders can provide a context to assist decision makers in understanding how proposed solutions are perceived by stakeholders. This is particularly important where decision makers do not have the same cultural or socio-economic background as the I&APs. A poor understanding of the world views and values of stakeholders could lead to the design of socially unacceptable solutions.

2.7 Summary and need for further research

South Africa faces many water management challenges, including declining water quality and a high demand for scarce water resources. Knysna faces similar challenges, and the ability of the Knysna Estuary to provide important ecosystem services is being threatened by poor water quality. The number of forums and environmental groups in Knysna is indicative of the value that is placed on environmental protection, however management approaches have been criticized as being fragmented. A cohesive water management strategy, informed by scientific data, and including stakeholder engagement, is required to effectively manage the quality and quantity of fresh water inputs to the estuary over the longer term.

Water quality concerns include elevated nutrients and *E. coli*, particularly in the Ashmead Channel and some of the rivers and stormwater systems that report to the estuary. Although literature has indicated that water clarity in the estuary is high, elevated TSS concentration remain a concern, particularly where sediment loading is significant due to sustained low loads, or elevated loads during storms. Elevated nutrient concentrations in the Ashmead Channel have resulted in eutrophic conditions within the channel, and an associated bloom of macroalgae. If these conditions are sustained, they could have very negative impacts on the functionality of ecosystems in the channel.

The Bongani River and the Knysna WWTW have been identified as likely sources of elevated nutrients to the estuary, however literature data on the water quality of streams draining the catchments surrounding the Knysna Estuary is limited in spatial extent and temporal scale. Water quality is dynamic, with changes in behaviours, land uses and hydrology all affecting pollutant concentrations, and therefore data is quickly dated. The National Estuarine Monitoring Programme (NEsMP) calls for a three-tiered approach to estuarine monitoring and management (Cilliers & Adams, 2016). Tier 1 requires the collection of physio-chemical and constituent data and Tier 2 the collection of abiotic and biotic system data (*ibid*) (see Figure 2-3). Tier 3 entails tailored monitoring aimed at addressing specific management concerns (*ibid*), such as the nutrient enrichment currently being experienced in the Ashmead Channel. The monitoring should be selected from the Tier 1, which includes the monitoring of fresh water flows, pH, turbidity, SRP, TIN and *E. coli* (*ibid*). Although not specifically aimed at addressing this monitoring requirement, the study undertaken for this dissertation aligns well with the proposed approach, through the monitoring of water quality data, and modelling of water quantity data, to inform management approaches to address pollution issues in the Ashmead Channel.

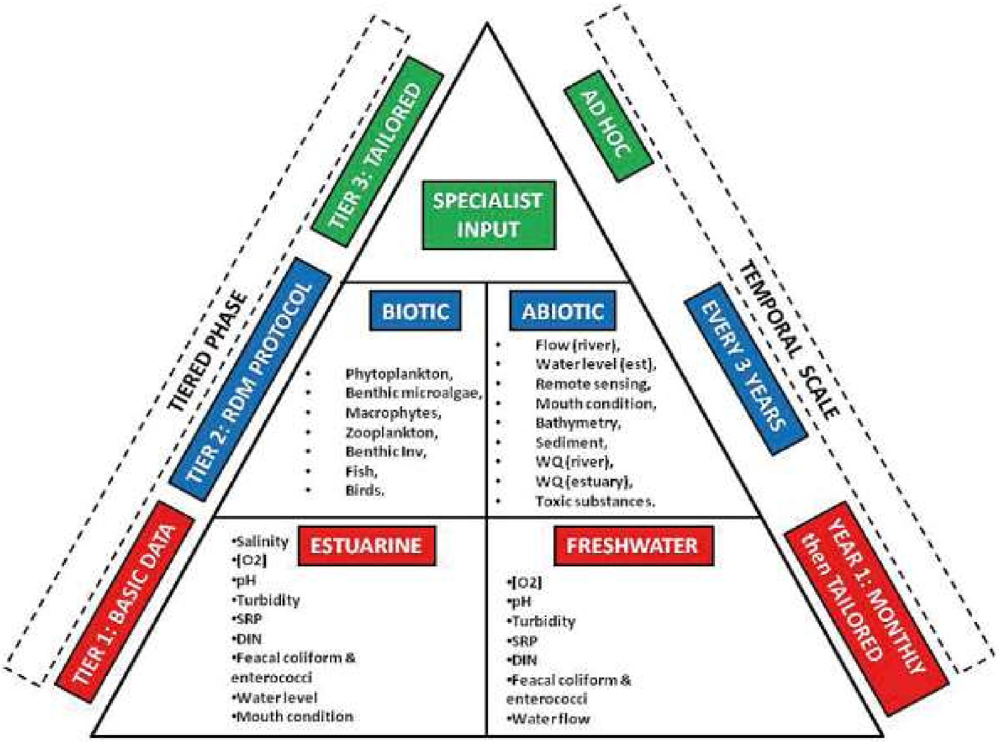


Figure 2-3: Tiered approach to estuarine monitoring (Cilliers & Adams, 2016)

For this research the entire urban catchment has been identified as the appropriate management unit. The modelling of a representative catchment and the assessment of water quality, and pollutant sources within the catchment, are seen as one step in the direction of sound Integrated Catchment Management. By focusing on a catchment-based approach this project could also help to bridge jurisdictional boundaries such as the management of the estuary by SANParks and the management of the surrounding catchments by the Knysna Municipality. In this way the study will go some way toward addressing the two aspects highlighted by Turpie *et al.* (2002) as vital to the health of estuaries: management of the estuary and ensuring the quality and quantity of fresh water inflows to these systems.

It is good practice to involve stakeholders in decision making processes, both to inform appropriate solutions, and to ensure social acceptability of the proposed solutions. Stakeholders can also provide valuable insight into water management challenges, and possible pollutant sources. Where pollution issues are partially the result of behavioural patterns, stakeholder engagement can assist in achieving community buy-in to behavioural reformations.

3. Method

3.1 Site Description

3.1.1 Location

The town of Knysna is located adjacent to the Knysna Estuary, along the Garden Route, in the Western Cape province of South Africa (Figure 3-1). The Garden Route is a portion of the South African coastline located between the town of Mossel Bay in the west and Storms River in the east, and is a major tourism attraction.

According to the Department of Water and Sanitation (DWS) classification system, the town falls with the Breede-Gouritz Catchment Management Area. The Knysna River has its headwaters in the Outeniqua Mountains, in Quaternary Sub-catchment K50A, before flowing to the estuary, located in Quaternary Sub-catchment K50B. Major tributaries of the river are the Gouna and Kruis Rivers. The Knysna River flows into the estuary at Charlesford weir, then progresses in an approximately south easterly direction to the ocean, flowing through a gap in the Knysna heads.

This study focused on the catchments to the north and east of the Knysna Estuary. These catchments were selected as they are more developed than the catchments to the south and west, and many drain to the Ashmead Channel, which the literature review identified as experiencing pollution problems. No water sampling was undertaken for Thesen Island, or Leisure Isle, as it would be more challenging to identify stormwater outflow points from these islands. The Salt, Bigai and Bongani Rivers fall within the study area. The Salt River has the largest catchment area of the north and western estuary rivers, with a catchment area of approximately 1530 ha. The Bigai River has a catchment of approximately 910 ha, and the Bongani River 630 ha. The N2 national highway passes through the study site in an east-west direction, and stormwater runoff from the highway drains to the estuary via numerous stormwater drains.

The Knysna Estuary is South Africa's only warm temperate estuarine bay (Turpie et al., 2002), with a surface area of 1827 ha at high spring tide (Allanson *et al.*, 2000). The estuary covers the base of a broad and flat valley, with large areas that are subject to tidal fluctuations (Largier *et al.*, 2000). The estuary is continually open to tidal influence, with extensive tidal flushing. The area dominated by oceanic waters extends from 4 to 7.5 km from the mouth (*ibid*). The Ashmead Channel surrounds Thesen Island on the northern, eastern and southern sides, with the main estuary to the west of the island. The channel is a warmer, shallow section of the estuary, with depths of 0.5 – 2 m (Switzer (2003) as cited by Human *et al.*, (2016)). The Bongani River, and stormwater runoff from a large part of the Knysna Central Business District (CBD), flows into the Ashmead Channel. The channel also receives effluent from the Knysna WWTW. The WWTW effluent and the Bongani River outflow both flow through culverts under George Rex Drive and then combine as they flow through a small wetland, before reporting to the Ashmead Channel (Allanson *et al.*, 2010).

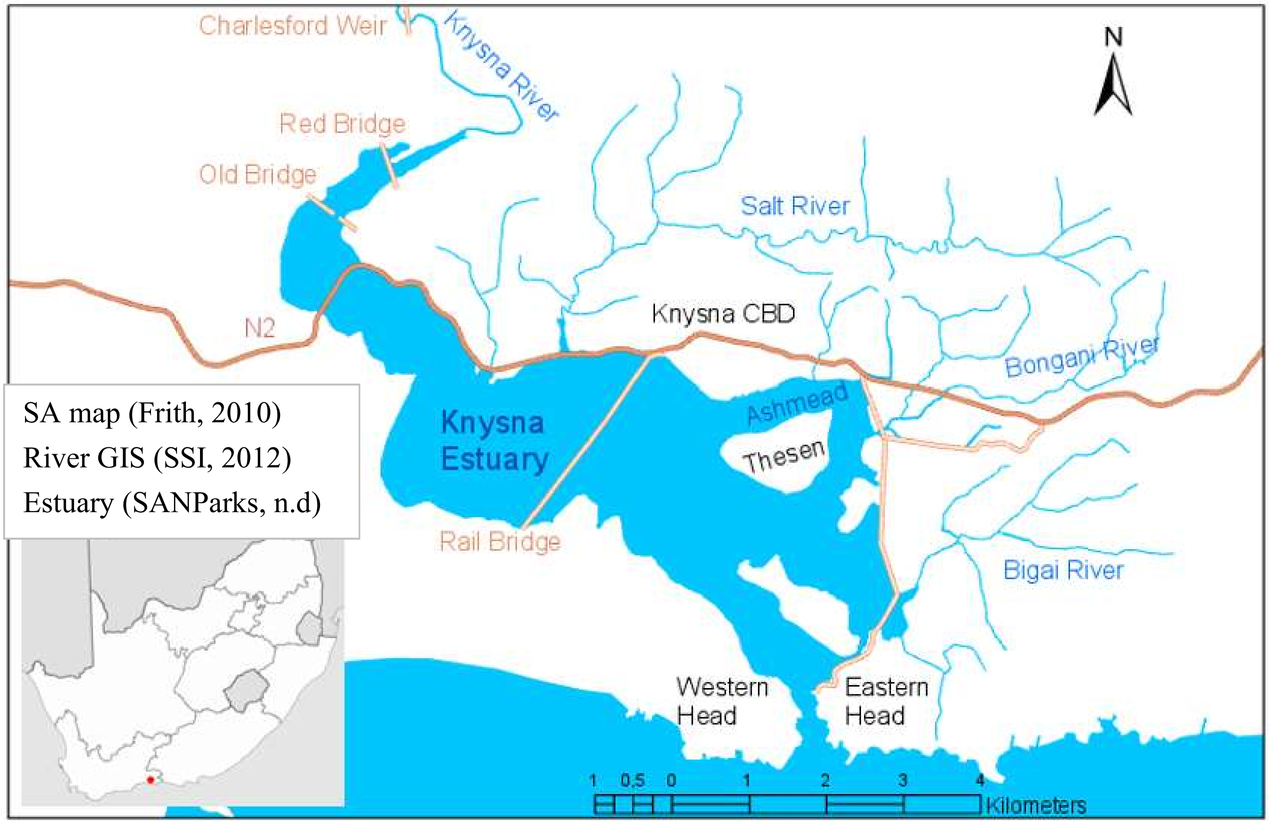


Figure 3-1: Map of Knysna Estuary, map of South Africa

3.1.2 Land use

The land use in the study area includes both formal and semi-formal urban development, the Knysna industrial area, commercial forestry, golf courses, parks and indigenous forests and fynbos. Forests comprise 25% of land cover in the entire Knysna Catchment, plantations 23% and upland fynbos 13% (Mander & Van Niekerk, 2013). This study included a portion of the bay area, and if this is excluded these numbers will increase. In the catchments surrounding the estuary, urban development, lowland fynbos, and alien/degraded land predominate (based on figure in Mander & Van Niekerk (2013)).

The coastal areas of the Heads and areas adjacent to the estuary are densely settled with formal urban development and include the Knysna CBD, its extensions to the west and east, Leisure Isle, and outlying suburbs (Marker, 2003). Historically Thesen Island was the site of a timber treatment plant but has subsequently been redeveloped into an urban settlement.

The plateau that is the watershed between the Salt River and Bongani River is densely populated, with large semi-formal developments dominating the headwaters of the two catchments. The northern portions of the Salt River catchment are largely undeveloped and land use is primarily natural and commercial forestry. Large tracts of the natural forest are classified as alien/degraded but land use along the middle reaches of the river is classified as indigenous forest (based on figure in Mander & Van Niekerk (2013)). The Simola Golf Course is located in the west of the Salt River Catchment. The other two large golf courses in Knysna are the Knysna Golf Course, located adjacent to the estuary between the Bongani and Bigai Rivers, and the Phezulu Golf Course, in the southern headwaters of the Bigai River.

In the Bongani Catchment the densely settled plateau drops into steep sided valleys dominated by Southern Afrotemperate Forest (SANParks, n.d.). Land use in portions of the middle reaches is classified as alien/degraded (based on figure in Mander & Van Niekerk (2013)). The Knysna Industrial area is located immediately to the south of the Bongani River, just upstream of the River Mouth.

The Northern headwaters of the Bigai River have been developed with semi-formal settlements. Land use in the southern headwaters of the Bigai River is dominated by low density settlements and lowland fynbos (*ibid*) as well as the Phezula Golf Course. The Southern catchments to the Knysna Estuary are less developed, with two formal urban settlements of Belvidere Estate and Lake Brenton. The dominant land use in these catchments is lowland forest, with portions of degraded/alien vegetation (*ibid*).

The estuary, and parts of the surrounding catchments are classified as ‘Special Nature Reserve’ (DEA, 2014) and are protected in terms of the Protected Areas Act (RSA, 2004). The Pledge Nature Reserve is situated just to the north of the Knysna CBD.

Figure 3-2: Semi-formal development in the Bongani Catchment

Figure 3-3: Indigenous forest in the Bongani Catchment

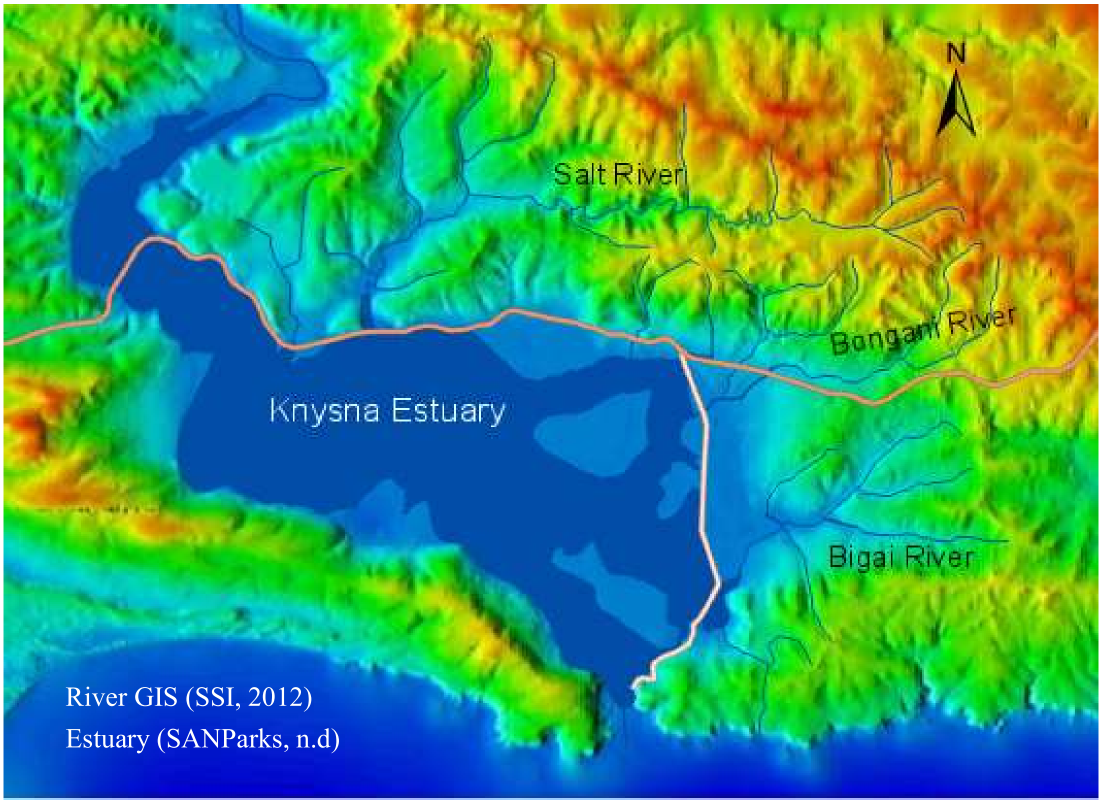
3.1.3 Topography

The plateau areas to the north and south of the Knysna Estuary range in altitude from 200 to 240 metres above mean seal level (mamsl) and form part of the coastal platform (Marker, 2000). Rivers and streams in the area have steeply incised the landscape and *'(t)he dominant characteristic everywhere is the scarcity of level land*' (Marker, 2003). The topographic relief of the estuary catchments is shown in Figure 3-4, with blue indicating areas with the lowest altitudes and red indicating the highest altitudes.

3.1.4 Climate

The recorded Mean Annual S-Pan Evaporation for Quaternary Sub-catchment K50B is 1400 mm, with a Mean Annual Precipitation (MAP) of 882 mm, of which 27% is estimated as runoff (Bailey & Pitman, 2015a). During the winter months of June to August the average minimum temperatures are 9 °C, with average maximum temperatures of 20 °C. During the summer months of December to February the average minimum temperatures rise to 17 °C and the average maximum temperatures reach 26 °C (based on 22 years of daily data supplied by the South African Weather Service (SAWS) for Station 0014123).

Historical daily rainfall data was obtained from the daily rainfall database developed by Lynch (2004), and the SAWS for Rainfall Station 0014063W (Knysna TNK). The rainfall station is situated on Thesen Island and is in close proximity to all modelled catchments. Data from 1900 to 2018 for this station yields a Mean Annual Precipitation (MAP) of 748 mm. As can be seen in Figure 3-5, Knysna experiences rainfall throughout the year, with higher than average rainfall in late winter and early spring (August to October) and lower than average late summer rainfall (December to February). Over the length of record, the highest recorded annual rainfall (1951) was 200% of the MAP, whilst the lowest recorded rainfall (2016) was only 50% of the MAP. Rainfall data used for this study is discussed in Section 5.1.1.



River GIS (SSI, 2012)
Estuary (SANParks, n.d)

Figure 3-4: Topographic relief of the catchments surrounding the Knysna Estuary

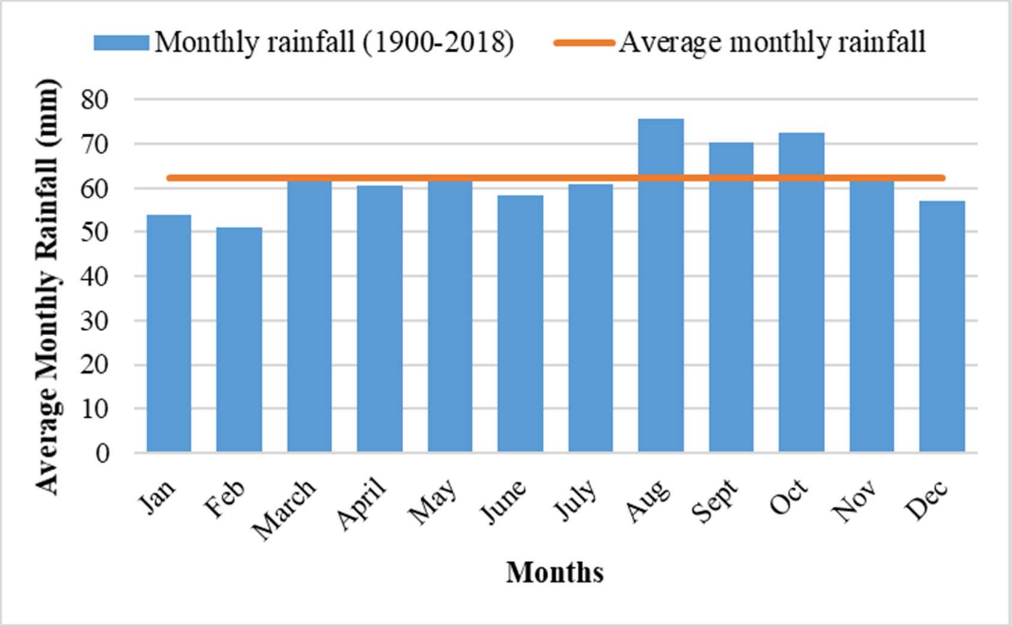


Figure 3-5: Average monthly rainfall – Knysna TNK (1901-2001)

3.1.5 Socio-economic profile

All data in this section is sourced from WCG (2017). The estimated population of Knysna for 2018 was 74 606, with 25 877 households and a projected growth rate of 4.8%. The number of indigent households was 1564 (or 6%). The unemployment rate was 22.1% in 2016 and the dependency ratio was 52.6 for 2018 (the number of children and seniors are approximately half the number of people of working age).

The largest three sectors of the Knysna economy (calculated as a percentage contribution to GDP in 2015) were finance, insurance, real estate and business services (25%), wholesale and retail trade, catering and accommodation (18.7%) and manufacturing (11.8%). The real Gross Domestic Product per Region (GDPR) per capita for Knysna was significantly lower than that measured for the Western Cape province. Income inequality, as measured by the Gini coefficient, rose between 2010 and 2016. In 2016 Knysna was assigned a Gini coefficient of 0.63 and a Human Development Index score of 0.71. Access to basic service delivery of water ('households with access to piped water inside the dwelling or yard or within 200 m from the yard') was 96.6% and access to sanitation ('flush or chemical toilets connected to the sewerage system') was 92.5% in 2016 (WCG, 2017, p. 17). Knysna has made significant progress in the provision of access to sanitation, with the percentage of households with access to sanitation increasing from 76.4% in 2011 to 92.5% in 2016. Of particular relevance to this dissertation is the decrease in informal sanitation (which should improve pollution issues) and the associated increase in sewage volumes to the Knysna WWTW.

3.2 Study approach

The study approach is shown in Figure 3-6. A literature review (Section 2) was undertaken to gather background information and recognize water quality concerns identified by previous researchers. Water sampling was undertaken at outflows from rivers and stormwater drains on the northern and eastern side of the estuary, including locations in the Knysna CBD, the Salt River, and locations discharging to the Ashmead Channel. The northern and eastern catchments were selected as these areas are the most developed catchments, and many of the catchments drain to the Ashmead Channel. As discussed in the literature review section of this paper, significant pollutant impacts are being noted in the Ashmead Channel.

Water quality samples were tested for nutrients, TSS and turbidity, pH, temperature and Electrical Conductivity (EC). The water quality sampling and testing methods are described in Section 0, and results are discussed in Section 4. The test results identified pollutants as well as establishing problematic catchments. A second phase of water quality sampling focused primarily on the WWTW outfall, and the Bongani, Salt, and Bigai catchments. The second phase of the testing allowed for more detailed comparison between catchments, and for identification of possible pollution sources within catchments.

The water quality results confirmed the Bongani Catchment as a significant source of pollutants to the Ashmead Channel. Hydrological modelling of the Bongani Catchment was undertaken to understand flows within the catchment. Model inputs were identified through site visits, literature review, and a desktop study of available information. The model was calibrated using observed water level data at two monitoring sites. Literature that informed the hydrological modelling approach is discussed in Section 3.4. Data collection and processing methods are discussed in Section 3.5, and modelling and calibration methods in Section 0. The model sensitivity analysis, calibration and outputs are discussed in Section 5.

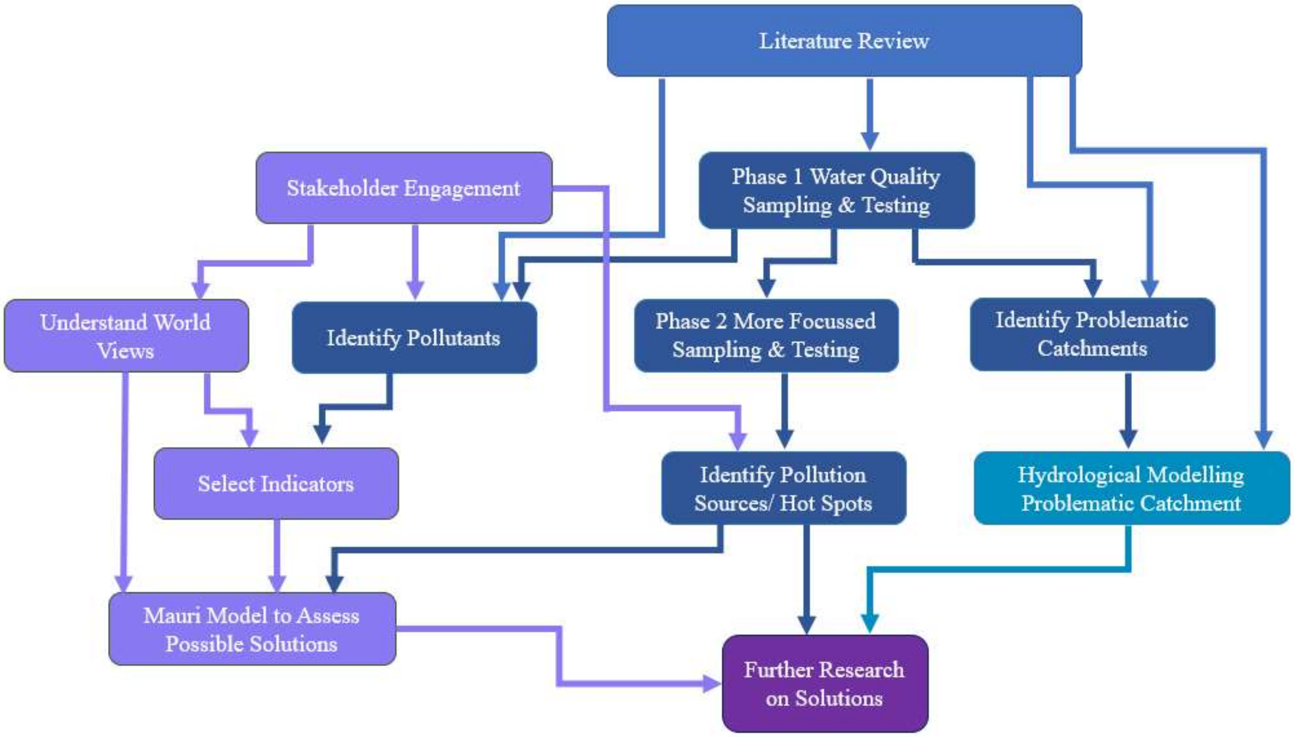


Figure 3-6: Flow diagram showing the study approach

Seventeen stakeholders were interviewed during the stakeholder engagement phase of the study. Stakeholders helped to identify water management concerns in Knysna, including possible pollution sources and locations. The researcher attempted to understand the world views of stakeholders through the use of an analytical hierarchy process described by Morgan *et al.* (2013). Stakeholders who prioritized certain dimensions within the world view helped to determine indicators in that dimension. Indicators are performance measures that should be used to assess proposed intervention measures. The indicators and world views were then used as inputs to the Mauri Model, a tool developed by Morgan (2006) to inform decision making processes. More detail of the method employed in the stakeholder engagement phase and for the Mauri Model is presented in Section **Error! Reference source not found.**, and results are discussed in Section 6.

The water quality testing, hydrological model, stakeholder engagement and use of the Mauri Model all inform an understanding of surface water runoff in catchments surrounding the Knysna Estuary, and how this runoff is contributing to pollution in the estuary. This knowledge can then be used to inform possible solutions or mitigation measures, as discussed in the conclusions and recommendations, Section 7.

3.3 Water quality sampling and analysis

3.3.1 Water sampling and in situ testing

During the first phase of water sampling, 18 sampling points were selected where streams or stormwater networks discharge to the estuary. Water quality data was collected monthly, or after large storm events, by the KBP. The sampling sites were selected at outflows to the estuary and were therefore influenced by tidal flows. Samples were collected at low tides to minimise the impact of tidal flows. Samples were transported to the Knysna Municipal Water Treatment Works (MWTW) and were tested for pH, conductivity, TSS, turbidity, Total Ammonia Nitrogen (TAN), nitrate, nitrite and Total Phosphorus (TP). Seven sample sets were collected between September 2017 and January 2018. The results of this first phase of water sampling were analysed to identify the catchments that are generating high pollutant loads. The Salt, Bongani, and Bigai catchments were selected for further investigation, along with isolated points in the CBD.

The second phase of water quality sampling focused on identifying possible pollutant sources within the selected catchments. Revised sampling points were selected within the catchments, as well as at the WWTW effluent discharge site. The KBP collected samples monthly at the revised sites. Ten sampling sets were collected between February and November 2018. The results of this phase of testing were used to determine what pollutants are originating in different parts of the selected catchments, and to statistically compare pollutant concentrations at different sites within the same catchments. Where possible pollutant concentrations were compared to historical data to assess changes over time.

For both sampling phases, samples were collected in new plastic bottles. The sample bottles were rinsed three times sequentially with water from the sample site. Samples were then collected and labelled with the site description, time and client identifier. For the first phase of sampling, the samples were transported immediately after collection to the Knysna MWTW for analysis. For the second phase of sampling the samples were transported to the KBP laboratory for testing, for reasons discussed in more detail in Sections 3.3.2 and 3.3.5.

During the March and April 2018 sampling events, OHAUS® hand-held probes were used on site to test for temperature, pH, Total Dissolved Solids (TDS), and EC. The pH and EC probes were calibrated immediately before the first site visit, according to standard procedures. The pH probe was calibrated using three pre-prepared standard buffer solutions of pH 4, 7 and 10. The probe was calibrated for each buffer solution sequentially, rinsing the probe in distilled water between calibration phases. The probe automatically corrects for temperature variation. The EC meter was calibrated using a pre-defined calibration standard of 1413 µS/cm.

On site, the probes were rinsed with distilled water before and after use. The probes were held in the streams until the reading stabilized, after which the reading, site, date and time were noted. At many of the sites the TDS and EC concentrations in the streams were in excess of the test limit for the probes. In such cases a water sample was obtained and then diluted with distilled water until the concentration fell within an acceptable range for the probes. The dilution volumes were measured using a measuring flask, and recorded. The TDS and EC concentrations were then calculated from the dilution ratio and the probe readings.

A significant database of *E. coli* results (184 sample dates between August 2009 and October 2018) was obtained from the Knysna Municipality. This was supplemented with additional sampling undertaken by the KBP and tested for *E. coli* at a SANAS accredited laboratory in October and November 2018.

3.3.2 Phase 1 sampling locations

The locations of the initial 18 monitoring sites are shown in Figure 3-7. The 18 sites with descriptions are listed in Appendix A, with the Department of Water and Sanitation (DWS) monitoring site names for sites that corresponded with the historical DWS monitoring programme. Comparison of the historical DWS monitoring data with water quality data collected as part of this study, allowed for an assessment of the changes in water quality over time. Results are presented in Section 4.1.

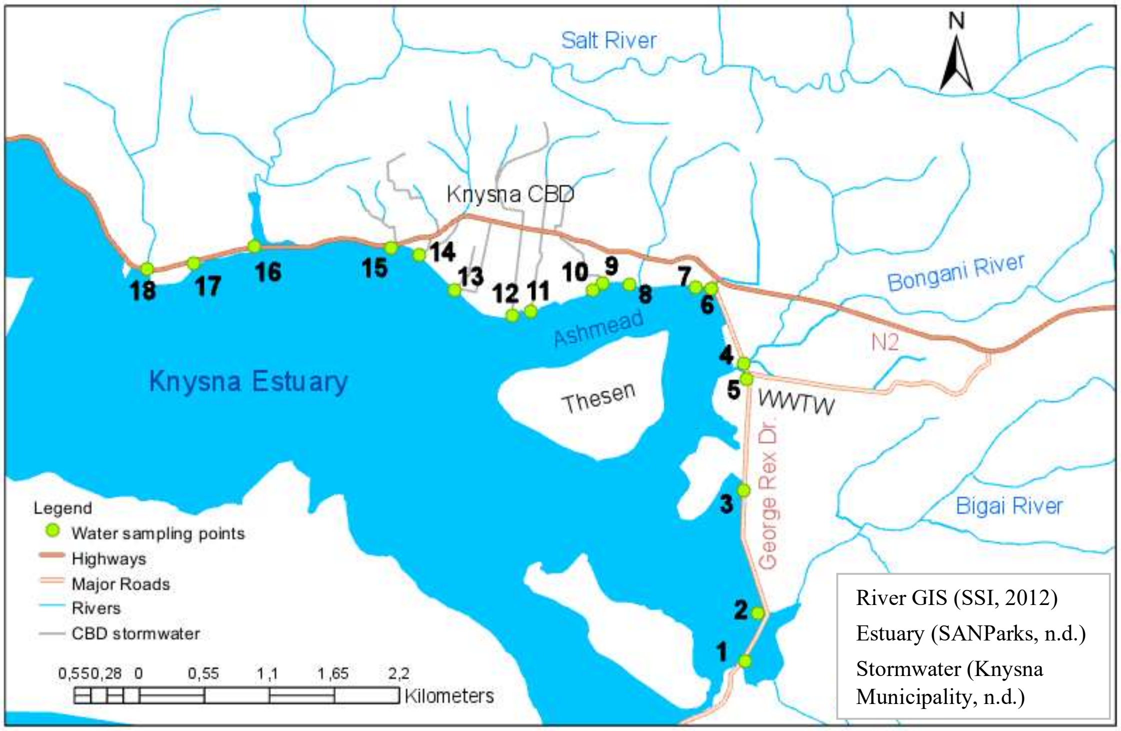


Figure 3-7: Original 18 water quality monitoring locations

3.3.3 Phase 2 sampling locations

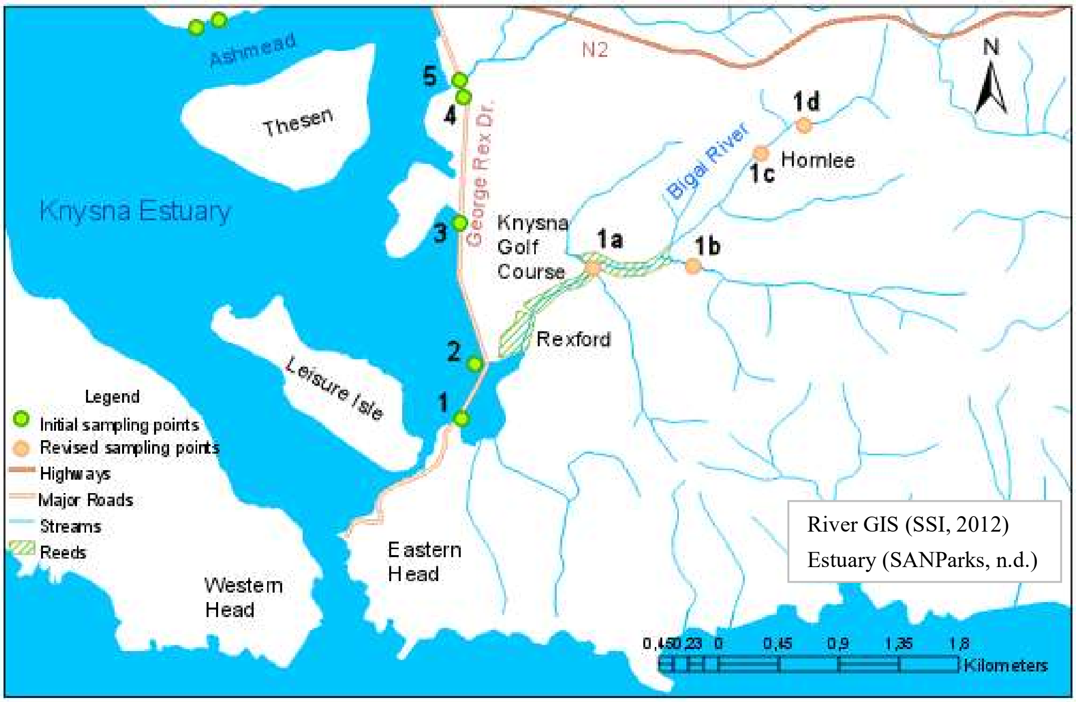
The sampling and testing for phase 2 of the study focussed on the Bongani, Bigai and Salt River catchments, with some additional sampling in the Knysna CBD and surrounds. The results are presented in Section 4.2.

3.3.3.1 Bichai River Catchment

Sampling sites in the Bigai River Catchment are shown in Figure 3-8. The Bichai River has a catchment size of 910 ha. The semi-formal development of Hornlee, and adjacent urban areas, comprising approximately 20% of the catchment, are in the river's upper headwaters. The river then flows through approximately 1.6 km of reed beds, parallel to Howard Street, Kennet Street and Rexford Road, in Rexford. Stormwater draining from the Rexford and Hunter's Home urban areas discharges to the river at road crossings in the densely reeded portion of the river. Lowland fynbos dominates the land use in the catchment of a large tributary of the Bichai River (approximately 230 ha), which confluences with the Bigai River immediately upstream of the reed beds. Smaller tributaries drain portions of undeveloped land, low density urban land,

and the Phezulu golf course, and confluence with the Bichai River before it crosses George Rex Drive. The portion of the Bichai River between Wilson Street and George Rex Drive is strongly tidally influenced, and may be regarded as part of the estuary.

Sampling Sites 1, and 1a to 1d were located in the Bigai River Catchment. Site 1 was located at the culverts under George Rex Drive. Site 1 was not retained as one of the revised sampling points due to concerns regarding the tidal influence at this site. Site 1a was located at the Howard Street Culvert, and within dense reed beds. The river flows very slowly at this road crossing, and dense reed beds make it challenging to obtain representative water samples at this location. Site 1b was located on the large tributary to the Bigai river, adjacent to Rexford. Sites 1c and 1d were located above the reed beds, in Hornlee. Although Site 1d was only approximately 430 m upstream of 1c, a small stream and at least 2 km of stormwater pipe discharge to the Bigai River between the two points.



River GIS (SSI, 2012)
Estuary (SANParks, n.d.)

Figure 3-8: Revised sampling points in the Bigai Catchment

Figure 3-9: Sites 1 (left) and 1a (right) on the Bigai River

Figure 3-10: Sites 1b (left) and 1d (right) in the Bigai River Catchment

3.3.3.2 Bongani River Catchment

The Bongani River has a catchment size of 630 ha. The catchment is shown in Figure 3-11. The densely settled semi-formal developments of Khayalethu and Bongani are located in the upper headwaters of the river. Streams originating in the headwaters descend steeply into the middle reaches, which are surrounded by indigenous Afrotemperate forest and degraded grassed areas, with little development. The River crosses the N2 national highway before flowing adjacent to the Knysna Industrial area. A tributary of the Bongani River originates in the semi-formal developments of Concordia and Joodse Kamp, before flowing through steep-sided valleys vegetated with natural forest. Stormwater from the formal urban area, Old Place, drains to the tributary, before it confluences with the Bongani River downstream of the industrial area. The Old Place garden waste disposal site is located in the catchment to this tributary. Stormwater from portions of the industrial area, as well as portions of the Fraaisig and Hornlee formal and semi-formal areas, flow via a stormwater network to the Vigilance Drive Drain. The Vigilance Drive Drain is located parallel to Vigilance Drive, adjacent to the Waste Water Treatment Works, and discharges stormwater to the Bongani River immediately upstream of George Rex Drive. The Bongani River flows through culverts under George Rex Drive where it enters a small wetland before discharging to the Ashmead channel.

Site 4, and Sites 4a to 4i were sampling sites within the Bongani River Catchment. Site 4 was located at the outflow of the river to the estuary at George Rex Drive, and has been discussed under Section 4.1. Site 4b was located on the Bongani River adjacent to the industrial area. Sites 4c, 4d, and 4e were located in the upper headwaters of the Bongani River, in the Khayalethu and Bongani semi-formal developments. Site 4g was located in the lower reaches of the Bongani tributary stream. Sites 4a was located on the Vigilance Drive Drain, and Sites 4h and 4i were sampling points at two large stormwater pipes that discharge to the Vigilance Drive Drain.

Site 5 was located at the WWTW discharge point, where the water flows in culverts under George Rex Drive, as shown on Figure 3-11. The effluent flows into the small wetland at the Bongani River outflow. The WWTW is located adjacent to the Knysna industrial area, on the opposite side of Vigilance Drive. Site 5 has also been discussed in Section 4.1.

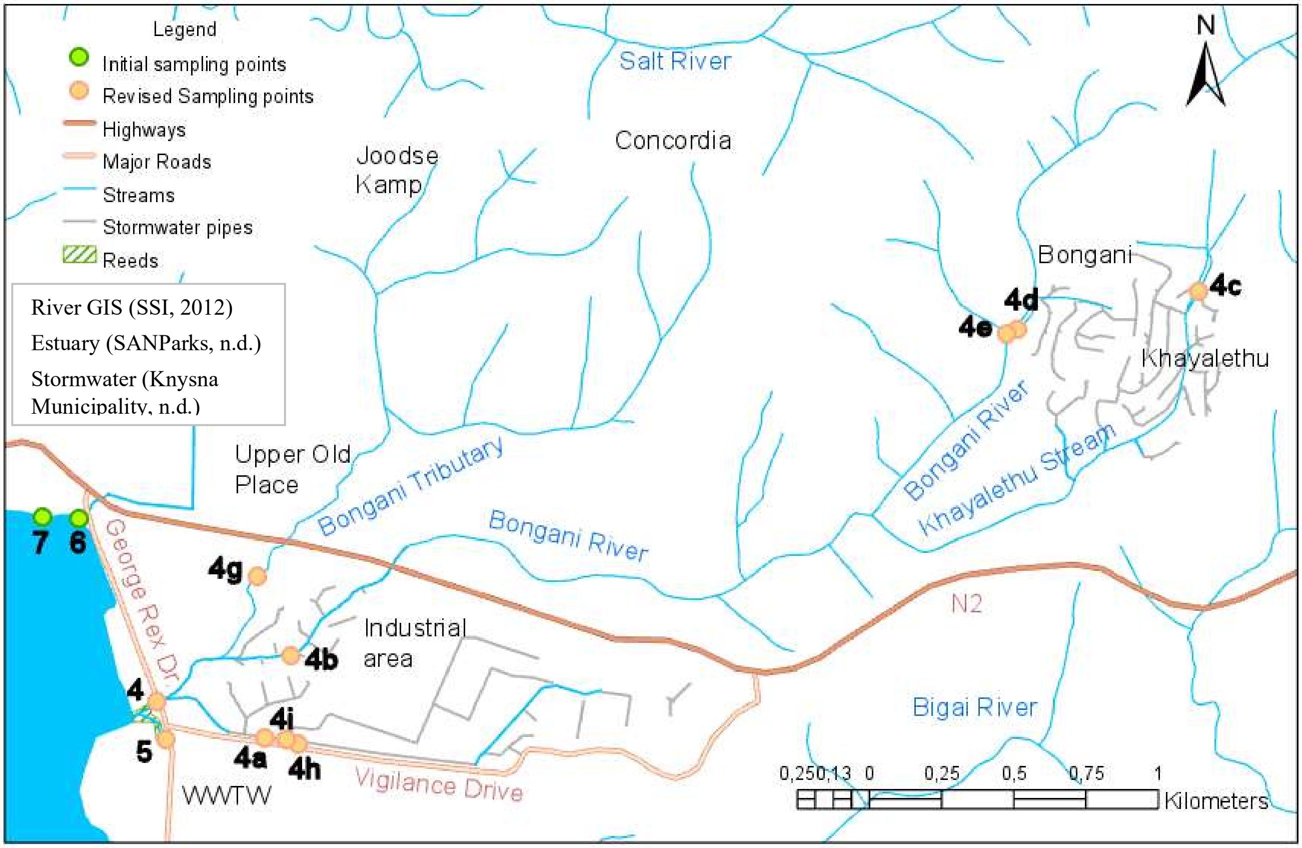


Figure 3-11: Revised sampling points in the Bongani Catchment

Figure 3-12: Sampling Sites 4 (left) and 4b (right) on the Bongani River

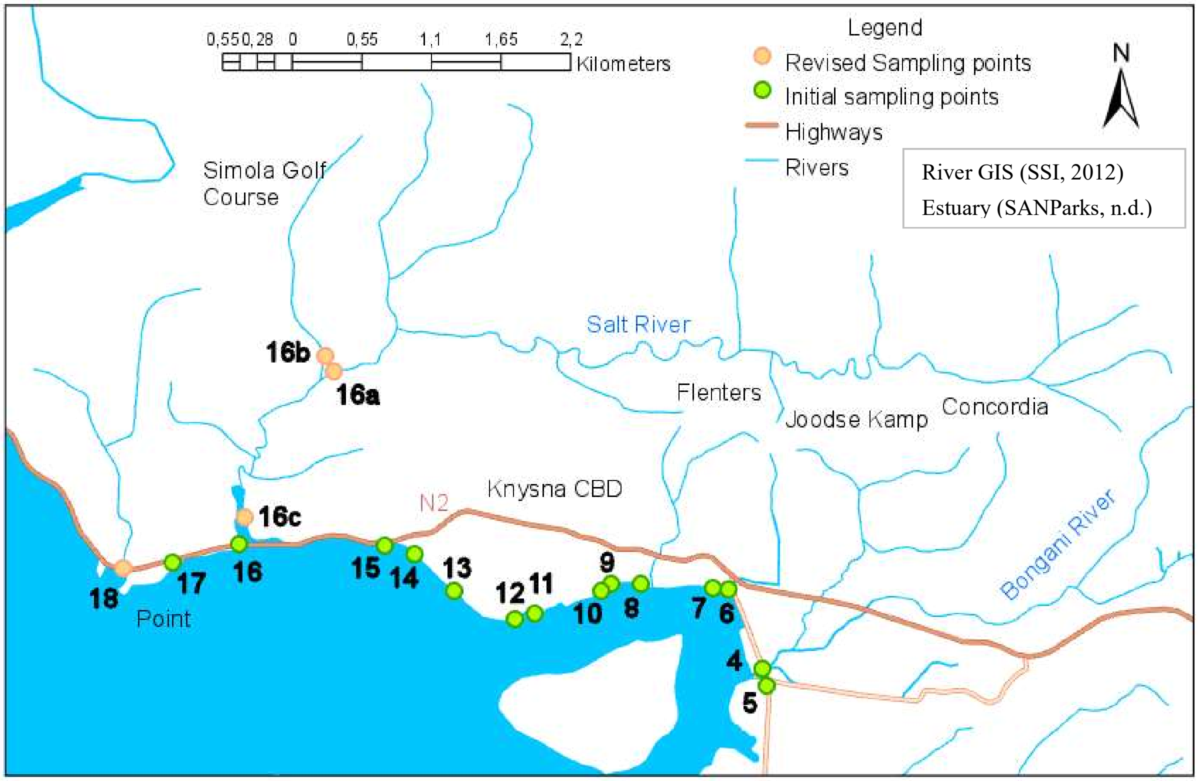
Figure 3-13: Sampling sites 4a (left) and 4c (right) in the Bongani River Catchment

Figure 3-14: Site 5, the location of the WWTW discharge

3.3.3.3 Salt River Catchment

The Salt River has the largest catchment (1530 ha) of the rivers that drain the northern and eastern catchments of the Knysna Estuary. For the majority of its length, the Salt River flows in a westerly direction, before flowing south and into the estuary at the N2 highway crossing. Small tributaries drain the southern and northern catchments to the river. The semi-formal developments of Concordia and Joodse Kamp are located on the watershed between the Bongani and the Salt River catchments. Part of Joodse Kamp, the majority of Concordia, as well as the semi-formal developments of Rhobololo and Flenters, occupy the southern headwaters of the Salt River. Land use in the northern headwaters is predominately commercial forestry. The Akkerkloof Dam, which is a source of drinking water for Knysna, is located in the upper headwaters of the Salt River Catchment. Stormwater runoff from the Simola Golf Estate drains to a tributary of the Salt River, with the confluence of the Salt River and the tributary located downstream of the Old Cape Road culverts.

Sampling Sites 16, and 16a to 16c were located in the Salt River Catchment. Site 16 was located at the mouth of the Salt River, at the N2 road crossing, and was discussed in Section 4.1. Site 16 was not retained as a revised monitoring point due to concerns regarding the tidal influence at this location. Sites 16a and 16b were located approximately 2.1 km from the mouth of the Salt River, at culvert crossings of the Old Cape Road. Site 16a was located at the Salt River crossing, whilst Site 16b was located at the crossing of the tributary which receives runoff from the Simola Golf Estate. Site 16c was located on the Salt River, approximately 250 m upstream of the river mouth.



River GIS (SSI, 2012)
Estuary (SANParks, n.d.)

Figure 3-15: Revised sampling points in the Salt River Catchment

3.3.3.4 Additional Monitoring Points

Monitoring included five points in the Knysna CBD, as shown in Figure 3-16. Site 14b was situated on a stormwater drain off Rawson Street, near the Stepping Stones School. The site was also selected as a flow monitoring point. Site 14c was situated downstream of Site 14b, on the same stormwater channel but included additional flow originating at the Pledge Nature Reserve, from the Brickelbos Stream. Single samples were taken at Sites 8a and 9a (below the Knysna Hospital) and Site 11 (Queen Street Drain in the Knysna CBD) and Site 18 (Point). Site 18 is shown in Figure 3-15. Thereafter sampling was primarily focused on the Bigai, Bongani and Salt River catchments, and the WWTW outflow.

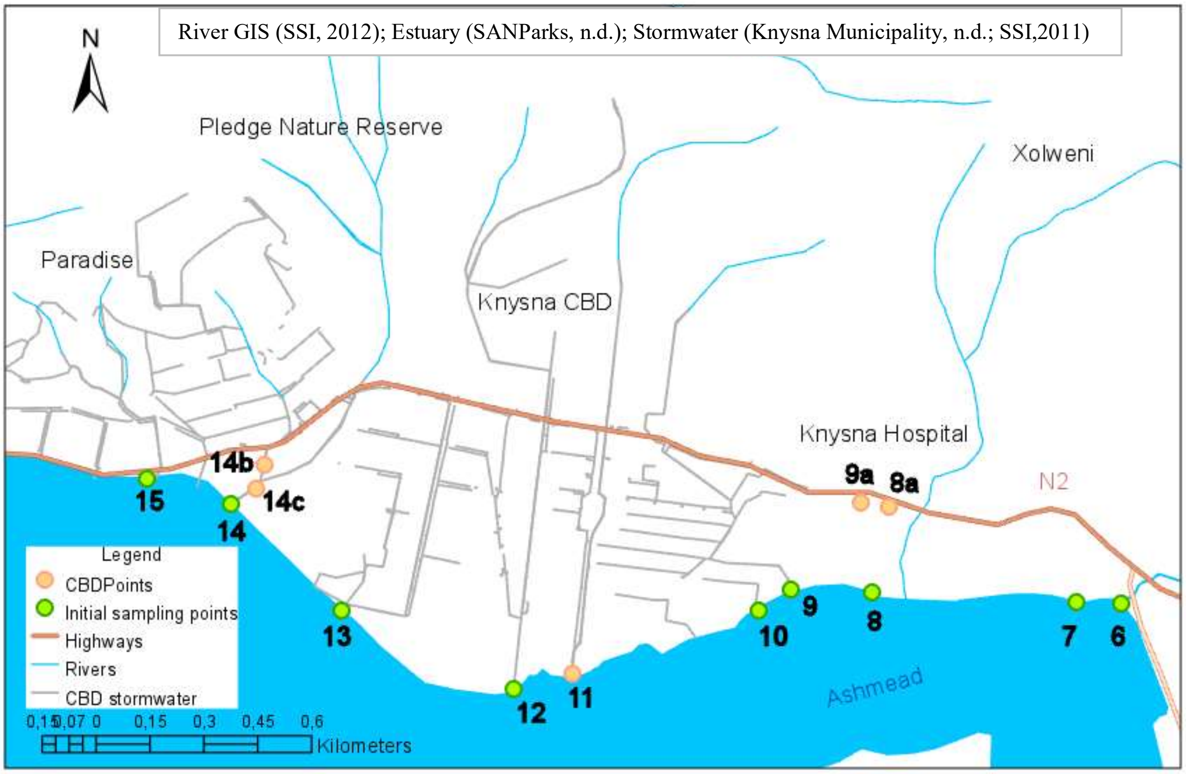

River GIS (SSI, 2012); Estuary (SANParks, n.d.); Stormwater (Knysna Municipality, n.d.; SSI,2011)

Figure 3-16: Revised sampling points in the Knysna CBD

3.3.4 Testing procedures

During the first sampling phase water samples were transported to the MWTW for testing. For nutrient analysis the MWTW laboratory used standard operating procedures for the Hach DR900 or DR5000 colorimeter with powder pillows. Analysis techniques were as follows: cadmium reduction method 8171 (nitrate), diazotization method 8507 (nitrite), HR salicylate method 10031 (TAN) and ascorbic acid method 10210 (TP) (Hach Company, 2013a, 2015a,b, 2016). Temperature, pH, Electrical Conductivity (EC), Total Suspended Solids and turbidity measurements were also recorded.

During a site visit in March, water samples were collected and transported to the MWTW. In addition, selected duplicate samples were collected and transported for analysis at the University of Cape Town (UCT) water quality laboratory. This secondary analysis was to ensure confidence in, or identify concerns regarding, the test results from the MWTW. The samples were tested at UCT using standard operating procedures for the Gallery^{TM} automated photometric analyser for nitrate, nitrite and TAN. The tests were conducted by UCT laboratory staff, with assistance from the researcher. Samples were placed in sample racks. Reagents were selected according to the test being conducted. Both sample and reagent racks were then inserted into the machine, and labelled accordingly in the analyser's interface. Calibration was undertaken if the calibration certificate had expired or the expected concentrations fell outside of the calibration curve. The analyser performed automatic dilutions and additions of reagents.

The analyser measures TAN concentrations by measuring the absorbance of the compound formed when ammonia reacts with hypochlorite ions, and then in turn reacts with salicylate ions in the presence of sodium nitroprusside (Thermo Fisher Scientific Inc., 2015a). Ammonium concentrations are expressed as TAN (mg/ℓ). The analyser measures Nitrite (NO_2) and Total Oxidised Nitrogen ($NO_x = NO_2 + NO_3$) concentrations using the Colorimetric Hydrazine method (Thermo Fisher Scientific Inc., 2015b). Concentrations are expressed as mg/ℓ of nitrogen (NO_2N and NO_xN). Nitrate as nitrogen (NO_3N) concentrations are calculated by subtracting the nitrite concentration from the NO_xN concentration.

Standard operating procedures were used for preparation of samples for Total Phosphorus (TP) analysis. The steps included digestion, filtration, addition of reagents, and analysis using a spectrometer. A calibration curve was developed during the test (based on samples of known concentration), and was used to convert the absorbance measurements to TP concentrations. If the calibration curve was not acceptable the test was repeated. Temperature and pH were measured with laboratory probes that were calibrated daily. The results are discussed in Section 4.1.2.1.

The results from the UCT testing were then compared to the results from the MWTW for the same sites. The test results at UCT showed significant discrepancies when compared with the MWTW results, particularly for TAN. Due to concerns that the results could have been impacted by heat during transport and the time delay before testing, a second set of duplicate samples was collected on site during the April monthly sampling. As before a full set of samples was delivered to the MWTW. Selected duplicate samples were transported in ice and tested at UCT the next day. The researcher undertook testing on these samples according to the same test procedures. The results again differed significantly from those received from the MWTW for nutrients (results are discussed in more detail in Section 4.1.2.1).

The fact that the two laboratories were producing very different test results for duplicate water samples raised doubts about the validity of the test results. It was necessary to determine which of the laboratories was producing accurate test results. In order to test this, a sample of known concentration was then prepared in the UCT laboratory. Since the concentrations in the sample were known, the sample could be tested at both laboratories, and the results from these tests could be compared to the known concentrations. In this way the accuracy of test results from the two laboratories could be assessed, and any issues addressed. Preparation and testing of this sample is discussed in more detail in Section 3.3.5.

3.3.5 Preparation of a solution of known concentration

The standard solution of known concentration was prepared to test for the following:

- Total Ammonia Nitrogen (TAN)
- Nitrate (NO_3)
- Nitrite (NO_2)
- Total Phosphorus (TP)

The following chemicals were used in the preparation of the sample of known concentration:

- TAN – Ammonium Chloride (NH_4Cl)
- NO_3 – Potassium Nitrate (KNO_3)
- NO_2 – Sodium Nitrite ($NaNO_2$)
- TP – Dipotassium Hydrogen Phosphate (HK_2O_4P)

The required mass of each chemical, to achieve the required concentrations, was calculated and interference levels were checked for the secondary products – chlorine, potassium, sodium. The calibration and analysis limits were checked for each test procedure. The sample was prepared according to the following steps:

- Chemicals were dried in the desiccator overnight.
- The calculated mass of each of the desiccated chemicals was weighed. The balance used has an accuracy of 0.1 mg.
- Each of the weighed samples were rinsed with distilled water into a single 1 litre volumetric flask and the flask was filled with distilled water.
- The solution was stirred with a magnetic stirrer. At the calculated concentrations solubility was acceptable.
- The sample was diluted ten-fold (1/10 dilution) by measuring 100 ml of the prepared solution in a volumetric flask, transferring this to a 1 litre flask and filling with distilled water (the required concentrations were extremely low for NO2N and NO3N, requiring very low masses of Potassium Nitrate and Sodium Nitrite. The solution was therefore prepared for an order of magnitude higher concentrations and then diluted).
- The pH of the solution was adjusted to 6.5 using Sulphuric Acid. This was required as the solution needed to be couriered to the MWTW and therefore could not be tested immediately. The magnetic stirrer was used.
- All calculations for the expected concentrations were updated with the actual weighed mass of the chemicals to account for any inaccuracies in the weighing process.
- This solution was further diluted two-fold (1/2 dilution) with distilled water to test a solution with half the concentration. 100 ml of the solution was mixed with 100 ml of distilled water.
- The initially prepared, undiluted solution was then diluted five-fold (1/5 dilution) to get a solution with double the initially calculated concentrations. 100 ml of the undiluted solution was mixed with 400 ml of distilled water.

The prepared samples were kept in refrigeration overnight and were then tested in the UCT laboratory according to the standard procedures used for testing the previous sample sets. Five plastic sample bottles were then filled with the prepared solutions. Three of the sample bottles contained the solution first prepared, one contained the solution with double the concentration of the initial solution, and one contained the solution with half the concentration of the initial solution. The sample bottle caps were firmly sealed and then the bottles and an ice gel pack were packed into a polystyrene box. The box was sealed and couriered overnight to the KBP laboratory. Three sample bottles of the same type were similarly filled with the three prepared solutions and retained at UCT. The KBP delivered the sample bottles to the MWTW, where they were refrigerated overnight and tested the next day. The staff at the MWTW were not informed that the samples had been prepared in the laboratory, and tests were conducted according to the standard procedures used for previous sample testing. The sample bottles retained at UCT were not refrigerated, and were tested at UCT on the same day as the testing at the MWTW. This ensured that any effects due to testing delays and heating of the samples could be accounted for. The results of the testing showed that typically the UCT laboratory results were acceptable, whilst those from the MWTW were inaccurate, particularly for TAN. Comparison of the results is discussed in more detail in Section 4.1.2.1.

3.3.6 Testing procedures at the KBP laboratory

Due to unresolved testing concerns at the MWTW, all samples were tested at the KBP laboratory from June 2018. The change in testing location applied to the second phase of water quality sampling. At the KBP laboratory standard testing procedures were used for the Hach DR900 colorimeter with powder pillows. Analysis techniques were as follows: cadmium reduction method 8171 (nitrate), diazotization method 8507 (nitrite), HR salicylate method 10031 (TAN) and phosphorus reactive method 8048 (SRP) (Hach Company, 2013a,b, 2015a,b). Early sampling included testing salinity levels as chlorine can interfere with the cadmium reduction method. Subsequent sampling was undertaken at catchment locations with no salt water intrusion. During testing, if sample concentrations exceeded the test limits, the samples were diluted until the sample concentrations were within the limits. The number of dilutions were noted and the actual concentrations were back calculated. Compliance with the test limits was again confirmed during analysis of the results. The results of the second phase of sampling, tested at the KBP laboratory, are discussed in Section 4.2.

3.3.7 Analysis of test results and database data

Water quality results were compared between and within catchments using student t tests ($\rho \leq 0.05$). Student t tests were also used to compare the data at some sites with historical water quality data collected at the same sites by the DWS (DWS, 2018a). For larger databases, such as water quality data measured in the WWTW effluent, a Kendall Correlation ($\rho \leq 0.05$) was used to determine trends over time.

3.4 Water quantity: hydrological modelling considerations

3.4.1 The need for hydrological modelling

Adequate freshwater flows are crucial to the functioning of estuary ecosystems, as they provide a source for nutrients, scour deposited sediment, and affect salinity profiles (Turpie *et al.*, 2002). In some cases urbanisation can reduce the flow of fresh water through use and abstraction processes (*ibid*), whilst in others urbanisation can lead to increased runoff peaks and decreased base flows as a result of the increase in impervious surfaces associated with cities. These changes from the natural water cycle and quantity of water can significantly affect the ecosystems in rivers, as well as receiving water bodies. Tier 1 of the National Estuarine Monitoring Programme (NEsMP) requires the collection of both water quality and quantity data for freshwater systems draining to estuaries (Cilliers & Adams, 2016). This data can be used to inform management decisions (*ibid*). Currently the DWS records flow data for the Knysna River at Charlesford. No water quantity data is available for the smaller rivers within Knynsa, including the Bongani, Bigai and Salt rivers. Hydrological modelling was undertaken for the Bongani Catchment as part of this study.

Hydrological models are representations of complex real systems, which can be used to understand the current and historical situation, as well as possible future scenarios (James, 2005). The purpose of the Bongani hydrological model was to understand current hydrological conditions, catchment response to rainfall events and the impacts of land uses within the catchment on runoff. The model was used to estimate pollutant loads and can be used to assess alternative pollution mitigation measures as part of further research. Without adequate hydrological information the design of pollution mitigation measures will be poorly informed and this risks damage to mitigating infrastructure, or unintended consequences of mitigation measures, for example, increased flooding.

3.4.2 Selection of modelling software

PCSWMM is a commercial software package that substantially improves the usability and functionality of the US Environmental Protection Agency software SWMM (Armitage *et al.*, 2014). This software was selected for hydrological modelling due to the researcher's familiarity with the software, the ease of interfacing with ArcGIS, cost, and its suitability for research purposes and modelling of SuDS devices. Once the modelling software had been selected, a literature review of modelling considerations and methods employed by other researchers was undertaken, as detailed in the following sections.

3.4.3 Model complexity

When building a hydrological model there is always a trade-off between model parsimony and model complexity, and increased model complexity does not necessarily lead to increased model reliability, particularly where there is significant uncertainty (James, 2005). The highest source of forecast uncertainty is due to uncertainty in rainfall data (*ibid*). This is discussed in more detail in Section 3.4.5. The second highest source is uncertainty in the rainfall-runoff relationship, and only third in importance is the input parameters (*ibid*). Within this third category falls uncertainty regarding land use types, the stormwater drainage network, as well as the model parameters for each land use, or drainage channel. James (2005) posits that where there is considerable uncertainty a simple model should be employed. A simpler model would imply a coarser spatial resolution. '*The trade-off is that coarser schematization requires more decisions on how to aggregate catchment properties*' (Rossman & Huber (2016) as cited by Lee *et al.* (2018)).

Various researchers have investigated the impacts of reduced spatial resolution on model performance. Krebs *et al.* (2014) showed that the runoff volume was not significantly affected by a reduction in spatial resolution, but the estimated peak flows were significantly impacted. The authors quote two previous studies that support this finding, whilst a third noted a reduction of runoff volume with increasing sub-catchment aggregation. Lee *et al.* (2017) argue that higher spatial resolution models are required if source controls are to be implemented, and that source controls are recognized as the most effective way to manage pollution issues. Where flow calibration is only possible at the outlet of a large catchment area it is difficult to determine whether the model calibration for a high spatial resolution is really giving more accurate results on a smaller, sub-catchment scale. If the sub-catchments are not more accurately represented using a complex, highly spatially aggregated model than using a simple model, then some of the advantages of using high resolution for source control design are lost. In addition, high resolution modelling requires detailed land use and stormwater network data, which is not always readily available in a South African context.

For lower resolution models, researchers are required to make decisions on how to aggregate catchment properties in a way that will still provide reasonable model performance. A weighted average approach to aggregating land use properties was recommended by Krebs *et al.* (2014) and Lee *et al.* (2017). The required level of model complexity is a topic grappled with by all hydrological modellers and the techniques adopted for this study are discussed in the method section of this dissertation.

3.4.4 Impervious and pervious area relationships

In addition to high spatial resolution modelling, Lee *et al.* (2017) recommend the separation of directly connected impervious areas (DCIA) from indirectly connected impervious areas (ICIA), as well as the separation of Buffer Pervious Areas (BPA) from standalone pervious areas (SPA). BPAs receive runoff from ICIAs, whilst SPA do not. The study found that modelling of these separate areas significantly impacted model performance for small storms, but not for larger storms (greater than a 1:5-year return period). Including all impervious areas as DCIA leads to higher runoff volumes and storm peaks (Krebs *et al.*, 2014; Lee *et al.*, 2018). Modelling all pervious areas as BPA was found to result in larger peaks once infiltration capacity has been exceeded (Lee *et al.*, 2018). It is common practice in SWMM modelling to assign a percentage routing to impervious areas, where the remainder would be routed to pervious areas, effectively assigning all pervious areas as BPA.

3.4.5 Rainfall data for model calibration

As noted in Section 3.4.3, one of the largest sources of model uncertainty is rainfall data. The rainfall period for calibration need not be long if a short calibration period sufficiently covers the range of events required for calibration and is accurate (James, 2005). Selecting rainfall that is accurate and representative can be challenging given that rainfall is both temporally and spatially distributed, particularly where mountainous topography is present. This is illustrated by Fisher-Jeffes (2015), who found that Mean Annual Precipitation (MAP) in a 2600 ha catchment in Cape Town varied from 600 to 1500 mm/year. When the modelling time step is reduced (for example to 5-minute intervals), spatial variability, even during a single storm, can become significant. Ideally, to overcome this challenge, multiple rainfall stations across a catchment should be used. Fisher-Jeffes (2015) used six rainfall stations, for a 2,600 ha catchment. Krebs *et al.* (2014) used three tipping bucket gauges for three relatively small catchments (5.9, 6.6 and 12.6 ha) that were up to 4 km apart. For smaller catchments, with less spatial variability, the proximity and reliability of a single rainfall station would need to be assessed for acceptability. Palla & Gnecco (2015) and Qin *et al.* (2013), used single rainfall stations for 5.5 ha and 60 ha catchments respectively.

'*The temporal distribution of rainfall – the distribution of rainfall intensities during an event – can significantly impact the timing and magnitude of the peak flow that is experienced during a storm event*' (Fisher-Jeffes (2015, p. 2-50) citing Knoesen & Smithers (2008)). This is particularly true for small catchments with short times of concentration. The rainfall time step should ideally be significantly less than the catchment time of concentration (Ormsbee, 1989) and Berne *et al.* (2004) suggest that time intervals of 3 minutes and 5 minutes be used for catchments of 100 to 1000 ha respectively (both as cited by Fisher-Jeffes (2015)).

3.4.6 Rainfall data for scenario modelling

Long-term rainfall records for scenario analysis need not be accurate but must be credible (James, 2005). This means that for any particular day, could credibly have occurred. For scenario modelling simulated rainfall records are therefore sometimes used, although these should be based on, and mimic, natural rainfall records. The rainfall records should be sufficiently long to include the extreme events that the model would like to assess. The rainfall record used for scenario modelling is very dependent on the outcome that the researchers are investigating.

3.4.7 Event or continuous monitoring

Historically event-based monitoring was common, particularly for engineering design, but in recent years continuous monitoring has become more prevalent. James (2005) expresses himself very strongly on the continued use of event-based modelling *'Arguments are presented that event modeling, and its associated design methodology, at best contributes to the destruction of aquatic ecosystems…Eco-sensitive design, on the other hand, demands the adoption of continuous modeling.'* This refers to the critical importance of antecedent moisture on pollutant runoff (for example first flush effects) and to a critique of designs that focus on events for flow routing and flood prevention, rather than aiming to also achieve water quality objectives.

Using an event-based model requires either that the modeller run a warm up period, or that parameters at the start of the simulation be assumed. The impact of selecting these starting parameters is not explicitly discussed by Qin *et al.* (2013), however the impacts of antecedent conditions on model performance is evident in the assessment of the storm time to peak. Palla & Gnecco (2015) demonstrate that initial saturation values have a significant impact on modelled peak flows and volume reduction, and a less pronounced impact on modelled time to peak. These findings support continuous modelling.

3.4.8 Sensitivity analysis

As part of model calibration, a sensitivity analysis is usually performed to understand which model parameters to focus on for calibration. Calibration effort would be focused on the most sensitive parameters. Various methods of sensitivity analysis are possible, including Monte Carlo analysis and factor perturbation (James, 2005). Mein & Brown (1978), as cited by James (2005), also developed a matrix of sensitivity gradients. The factor perturbation method, which involves holding all other parameters fixed whilst varying a single factor, is very common. The limitations of this method are (James, 2005):

a) The sensitivity gradient is assumed to be linear, an assumption that may be valid only over a limited range of the parameter (most hydrologic models are thought to be nonlinear).

b) The sensitivity is estimated by holding the other parameters constant at some expected value, which may not be valid for real-world processes.

c) The method gives a single-valued indication of the effect on the objective function. In most cases, the decision maker would prefer to have an idea of the distribution of the design parameter.

The Monte Carlo method can provide important information about certainty bands but requires significant computation time and is thus less commonly applied. PCSWMM has a built-in sensitivity analysis which uses factor perturbation.

3.4.9 Calibration and validation

Once the sensitivity analysis has been completed the model can be calibrated against known data. Typically, a portion of the observed data is used for calibration, and the remainder is used for validation. There does not seem to be a consistent approach to the selection of calibration and validation events in the literature reviewed. Krebs *et al.* (2014) used three to six events for calibration of the three catchments, and eight to eleven events for validation, giving calibration to validation ratios of 1:1.33 to 1:3. Lee *et al.* (2017) calibrated their model on only two months of data and did not perform validation, whilst Palla & Gnecco (2015) used one storm for calibration and six for validation. Only one storm was used for calibration and a second for validation in the study undertaken by Qin *et al.* (2013). Fisher-Jeffes (2015) used a calibration : validation ratio of 2:1.

A key component of the calibration is the selection of the objective and performance functions (James, 2005). Consideration should be given to the intended use of the model when selecting the objective function. It is not generally possible to achieve a perfect calibration and therefore selecting the appropriate objective function for the model use is important, for example a model that intends to assess culvert sizing would prioritize peak flows over flow volumes. Performance functions can assist in determining the correlation between modelled and observed flows, and overall 'goodness of fit'.

3.5 Hydrological model data collection and processing

This section discusses the data collection and processing methods used to determine the inputs to the hydrological model. There are many sources of uncertainty in the hydrological inputs and modelling, and therefore the model was calibrated with observed flow data. The methods of obtaining flow data are discussed in more detail in Section 3.5.6.

3.5.1 Rainfall data

Rainfall data was obtained from the South African Weather Service (SAWS) for five rainfall stations in the Knysna Area. For one of the stations, additional patched rainfall data was obtained from the daily rainfall database (Lynch, 2004). There can be significant uncertainty associated with rainfall data, as rainfall varies spatially and temporally. To augment the data supplied by the SAWS, requests for rainfall data were placed in local newspapers and on the KBP's website. Data from seven private rainfall stations was obtained. Rainfall data supplied by the KBP for Thesen Island was used as input to the PCSWMM model. The analysis of rainfall data and motivation for the selection of the KBP data is detailed in Section 5.1.1.

3.5.2 Evaporation and temperature data

Evapotranspiration for the hydrological model was calculated in PCSWMM using the Hargreave's method. This method has the advantage of simplicity with low data requirements. The only inputs to the method are latitude and maximum and minimum daily temperatures.

Temperature data was available for two stations, the KBP gauge on Thesen Island and the SAWS Knysna gauge in Fisher Haven, on the mainland. Hourly data was measured at the KBP gauge between 2015 and 2018, whilst daily minimum and maximum temperature data was recorded for the SAWS Knysna gauge from 1996 to 2018. Comparison of data showed that the island has slightly more moderate temperatures than the mainland. The catchments modelled are all located on the mainland and therefore the SAWS Knysna data was used as input to the Hargreave's method.

3.5.3 Topography

Elevation data for the Knysna area was obtained from a 5 m grid DEM file, supplied by the Knysna Municipality. The DEM was based on aerial photos with a 25 cm resolution. Arc GIS was used to create a surface over the DEM points to enable the construction of a higher resolution 1 m DEM grid for use in PCSWMM. The 1 m DEM cannot have a higher accuracy than the source file, but the interpolated points allow for more spatial resolution in PCSWMM. The 1 m DEM file was used to calculate catchment slopes, node elevations and irregular cross-section profiles in PCSWMM. A 2 m contour file was also obtained from the Knysna Municipality and was used selectively to supplement the DEM where there was a lack of DEM detail, particularly for certain river cross-sections.

3.5.4 Land use and soils

Current land uses within the catchments were delineated from satellite imagery. Land uses were classified as forest, grassed, bare earth, industrial, formal urban, semi-formal urban, or highway. The land uses, and associated characteristics, were also verified during sites visits to various locations within the catchments. The use of this data in the hydrological model is discussed in Section 3.6.1.

Infiltration modelling is required to model runoff from pervious surfaces. PCSWMM has a number of alternative infiltration modelling processes. For this dissertation the Green-Ampt infiltration calculation method was selected, as many studies in the literature use this method, which therefore allows for comparison. Green-Ampt parameters are used as inputs to the model, and are based on soil types.

Soil types were obtained from the Agricultural Research Council (ARC) land type maps (Land Type Survey Staff, 2006a). These 1: 250,000 maps are available for the whole of South Africa, and were compiled from desk-top studies, supplemented with site visits and selected geotechnical testing. Detailed soils information for each land type was obtained from the accompanying ARC memoir (Land Type Survey Staff, 2006b). The texture classes from the memoir were interpreted based on the information published in Macvicar *et al.* (1977). Green-Ampt parameters for the different texture classes were assigned from Table A2 in Krebs *et al.* (2014), reproduced from Rawls *et al.* (1992) and Oram (2012). Where the texture class was given as a range (e.g. fine Sand - Sandy Loam) the two classes were assumed to occur equally (e.g. 50% Sand and 50% Sandy Loam). Weighted averages of the Green-Ampt parameters were then calculated for each land type, and the land use types identified in each catchment were used to calculate weighted average

Green-Ampt parameters for each catchment. Soil parameters were also obtained using the classification from WR2012 (Bailey & Pitman, 2015b) for comparative purposes. A more detailed discussion of the soils information is presented in Section 5.1.2.

3.5.5 Drainage network data

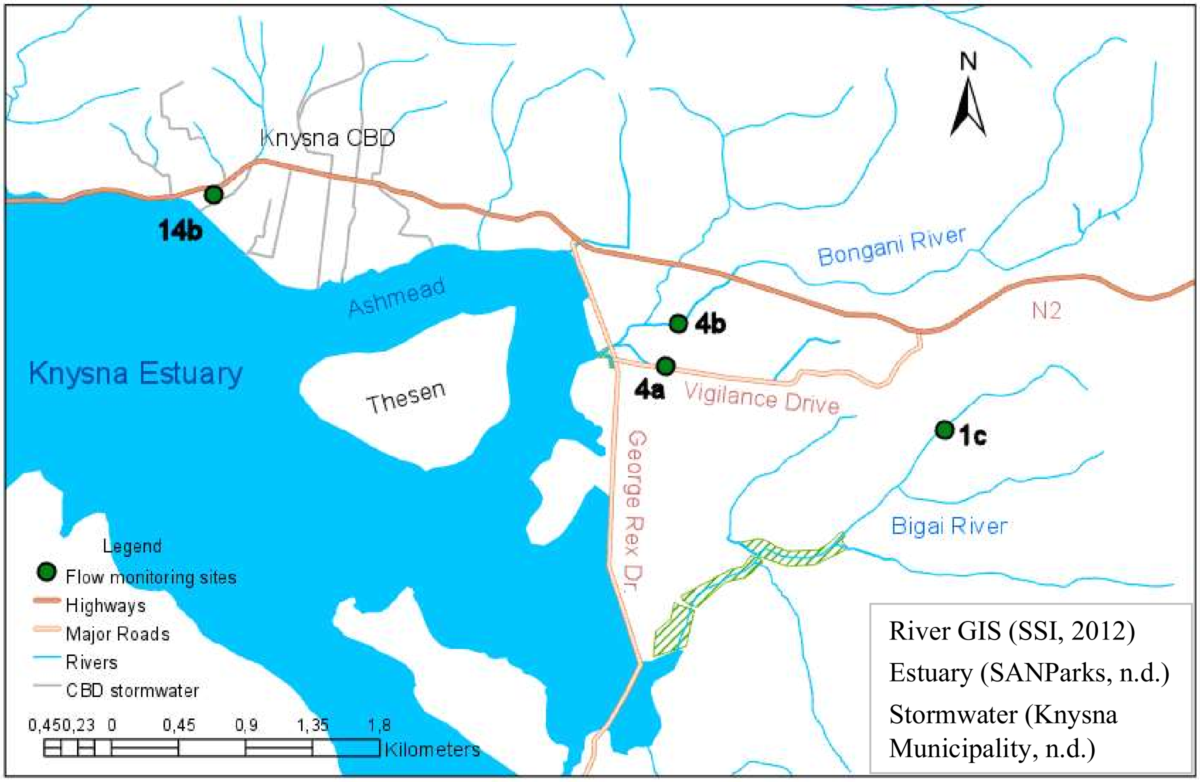
Stormwater networks for the Knysna Area were detailed in GIS files obtained from the Knysna Municipality. In the Bongani Catchment the GIS file details the stormwater network in the Knysna Industrial Area and in the Khayalethu semi-formal settlement. Pipe sizes were obtained from these files. In selected cases on-site measurements of pipe diameters were used in the model. The stream and river network were also obtained from a GIS file, and adjusted where required to suit the satellite imagery and DEM data. During site visits a tape measure or laser pointer device was used to measure culvert sizes. At inaccessible locations the size of the culverts was assumed based on the sizes of culverts upstream and downstream of the unknown culverts. Manning's *n* values for the culverts, storm drains and stream sections were assigned based on photographs taken on site, and comparison with literature values. Typical values based on adjacent river sections were assumed for river sections where no site visit was undertaken.

3.5.6 Flow data

3.5.6.1 Monitoring locations

Flow depths were measured between April and October 2018 at four locations, two in the Bongani Catchment, one in the Knysna CBD and one in the Bigai Catchment. No appropriate flow monitoring locations were identified in the Salt River Catchment. Figure 3-17 shows the location of the four monitoring stations. The carefully selected locations were chosen on the basis that flow would be reasonably uniform and thus could be back-calculated from depth using Manning's equation. Analysis of the water quality testing identified the Bongani River as the catchment with the highest pollutant concentrations. The Bongani Catchment was therefore selected for the hydrological modelling. Water depth data collected at the Bigai River and Rawson Drain (in the Knysna CBD) were not used in the hydrological model and are therefore not further discussed, although this data is available for future use.

The two monitoring locations in the Bongani Catchment were situated in a concrete stormwater channel (Site 4a) and at a trapezoidal section of the Bongani River, adjacent to the industrial area (Site 4b). The stormwater channel is located parallel to Vigilance Drive, on the same side of the road as the industrial area and on the opposite side of the road to the Waste Water Treatment Works. The channel conveys stormwater flow from the industrial and urban areas to the Bongani River, downstream of Site 4b. The monitoring site on Vigilance Drive is shown in Figure 3-18 and the site on the Bongani River is shown in Figure 3-19. Two types of devices were used to measure water level depths, an automated water level sensor, and chalk sticks. Flow data was calculated from the depth data, and was used to calibrate the hydrological model. Calibration is required due to the significant uncertainty associated with hydrological modelling.



River GIS (SSI, 2012)
Estuary (SANParks, n.d.)
Stormwater (Knysna Municipality, n.d.)

Figure 3-17: Location of four flow level monitoring devices

Figure 3-18: Vigilance Drive Drain water level monitoring point 4a

Figure 3-19: Bongani River water level monitoring point 4b

3.5.6.2 Automated monitoring sensors

Automated water level sensors were installed at both monitoring locations in March 2018. The automated water level sensor is a low cost measuring device developed by researchers at UCT (Fell *et al.*, 2017). As shown in Figure 3-20, the device used an ultrasonic ping sensor to measure the distance between the sensor and the water surface. Flow depth was then calculated by subtracting the recorded distance from the distance between the sensor and the canal base. Data was collected in five-minute intervals and transmitted every 2.5 hours to a central server at UCT by a Particle Electron microcontroller over the GSM network (*ibid*). The data transmitted to the server included a measure of the charge remaining on the lithium ion batteries, and when the charge was low the KBP team was notified and would change the batteries.

The sensors were originally housed in lunch boxes that were mounted in a marine plywood housing. Contact adhesive was used to secure the housing to the underside of the wooden bridge at Site 4b, and to the underside of the concrete ramp at Site 4a. The lunch boxes were held in the housing with bolts secured by wing nuts. The wing nuts could be easily loosened and the lunch boxes removed for maintenance purposes and to change the batteries. Both sensors were sabotaged or stolen within two weeks of installation.

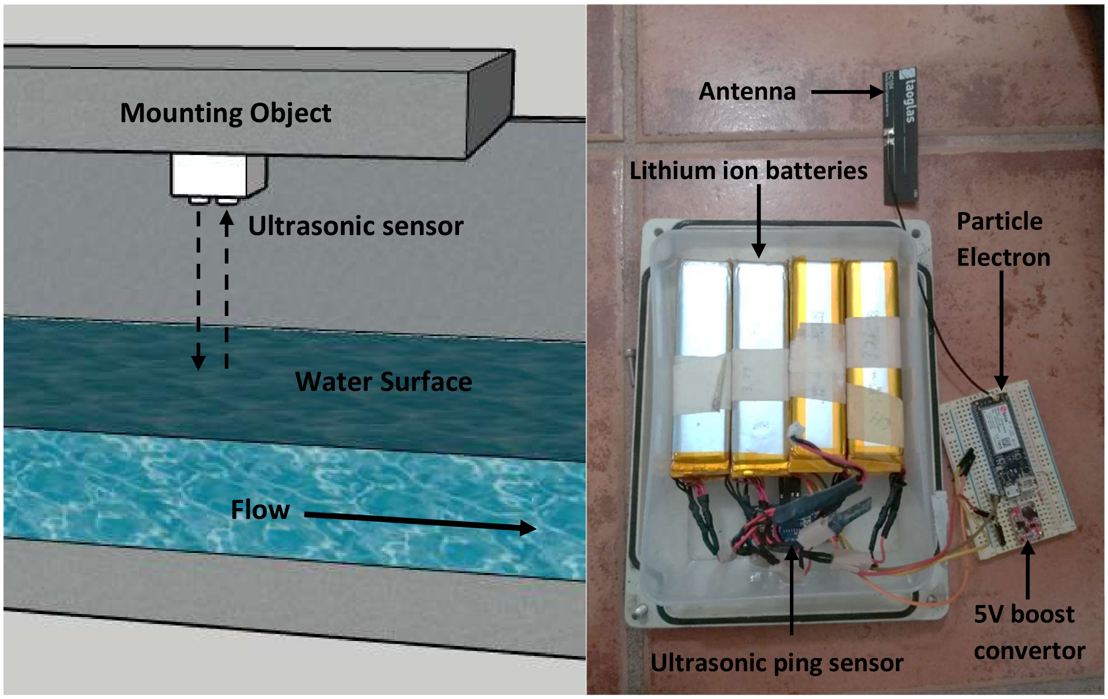


Figure 3-20: Automated water level sensor after Fell *et al.* (2017)

New sensors were installed in April 2018. New housings for the sensors were developed to minimise the risk of data and equipment loss due to external tampering. The sensors were housed in electrical junction boxes that were bolted into the concrete or wooden mounting objects. The junction box size was selected to house the sensor and up to 20 batteries. The lids of the junction boxes could be removed to access the sensor. Screws with different screw heads were used to secure the lids of the boxes to minimise the risk of tampering. To open the box both a screwdriver and the correct sized hex key were required. Testing showed that the electrical junction boxes were not water-tight and therefore plastic lunch boxes with water-tight lids were placed inside the junction boxes. The sensors were installed inside the lunch boxes to protect the electrical components from water damage. Silicone sealant was used to seal around the ping sensors, which protrude from the housing. Silver duct tape and cardboard were wrapped around the outside of the housings to ensure they were less visible. The original and revised housings are shown in Figure 3-21.

Data was collected with the new sensors from April to October 2018. The sensors were removed in November 2018. Data collection was intermittent, and the largest storm during the period was not captured on either sensor due to equipment errors. Data loss resulted from theft incidents, uncharged batteries, loose wires that needed to be reconnected, a crash of the receiving server, and insufficient funds being maintained on the devices' cellular accounts. When the batteries were replaced the devices would restart and send an initial depth measurement to the server. This could be accessed by the researcher to confirm the measurement or address any error messages. The KBP team did not have access to the server and therefore on some occasions faults were only identified after the team had left the field.

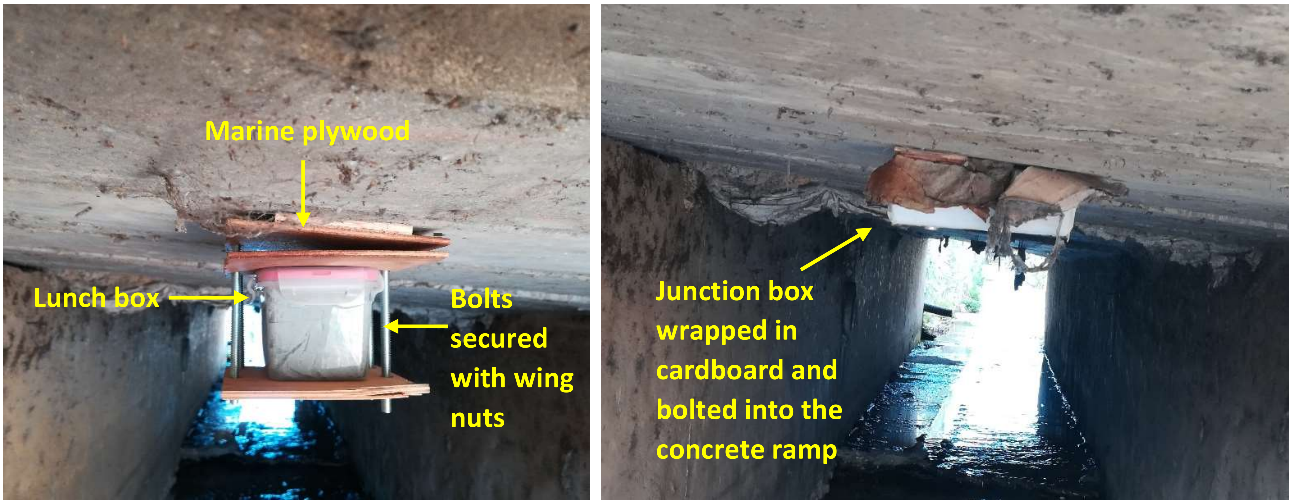


Figure 3-21: The initial (left) and revised (right) housings for the automated sensors

3.5.6.3 Chalk sticks

A simple, low cost, alternative water level measurement device was adapted from Kolsky (1998). Wooden sticks, 19 mm wide by 6 mm thick, were cut to lengths of 1 or 2 m. The sticks were marked out as rulers in 10 mm increments. The faces of the rulers were coated with blackboard chalk. When the chalk was exposed to water it would wash off, showing the high-water mark. It was found that the chalk washed off more easily if the wood was varnished, although fine sanding and varnishing yielded a surface that was too smooth and the chalk did not bond to the surface. A chalk paste, made by crushing the chalk and mixing it with water, bonded too strongly to the wooden sticks and did not wash off effectively when exposed to water. The sticks were therefore lightly sanded and varnished, and the chalk was drawn onto the face.

Custom-made housings were developed to prevent rain from washing the chalk off the rulers. The housings were made from 40 mm wide by 16 mm thick plastic trunking, cut to lengths of 1 or 2 m. Holes were drilled in the trunking to allow stormwater to flow into and out of the housing. As the water level rose it would wash off the chalk. The housings were fixed with contact adhesive to the sides of the Vigilance Drive and Rawson Street stormwater channels, and the side of a culvert on the Bigai River. The rulers could be pulled out vertically to remove them from the housing. Alternatively, for areas with restricted space, the front of the trunking could be opened to remove the ruler (Figure 3-22). After a storm the KBP read off the high water-level mark and then re-chalked the sticks. The measurements could be compared to the data obtained from the automated sensors, or serve as alternative measurements when the automated sensors malfunctioned. The chalks sticks functioned well but data was lost for some storms due to theft. For covered culverts not exposed to rain, the ruler and chalk could be drawn directly onto the culvert wall. This would eradicate theft incidents but would leave the chalk exposed to manipulation.

Figure 3-22: Chalk sticks used to measure the depth of peak flows

3.5.6.4 Calculation of flow from measured depth

For both types of sensors, the associated flow was calculated from the measured water depth using Manning's equation (see equation 3.1).

$$Q = \frac{A^{5/3} P^{2/3} S^{1/2}}{n} \tag{3.1}$$

where Q = flow (m^3/s); A = cross-sectional flow area; P = wetted perimeter; and S = slope. Geometric properties used to calculate the area and wetted perimeter were measured on site and the approximate slope of the channels was calculated from a dumpy level survey undertaken by the researcher in April 2018.

Dry weather base flows were calculated using Manning's equation and the mean dry weather flow depths. It was not possible to determine the source of base flows, or how far up the catchment the base flows originated. For modelling purposes, the base flows were assigned to nodes in the headwaters of the Bongani River and at the start of stormwater drains for the Vigilance Drive Drain. Analysis of the calculated flow depths is discussed in Section 5.1.3.

3.6 Hydrological modelling

3.6.1 Catchment delineation and spatial resolution

For the Bongani Catchment, 107 sub-catchments were manually delineated from the 2 m contour file. In urban areas, where a stormwater network was present, sub-catchment sizes were dictated by the stormwater network and tended to be small, with half of all sub-catchments having an area less than 2.5 ha. For undeveloped areas or areas with no stormwater network, the sub-catchments were larger with a maximum size of 35 ha. Aerial photographs were used to classify land use into one of seven categories using ArcGIS. The percentage of land falling into each category is shown in Table 3-1. The land use categories were then overlaid over the sub-catchments and the land use fractions within each sub-catchment were determined.

Table 3-1: Land use categories

Land use category	Area	Fraction
	Ha	%
Forest	224.9	36%
Semiformal	162.8	26%
Open grassed	151.6	24%
Industrial	46.7	7%
Formal	35.2	6%
Bare Earth	3.4	1%
Highway	5.1	1%
TOTAL	629.7	100%

SWMM input parameters were obtained from a literature search of seven studies or reports (Section 3.6.2). Parameters were readily obtained for forest, grassed, highway and roofs from literature (James *et al.*, 2010; Qin *et al.*, 2013; Krebs *et al.*, 2014; Palla & Gnecco, 2015; and Lee *et al.*, 2017). For the urban, semi-formal and industrial areas, additional spatial resolution data was required. As discussed in Section 3.4.3 the degree of spatial resolution, as well as the relationship between Indirectly Connected Impervious Areas (ICIA) and Buffer Pervious Areas (BPA), have been shown to impact model performance. Based on practical data and time constraints it was deemed impractical to determine a detailed spatial resolution such as that employed by Krebs *et al.* (2014) or Lee *et al.* (2017). It is worth noting that the Bongani River catchment area was 629.7 ha, whilst the afore-mentioned two studies had catchments of 25 and 100 ha respectively.

Two or three areas were selected as being representative for each of the industrial, urban and semi-formal categories. Areas varied between 3.7 and 12.8 ha. Within each area, aerial images were used to manually categorize land use as forest, open grassed, bare earth, paved / asphalt roads or roofs. Each of these categories was assumed to be relatively homogenous in terms of hydrological response, and input parameters could be assigned for each land use type based on available literature values. The areas classified under each category were expressed as a percentage of the total area and then compared with the values generated in the same way for the other areas in the same industrial, urban or semi-formal category. For example, three areas were selected to represent the semiformal category, and the measurement of the percentage of roofs in the three areas was 28%, 18% and 20%. Significant differences in the fractions of land use within the same category (for example, 28% is substantially higher than 18% and 20%) were investigated. The accuracy of the measurements was confirmed and then reasons for the difference were assessed (for example large municipal and school buildings increased the roof fraction in one semi-formal area). The representativity of the areas was revisited (for example, are there other areas within the catchment where large roofs increase the roof fraction substantially, is this a reasonable representation of the whole?). Mean values across the two/ three areas for each land use were then assumed to be representative of all areas within this land use category (for example, a mean roof fraction of 22% was applied for semi-formal areas).

Green-Ampt soil parameters were obtained as described in Section 5.1.2. A Microsoft Excel spreadsheet was compiled from the land use and soil categorization and weighted average values determined for each of the sub-catchments according to the process advocated in Lee (2018). Weighted averages are considered a reasonable means of aggregating catchments with fairly uniform characteristics (Krebs *et al.*, 2014; Lee *et al.*, 2018). Lee *et al.* (2018) advocated separating impervious areas into Indirectly Connected Impervious Areas and Directly Connected Impervious Areas, and also separating the pervious areas into those that receive runoff from impervious areas, and those that do not. No information regarding areas that receive runoff from impervious areas was available for this study, and use of the advocated method would require further modelling assumptions. The method would also introduce additional model complexity for a model where significant uncertainty exists and the data is limited. The relationship between indirectly connected areas and pervious areas was therefore modelled using the 'sub-area routing' and '% routed' PCSWMM parameters.

3.6.2 Input parameters

Input parameters for surface Manning's *n* and depth of depression storage were obtained from seven sources, with varying degrees of detail (James *et al.*, 2010; Qin *et al.*, 2013; Krebs *et al.*, 2014; Fisher-Jeffes, 2015; Palla & Gnecco, 2015; Lee *et al.*, 2017). As advocated by James (2005) the values were compared and extreme values disregarded. Initial model parameters were selected based on the remaining values. The percentage imperviousness was calculated based on the land use categorization. A default starting value for percentage of impervious area with no depression storage was assumed to be 25% and percentage routing to impervious areas was assumed to be 25% (Fisher-Jeffes, 2015). Green-Ampt parameters were assigned as described in Section 5.1.2. A model sensitivity analysis was performed for each of these input parameters (Section 3.6.3).

3.6.3 Model sensitivity

A model sensitivity analysis was undertaken using the PCSWMM Sensitivity-based Radio Tuning Calibration (SRTC) tool. The tool uses the factor perturbation method, which involves holding all other parameters fixed whilst varying a single factor. Parameters with a high degree of certainty, such as area, were not included in the sensitivity analysis. The parameters varied were catchment width, catchment slope, percentage imperviousness, percentage routed, Manning's *n* (N) and depression storage (D) for impervious and pervious surfaces, and percentage of the impervious area that has no depression storage. The final three parameters assessed were the Green-Ampt soil parameters of suction head, conductivity and initial deficit.

Starting input parameters were varied by -50% / +50%, and the impacts on flow peaks and storm volumes was assessed. During small rainfall events the model does not generate any runoff from pervious areas (grass and forest). The sensitivity of flows at the Bongani River monitoring point was therefore assessed for two storms, one small storm which generated no pervious runoff in the model, and one larger storm. At the Vigilance Drive monitoring point, a small storm that generated limited pervious runoff and a larger storm were assessed. For each sensitivity analysis the model was run for a period longer than the individual storms, with at least one rainfall storm, and at least seven days preceding the assessed storm. This minimised the impacts of assumptions regarding antecedent conditions on the model results. The sensitivity of the model was then assessed for the four storm events, ranging from 15 to 21 hours in duration. The results of the sensitivity analysis are discussed in Section 5.2.1.

3.6.4 Model calibration and validation

For model calibration an attempt was made to use 2/3 of the rainfall water level response data for calibration, and 1/3 for validation. This resulted in four calibration rainfall events for the Bongani, and two validation events. For Vigilance Drive, the runoff response to more rainfall events was recorded, with eight rainfall events used for calibration and five for validation. Calibration events were selected by comparing the rainfall hyetograph with water level response and selecting events where the water level best mirrored rainfall patterns.

Calibration used a combination of manually changing input parameters, and the PCSWMM SRTC tool. The Vigilance Drive Drain was calibrated first as it has a relatively small catchment, with a high imperviousness and less uncertainty than the Bongani Catchment. The impervious parameters were then transferred to the Bongani Catchment, where factors specific to the semi-formal settlements were varied to achieve the required calibration for the impervious areas. Pervious area parameters were varied to achieve a calibration for the larger storm. The results of the model calibration are presented in Section 5.2.2.

3.7 Decision support tool

3.7.1 Stakeholder selection

Application of the Mauri Model requires the participation of stakeholders who represent a broad spectrum of interests, socio-economic and cultural backgrounds. As part of the stakeholder engagement process 17 stakeholders were interviewed. Of the stakeholders interviewed, six were private residents, five represented four different environmental organisations and two municipal representatives were interviewed. Additional stakeholders included representatives of the Knysna Residents' Association, the House of Judah Rastafarian community, the local Xhosa initiation school, and a participant from the forestry industry. A single person was interviewed in each case, with the exception of two interviews where groups of two and three stakeholders were interviewed.

Stakeholders were asked to rate the four dimensions (environmental, cultural, social and economic) according to the Analytical Hierarchy Process described in Section 3.7.3, and were asked a series of generic questions about their opinion of water management in Knysna, which helped to identify current water management challenges. Wherever practicable stakeholders were also consulted on the selection of appropriate indicator sets, discussed in more detail in Section 3.7.3. One of the interviews consisted of a general discussion, rather than following the compiled list of questions. The list of questions is provided in Appendix C.

3.7.2 Ethical considerations in stakeholder engagement

Ethics approval was granted by the UCT Faculty of Engineering and the Built Environment and is attached in Appendix D. Informed consent was obtained in writing from all participants, with the exception of one stakeholder, who did not return the required form. The information supplied by this stakeholder has not been used in any form in this dissertation. The information that was gathered about participants was not of a compromising nature. Where participants requested that certain information remain confidential or anonymous their wishes have been respected, and this information will not be publicly disclosed or attributed to the participants. Participants were given the means to contact the researcher directly and to withdraw from the study, should they become uncomfortable with the disclosure of any information. No deception was involved in this study. To protect the privacy of participants in the study the material will not be made available for purposes other than archiving. No risk of harm has been identified for this study. Participants did not receive gifts or pecuniary assistance for participation in the study.

3.7.3 Application of the Mauri Model

Application of the Mauri Model comprises of seven steps as discussed in Morgan *et al.* (2013):

- **Analytical Hierarchy Process (AHP)** – stakeholders were asked to prioritise the four dimensions of the model through a series of questions based on a Likert scale. The Likert Scale ranged from -3 (strongly less important), through 0 (equally important), to +3 (strongly more important). Repetition of questions during the AHP process highlighted any inconsistencies in the participants' answers and when these were found, the relevant questions were reviewed and the participants were asked to clarify their prioritization.
- **Normalisation** – the results of the AHP were then normalised and converted to percentage weightings. The outcome was a percentage weighting for each of the dimensions. For example, a stakeholder who values economic considerations highly and does not value cultural considerations might achieve the following rating: Economic – 50%, Social – 31%, Environmental – 11%, Cultural – 8%. The normalisation is structured in such a way that the maximum possible weighting is 50% and the minimum is 0%. All stakeholders, with the exception of two who were interviewed in a more informal manner, were informed of the normalized weighting and asked if they felt this to be a fair representation of their world view. When stakeholders were dissatisfied with the weighting, the AHP was reviewed and adjusted accordingly.
- **Selection of indicators** – performance indicators were selected for each dimension. The model aims for an active inclusive process and therefore stakeholders with the highest vested interest in each dimension were consulted regarding the selection of appropriate indicators. Indicators need not be limited to scientifically quantifiable parameters, for example stakeholders might have spiritual or cultural beliefs that are not quantifiable. Environmental considerations are also often not easily

quantifiable. After the interview process the researcher compiled the indicators proposed by different stakeholders and selected indicators for use in the model. Indicator selection favoured indicators selected by a large number of stakeholders. The Mauri Model requires that the number of indicators be the same in each of the four dimensions.

- **Assessment of indicators** – The performance of each proposed mitigation measure was then assessed based on the selected indicators. The performance in terms of each indicator was given a score from -2 (reducing sustainability, degrading value) to 2 (enhancing sustainability, restoring value). To ensure transparency and reproducibility, the measures of each indicator should be detailed (i.e. the scores of -2 and 2 are clearly defined). For this study more data and specialist input would be required in order to detail measures of each indicator. As noted above some indicators will be quantifiable whilst others will remain qualitative.
- **Average scores were determined** – the scores for each indicator were then averaged to give an overall score for each dimension. The model equally weights all indicators within a dimension. At this stage all the proposed mitigation measures could be compared in terms of a ‘balanced’ world view (where each of the four dimensions are weighted equally).
- **Sensitivity to world views** – Each proposed mitigation measure was then assessed for sensitivity to world views. By applying the weightings obtained for each stakeholder the researcher can understand why stakeholders may favour one solution over another. For example, a solution that scores well on economic considerations but poorly on cultural considerations may be favoured by a stakeholder who values economic and not cultural considerations. The same solution would be scored unfavourably by a stakeholder who values culture above economy. A solution which is very sensitive to world views in unlikely to be preferred.
- **Option selection –** recommendations were then made on the preferred option and further studies are suggested.

4. Water quality sampling and testing

Poor water quality is threatening the health of the Knysna Estuary, and in particular the Ashmead Channel. In order to identify the sources of pollution, 18 monitoring locations were selected at catchment outflows to the estuary (Section 4.1). The key pollutants identified during the literature search were nutrients and Total Suspended Solids (TSS). Samples collected at the 18 monitoring locations were tested for nutrients and TSS concentrations, as well as for pH, conductivity and turbidity. The results of the first phase of water quality testing were used to identify key catchments that were contributing to pollution. The Salt, Bigai and Bongani Catchments were selected for further investigation.

As a second phase of sampling, revised river sampling points were selected within each of the identified catchments, to try to isolate possible pollution sources within the catchments. This is discussed in Sections 3.3.3 and 4.2. The results of the second phase of water quality sampling were analysed to determine what pollutants are originating in different parts of the selected catchments, and at what concentrations they are present in the streams, rivers and stormwater system. Where possible, the data was compared to historical data, to determine how pollutant concentrations have changed over time.

4.1 Phase 1: Initial 18 sampling sites

4.1.1 Location and sampling regime

The initial 18 monitoring sites were selected at outflows to the estuary from the northern and eastern catchments (see Section 3.3.2). These catchments were selected as the focus of the monitoring regime as they are more developed than the southern and western catchments, and many of the catchments drain to the Ashmead Channel. No monitoring was undertaken for sites on the southern and western shores, nor for Thesen Island and Leisure Isle. Seven sample sets were collected between September 2017 and January 2018. Samples were transported to the Municipal Water Treatment Works (MWTW) where they were tested for pH, conductivity, TSS, turbidity, TAN, nitrate, nitrite and Total Phosphorus. The results were compared to determine the catchments that were contributing the highest pollution concentrations to the estuary.

4.1.2 Results

4.1.2.1 Assessing validity

Confirmatory testing was not undertaken for TSS or turbidity. A visual assessment of the turbidity results for a storm show that high turbidity results corresponded well with poor water clarity as shown in Figure 4-1 and Figure 4-2. TSS results for the 18 monitoring points are discussed in Section 4.1.2.2. The results are also compared to historical and literature data.

Selected duplicate samples were collected and transported for analysis at the UCT water quality laboratory for two sampling events. This secondary analysis aimed to ensure confidence in, or identify concerns regarding, the analysis results.

The pH results obtained from the MWTW and UCT were compared to readings taken on site using a hand-held probe (Figure 4-3). These results were for the March sampling event, and time delays before testing and temperature changes during transportation may have impacted the results at UCT. The MWTW pH values were higher than the UCT and hand-held probe results for all samples. The UCT test results were typically lower than the hand-held probe results, and showed some variation in measurements for samples collected at the same sites. An additional five samples were tested for pH at the MWTW and using the hand-held probes, but were not tested at UCT. These results showed a similar trend, with MWTW results higher than the probe results for four of the five samples. The difference in pH between the MWTW and the probes varied from -0.03 to +0.79.

Figure 4-1: Samples collected after a storm 15/11/2017 (Claassens, 2017)

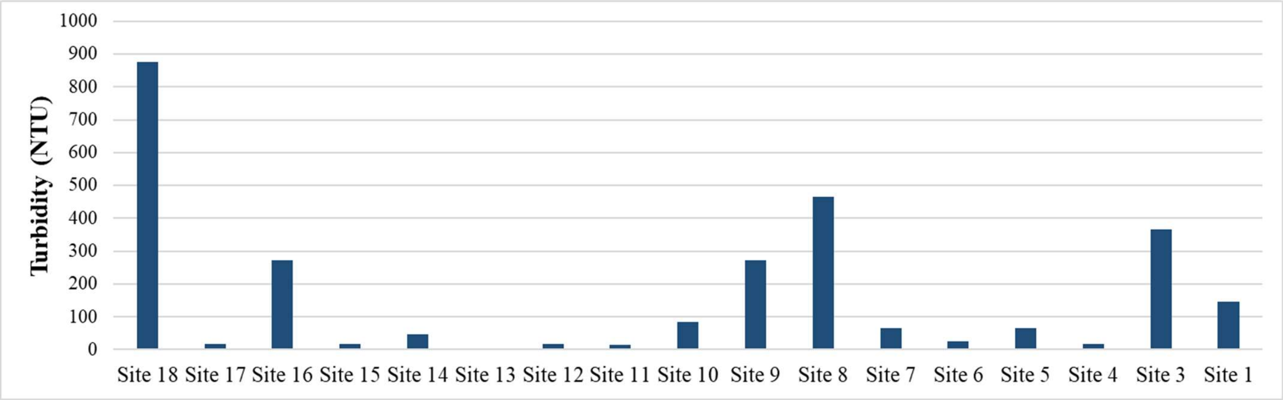


Figure 4-2: Turbidity measurements after a storm 15/11/2017

No pH values were measured at UCT for the April sampling event. In April the MWTW pH results were lower than the results obtained using the hand-held probes, with differences between -0.83 to -0.21. One result from the probes was discarded as it was very high and on-site notes commented that the flow could be too low for accurate readings. In this dissertation pH values are used only for reporting purposes and for the calculation of ammonia toxicity, and the variation in pH values is deemed to fall within an acceptable range.

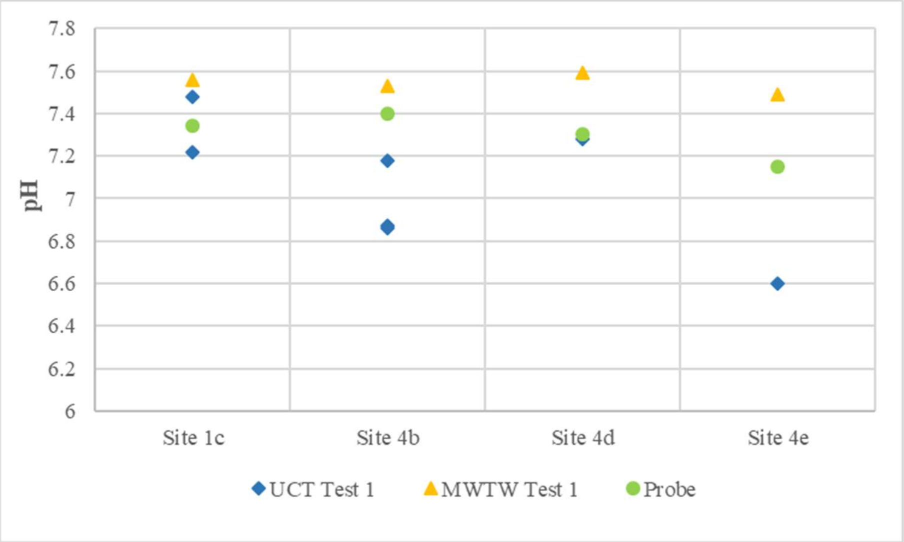


Figure 4-3: Comparison of pH results from two laboratories and probes

The test results at UCT showed significant discrepancies compared with the MWTW results for nutrients. Due to concerns that the results could have been impacted by heat during transport and the time delay before testing, a second set of duplicate samples was collected on site and transported in ice and tested the next day. The researcher undertook testing on these samples according to the same test procedures. The results again differed significantly from those received from the MWTW for nutrients. Calibration at the UCT laboratory is undertaken when the calibration certificate for a test expires or before testing if the calibration curve is not considered to be acceptable. Calibration of the instrumentation at the Knysna Laboratory is completed by the instrument manufacturer. No calibration schedule for the instrument was obtained from the Knysna Laboratory.

The results for TAN are shown in Figure 4-4, where Tests 1 and 2 are the first and second sampling and testing events. For all sites and tests the TAN concentrations measured at the MWTW were higher than those measured at UCT. Averaging across samples for the same test event and lab, the MWTW results were 260% to 440% higher than those recorded at UCT, with the exception of Site 16, which is 4710 % higher.

The concentration of TAN can change significantly if samples are not kept cold (as was the case during the first test event at the UCT lab). However, the UCT results, for example at Site 4b, were reasonably consistent between the two sampling events. The mean and standard deviation of the test results are shown in Table 4-1. The precision of the UCT results, particularly for the second sampling event, was good, with low standard deviations. The standard deviations of the results from the MWTW varied from 0.07 to 8.69.

Table 4-1: Comparison of TAN results from two laboratories

	Mean and standard deviation of TAN			
Site	**UCT test 1**	**MWTW test 1**	**UCT test 2**	**MWTW test 2**
	mg/ℓ	**mg/ℓ**	**mg/ℓ**	**mg/ℓ**
Site 1c	0.23 +/- 0.16	0.3*	9.08 +/- 0.1	31.13 +/- 1.7
Site 4b	9.75 +/- 1.84	43.1*	10.14 +/- 0.16	31.35 +/- 0.07
Site 4d	0.03*	0.1*	n/a	n/a
Site 4e	12.15*	31.9*	n/a	n/a
Site 16	n/a	n/a	0.155 +/- 0.06	7.3 +/- 8.69

* Single sample

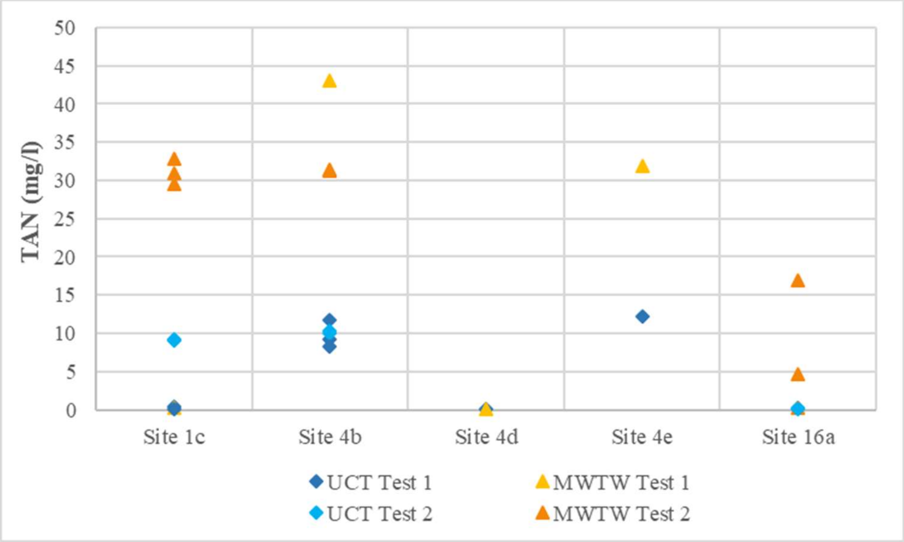


Figure 4-4: Comparison of TAN results from two laboratories

Samples of a known concentration were then prepared in the UCT laboratory to test for TAN, nitrate, nitrite and Total Phosphorus, according to the method described in Section 0. A summary of the test results is shown in Table 4-2.

Samples from the same prepared solution, as well as the same solution with dilution factors of 2 and 0.5 were then prepared and couriered overnight to the Knysna MWTW. The test results are summarised in Table 4-3. TP could not be tested, the results from UCT and the MWTW concurred for NO_2N (assuming a unit error for the Knysna laboratory), and the results for NO_xN differed for both laboratories, with significant inaccuracies. The UCT laboratory testing showed a good accuracy for TAN, however of significant concern, the MWTW had percentage errors of 295% to 350% for this constituent, meaning that TAN levels are significantly over-reported. The samples that were retained at UCT and not refrigerated were tested on the same day that the MWTW conducted their tests. This was to account for any changes due to heat during transport and delay before testing. The results at the UCT laboratory were comparable with the first set of tests (TAN 10.5% error, NO_2N 83% error, NO_xN 14.5% error and TP not tested). It can therefore be concluded that the discrepancy between the test results at the MWTW and UCT did not result from heat or delay in testing. The comparative results for TAN measured at UCT and at the MWTW, as well as the theoretical line, are shown in Figure 4-5. The figure shows that the UCT laboratory results were close to the theoretical line (based on the calculated concentrations of the known solution) but the results from the MWTW were substantially higher, for example for the theoretical concentration of 20 mg/ℓ, the concentration measured at the MWTW was 75 mg/ℓ. In addition, some test results received from the MWTW laboratory exceeded the manufacturer test limits for the test procedures used, and the laboratory did not note these discrepancies. It was also unclear whether calibration had been undertaken for samples with elevated interference levels (for example chloride due to salt water ingress). Further engagement with the MWTW laboratory was unsuccessful at resolving these issues.

Table 4-2: UCT results from tests of known concentration solution

	Precision		**Accuracy**	**Comment**
Parameter	**Standard Deviation**	**Percentage Deviation**	**Percentage Error**	
TP	0.049	1.2%	-3.7% to -2.6%	Excellent accuracy and precision
TAN	0.821	18.2%	-15.7% to -0.3%	Two excellent, one poor accuracy and precision
NO_2N	0.006	0.6%	78% to 82%	Precision is excellent, accuracy poor. Low mass could have led to inaccuracies.
NO_xN	0.047	8.0%	-23% to -17%	Precision poor, accuracy poor. Low mass could have led to inaccuracies.

Table 4-3: MWTW results from tests of known concentration solution

	Precision		**Accuracy**	**Comment**
Parameter	**Standard Deviation**	**Percentage Deviation**	**Percentage Error**	
TP				Equipment in for repairs
TAN	3.055	14.0%	295% to 350%	See further discussion on accuracy
NO_2N	0.010	4.5%	18 600% to 19 400%	Likely unit error. Previous results were not orders of magnitude higher than that expected. Note: if factor of 100 is assumed then results were very close to those for NO_2N from UCT, indicating that the concentration may be higher in the synthetic sample.
NO_xN	0.153	15.8%	50% to 74%	Confirms that NO_2N above is orders of magnitude too high and likely a unit error.

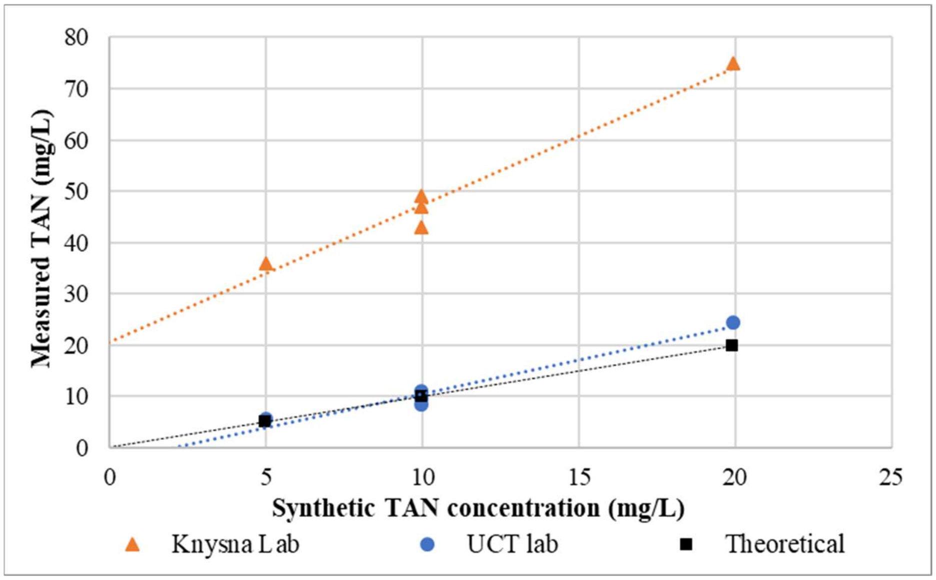


Figure 4-5: Comparison of Knysna and UCT test results for TAN

Given the uncertainty in the results from the MWTW, from June 2018 all samples were tested at the KBP laboratory according to the standard testing procedures detailed in Section 3.1. The accuracy of these results is discussed under Section 4.2.2.1. No analysis of the accuracy of TP results was possible, however comparison with later SRP results is discussed in Section 4.2.2.1.

4.1.2.2 Total Suspended Solids and turbidity

Total Suspended Solids (TSS) data was assessed for sampling undertaken between September 2017 and April 2018. The test results were processed by the Knysna Municipal Water Treatment Works (MWTW). Turbidity data was also available for eight sampling events between September 2017 and April 2018, tested by the MWTW, and three sample events between July and September 2018, tested by the KBP. No confirmatory testing was undertaken for either laboratory. Figure 4-6 shows TSS data collected at the original 18 monitoring points for samples collected between September 2017 and January 2018 and includes data for the WWTW discharge from January 2013 to June 2017. Figure 4-7 shows turbidity data for the same period.

The most problematic sites in terms of TSS were Sites 8 and 9 (below the hospital), Site 16 (Salt River) and Site 18 (Point). High outliers, such as the outlier at Site 16 that skews the mean value, were typically sample results collected during or shortly after rain storms. The 40 mm of rainfall that fell on the 15th of September 2017 resulted in elevated TSS values at Sites 3, 5, 8, 15, 16 and 18. The WWTW discharge had only a 14% compliance with the 10 mg/ℓ licence condition (DWS, 2014) for TSS for the period analysed, however the concentrations were low when compared to many of the monitoring sites. The WWTW contributes consistently high volumes of discharge to the estuary and so TSS loads over time can be considerable.

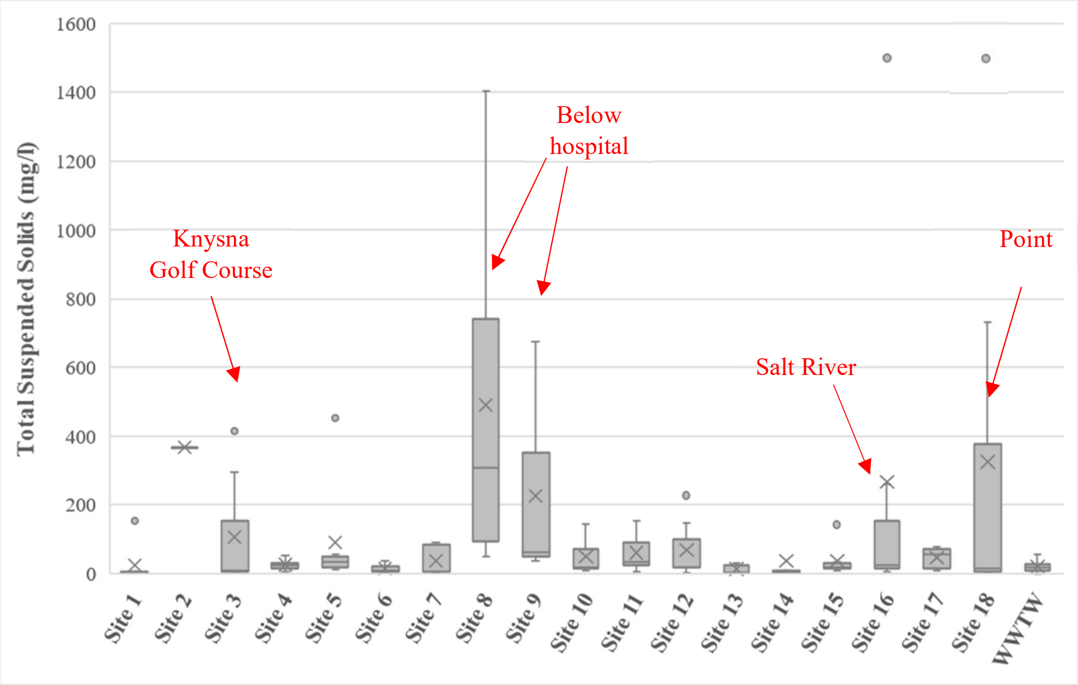


Figure 4-6: TSS comparison for the original 18 monitoring sites and the WWTW

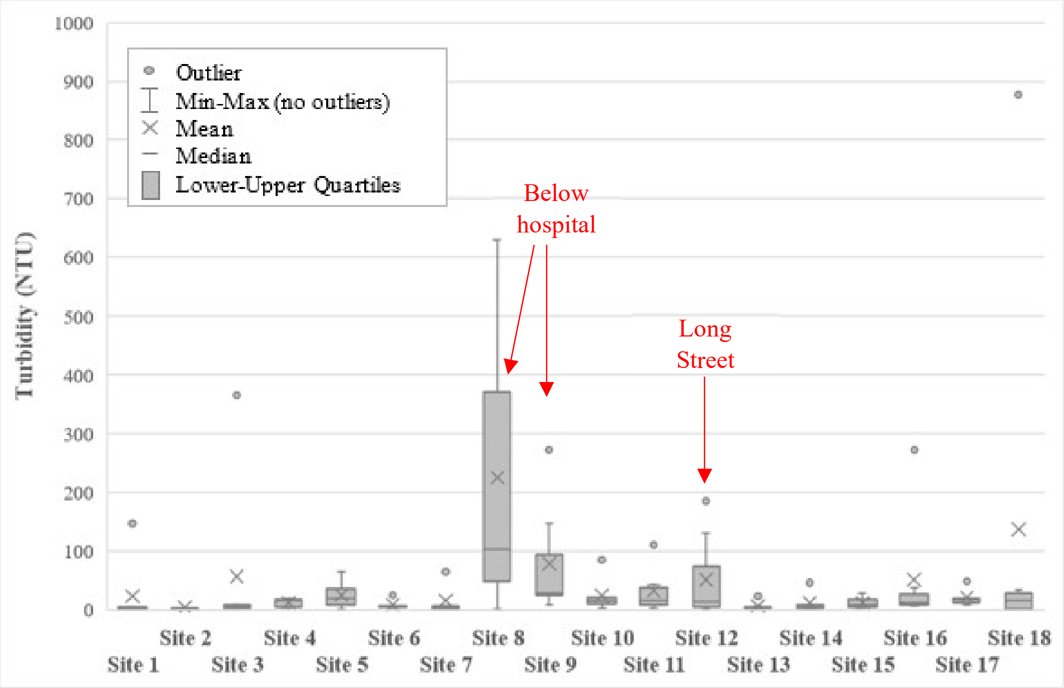


Figure 4-7: Turbidity comparison for the original 18 monitoring sites

High mean turbidity was recorded at Sites 8 and 9 (below the hospital) and Site 12 (Long Street) for sampling between September 2017 and April 2018. It is not clear why high TSS rates at Sites 16 (Salt River) and 18 (Point) did not result in correspondingly high turbidity rates. 27 mm of rain fell on the 15th of November 2017. Elevated TSS values were recorded for this date only at Site 3, however elevated turbidity values resulted in high outliers at Sites 1, 3, 6, 7, 9, 10, 14, 16 and 18. Figure 4-1 shows samples collected on 15th of November 2017 and Figure 4-2 shows the corresponding turbidity measurements.

Table 4-4 shows mean and median TSS values and percentage compliance with the 100 mg/ℓ DWAF limit for aquatic ecosystems (DWAF, 1996a). Mean and median values that exceeded the aquatic ecosystem limit are shown in bold typeface. As can be seen in Figure 4-6, high TSS values during storms can considerably skew the mean values. All the sites were located at outflows to the estuary, and therefore the guidelines for marine systems were also consulted. The guidelines note that due to the variability in TSS concentrations in marine waters, no guideline value is supplied, but should rather be calculated for each location from a reference system (DEA, 2018). Such data is not currently available for the estuary.

Table 4-4: TSS compliance with DWAF standards for 18 monitoring sites

Site	Description	Percentage compliance**	Mean	Median
			mg/ℓ	mg/ℓ
Site 1	George Rex, East of Leisure Island	89%	23.6	3.0
Site 2*	George Rex, near Armstrong Rd	0%*	**367.0**	**367.0**
Site 3	George Rex, Knysna Golf course	75%	**105.9**	7.5
Site 4	Bongani River outflow	100%	24.9	23.5
Site 5	George Rex - Knysna WWTW discharge	90%	90.4	38.0
Site 6	George Rex, drains from old place	100%	14.3	9.0
Site 7	Below N2 – George Rex junction	100%	37.2	6.0
Site 8	Below Costa Sarda & Knysna Hospital	25%	**489.9**	**425.5**
Site 9	Western culvert below Knysna Hospital	63%	**225.9**	77.0
Site 10	At end of Union Street	71%	48.3	17.0
Site 11	CBD: Queen Street Drain	78%	59.9	36.0
Site 12	CBD: Long Street Drain	78%	68.7	30.0
Site 13	CBD: Station Drain	100%	12.1	3.0
Site 14	CBD: KADA Drain	89%	36.2	7.0
Site 15	Drain below Paradise	86%	36.4	16.0
Site 16	Salt River mouth	78%	**266.7**	27.0
Site 17	East Point	100%	45.6	55.0
Site 18	West Point at stream mouth	71%	**325.4**	15.0

* Only one sample was taken at Site 2. The site was not further monitored due to lack of flow

** Percentage compliance with DWAF (1996a) limit for aquatic ecosystems (100 mg/ℓ)

Russel (1996) gives mean TSS values from data samples collected between 1991 and 1994. The mean TSS values for the Ou Plaas (106 mg/ℓ) and Salt catchments (591 mg/ℓ) were considerably higher than data measured in this study at Sites 4 (24.9 mg/ℓ) and 16 respectively (266.7 mg/ℓ). A student t test was used to compare TSS data collected by the KBP for this study at the Salt River, to data collected by Allanson *et al.* (2000) between 1996 and 1997 and data collected by Mr R. Milne in 1998 and 1999 (as reproduced by Allanson *et al.*, 2000). The results show that TSS data for 2017/2018 was significantly lower than the 1996-1999 data. Although it should be cautioned that the KBP database is small, this result is expected because the Simola golf course failure in 1996 lead to the mass mobilisation of sediment into the Salt River over several years (Allanson *et al.*, 2000; Marker, 2000). Similar assessments for the Bongani River, and the Long Street Drain, also showed a significant decrease in TSS values since the 2000 study. There is some ambiguity about the location of the Bongani sampling in the 2000 study and the comparison may not be accurate.

Both the turbidity and TSS data indicate that Site 8 (below the hospital) is potentially a point source of sediment. The site was not selected for on-going monitoring as part of this project because the flows appeared to be low and therefore pollutant loads will be low. The semi-formal development of Xolweni is located in the upper headwaters of the stream that flows to Site 8 (Figure 4.1). Satellite imagery indicates that there is significant development and associated earthworks being undertaken in Xolweni. It is possible that the high TSS values measured at Site 8 were as a result of sediment being mobilised at these construction sites, and it is recommended that further monitoring be resumed at this site, and at the location where the stream crosses the N2.

Elevated TSS and turbidity at Site 9, adjacent to the Knysna CBD, could indicate pollutant sources, and could be further investigated as part of on-going monitoring. Further monitoring at Site 3 could help to determine whether the Knysna golf course is contributing high TSS loads to the estuary. The source of elevated TSS values at the Long Street Drain (Site 12) were not further investigated as part of this project but could be further investigated to determine the source of the elevated TSS concentrations.

Only one additional sample was taken for Site 18 (the Point), during a storm event on the 14th of July 2018. A high turbidity value of 101 NTU was recorded on this date. It is recommended that sampling at this site be extended as it appears to be a source of sediment load during storms. The catchment area to point 18 is not insignificant (approximately 160 ha, 25% of the Bongani Catchment), and therefore elevated TSS concentrations could contribute significant loads to the estuary. Elevated TSS values at Site 16 (Salt River) are of concern, although as noted above they are significantly lower than historical values obtained from literature.

4.1.2.3 pH

Hand-held probes were used on site to test for pH during two sampling events. The MWTW also reported pH values for all samples. Comparison between the two sampling methods is discussed in Section 4.2.2.1. The pH values for the 18 monitoring sites for eight sampling events between September 2017 and February 2018 are presented in Figure 4-8. After this date, the sampling locations were changed and this data is discussed in Section 4.2.2.3. The pH values ranged from 4.7 to 9.6.

The change in pH over time is shown in Figure 4-9. Values presented in the figure are mean pH values across all sites. A distinct increase in pH is observable between the October and November sampling events. This change could be seasonal or could be due to measurement errors. Confirmatory testing was only undertaken for later sampling events. After November the pH gradually increased to a peak in December, before decreasing again between December and February. Site 4 (the Bongani River outflow) and Site 5 (the WWTW discharge) were the only sites retained for on-going monitoring. The pH values at Site 5 will be impacted by treatment at the WWTW. The change in pH over time is shown for Site 4 in Figure 4-10. A distinct seasonal pattern is not observed for the later data tested at the KBP laboratory, with all pH measurements falling within pH values of 6 and 7. Many of the monitoring sites were influenced by tides. pH values can increase with increased salinity, and the typical pH values measured in the estuary range from 6.7 to 8.2, measured during summer (Allanson *et al.*, 2000).

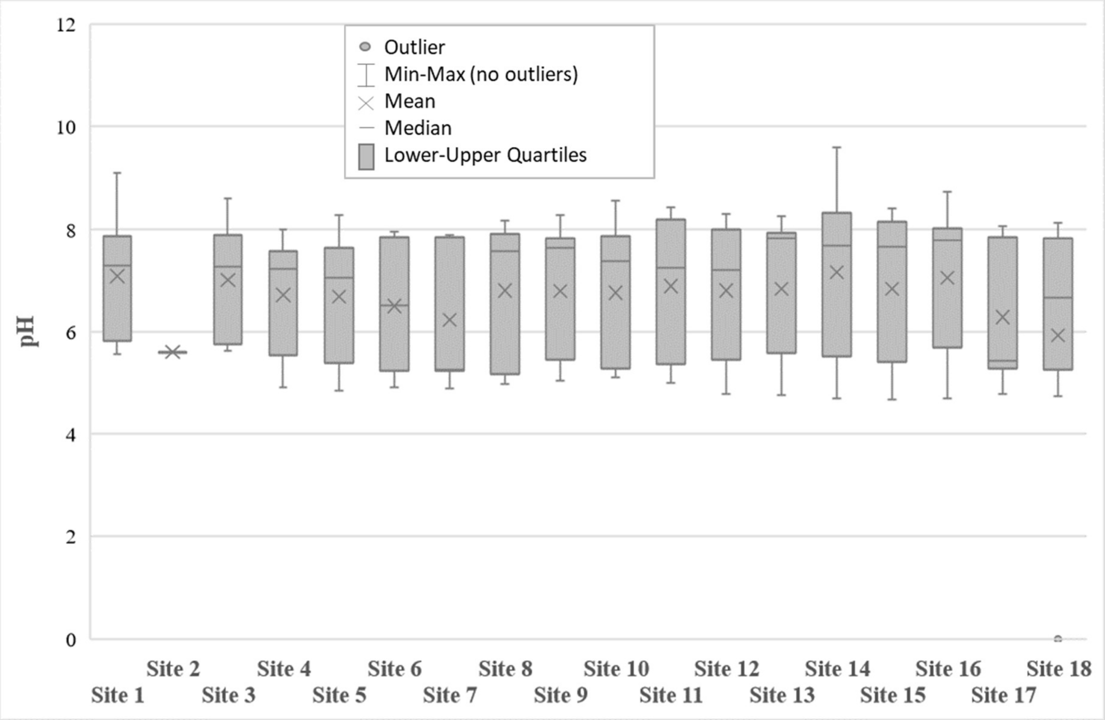


Figure 4-8: pH comparison for the initial 18 monitoring sites

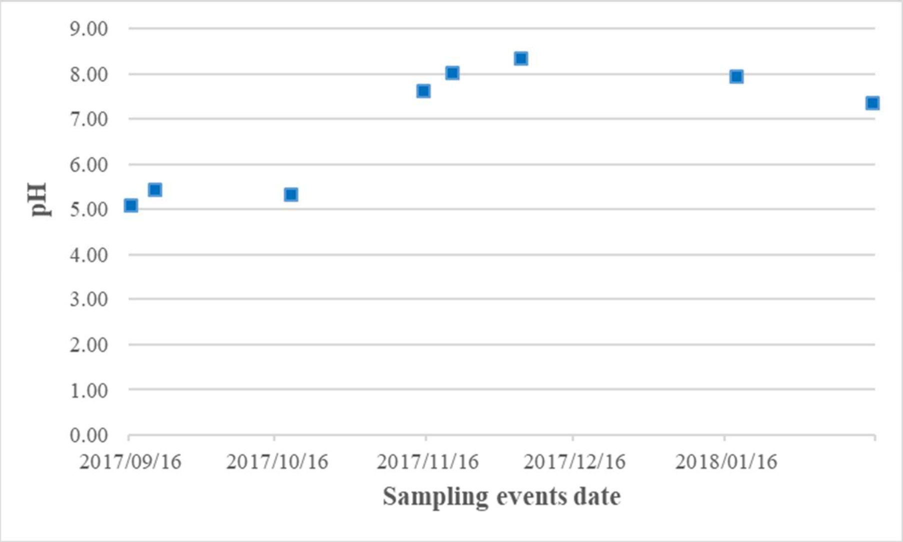


Figure 4-9: Mean pH across all sites for eight sampling events

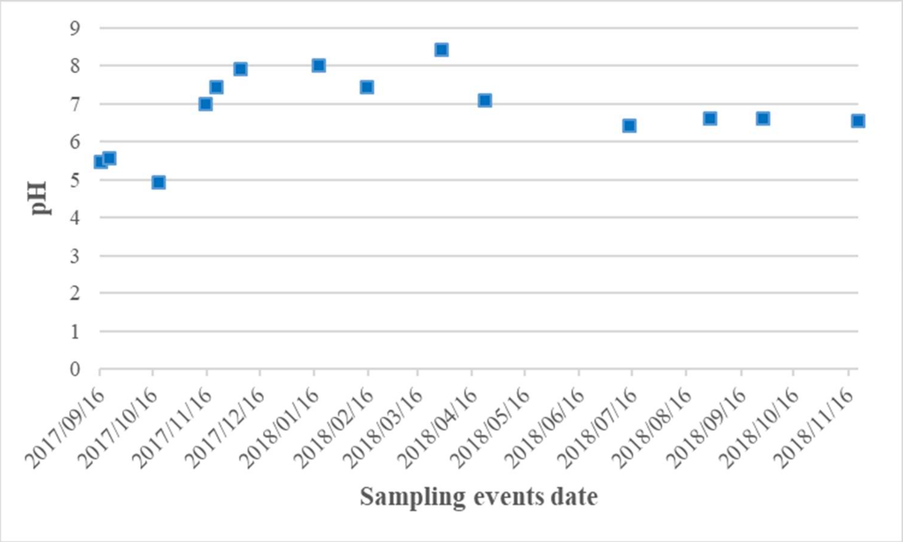


Figure 4-10: Changes in pH for Site 4 over time

4.1.2.4 Nutrients

As discussed in Section 4.1.2.1, confirmatory testing at UCT raised concerns about the accuracy of nutrient testing at the MWTW. The results of this testing are therefore not presented here. The data from these 18 monitoring locations was used to determine which catchments should be the focus for on-going monitoring. Although the nutrient data from the MWTW may be unreliable, it is believed that the relative values measured at the different sites should be acceptable and can therefore be used to prioritise problematic catchments. Total Inorganic Nitrogen (TIN) is calculated by adding the concentrations of NO_2, NO_3 and TAN, where all concentrations are expressed in mg/ℓ of nitrogen. The mean TIN concentrations for the seven water quality sampling events between September 2017 and January 2018 were used to prepare Figure 4-11. Data for February to April has not been included as not all 18 sites were sampled during these months. The size of the markers in the figure are used to represent the relative magnitude of TIN concentrations, thus large markers are points of elevated TIN. The Bongani Catchment clearly showed elevated TIN concentrations, as did Sites 3 (golf course), 8 and 9 (below the hospital) and the Salt River.

Similarly, Figure 4-12 shows relative mean Total Phosphorus (TP) concentrations for four sampling events (January to April 2018). No TP test results were available for earlier sampling events, and not all sites were sampled for each sampling event, and therefore the data is less representative than the TIN data. Site 8 (below the hospital) and the Bongani Catchment (Site 4) show the highest mean TP concentrations.

A decision was taken to focus on the Bongani, Salt, Bigai and Knysna CBD catchments for this study. The Bigai was included to determine if the river water above the reed beds was of an acceptable quality. Site 8 was not monitored further as flows appeared to be low and therefore pollutant loads would be low for this site. It is recommended that the source of elevated nutrients at Sites 3, 8 and 9 be investigated as part of further research. Site 3 is located downstream of the Knysna Golf Course, Site 8 is located downstream of the Knysna Cemetery, Knysna Hospital and Xolweni semi-formal development. Site 9 receives runoff from the eastern portion of the Knysna CBD.

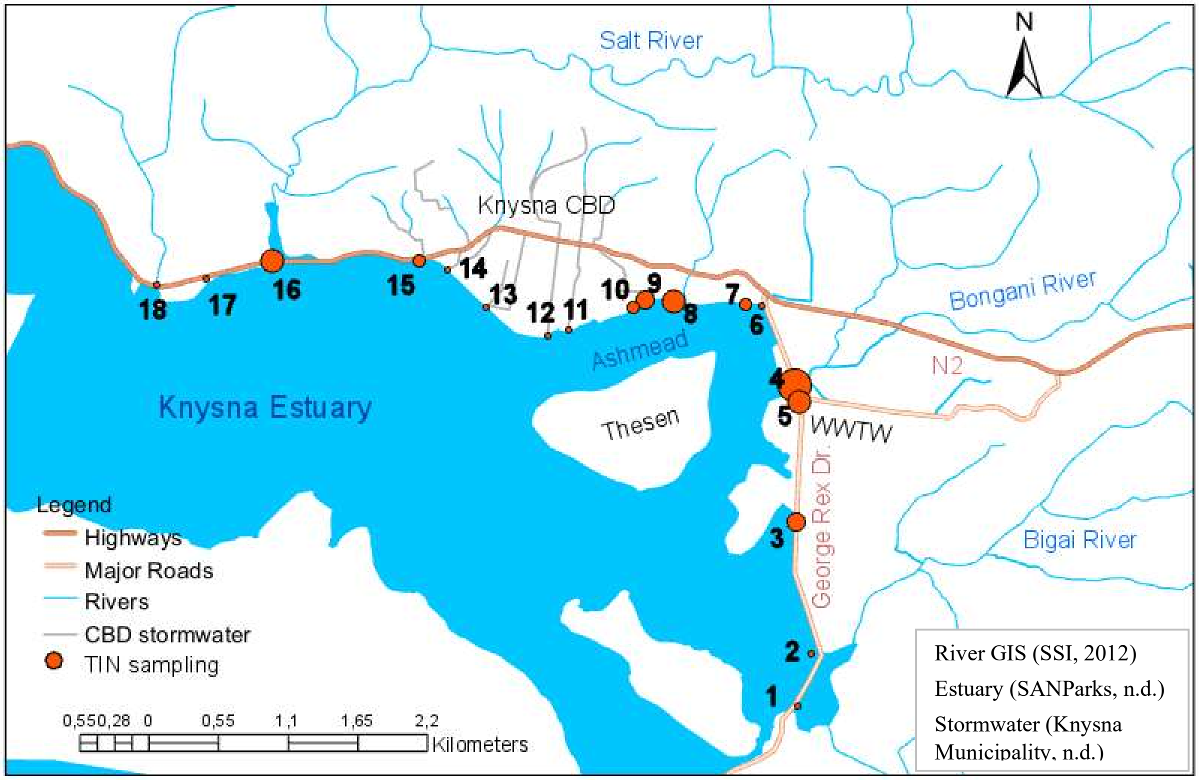


Figure 4-11: Relative Total Inorganic Nitrogen concentrations at 18 monitoring sites

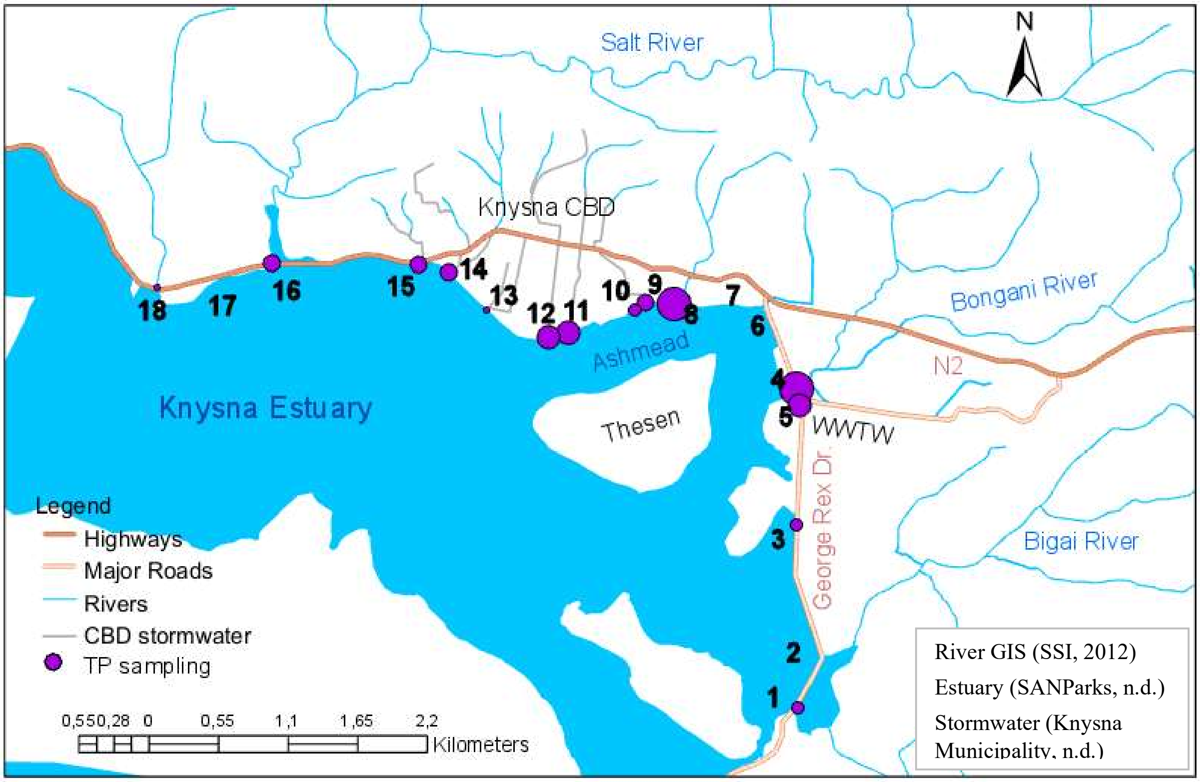


Figure 4-12: Relative Total Phosphorus concentrations at 18 monitoring sites

4.1.2.5 Ammonia

The water quality testing for Total Ammonia Nitrogen (TAN) measures the presence of both ammonium (NH_4^+) and un-ionized ammonia (NH_3). Un-ionized ammonia is toxic to aquatic fauna, whilst ammonium is not toxic but contributes to eutrophic conditions. Ammonium is converted to toxic un-ionized ammonia at elevated temperatures and high pH values. Hand-held probes were used to collect on site temperature and pH data at a number of sites during the March and April sampling events. No calculation of un-ionized ammonia levels was attempted for this phase of testing, due to concerns regarding the accuracy of ammonia concentrations reported by the MWTW laboratory.

4.1.2.6 Coliform bacteria

As discussed in Section 2.4.3, *E. coli* is a common indicator species for the presence of faeces of human or warm-blooded animal origin (DWAF, 1996b). The bacteria are a measure of faecal pollution and serve as an indicator of the possible presence of other bacteria and viruses which may cause a variety of infections and diseases. A large database of *E. coli* monitoring data was obtained from the Knysna Municipality. In the database 26% of data from 2011 to 2015 had the same *E. coli* count (2419 Colony Forming Units (CFU) per 100 mℓ). Data for this period is therefore strongly skewed, and the 510 measurements prior to 2016 were therefore not analysed. Six of the municipal monitoring points correspond with KBP monitoring sites. Data for these sites, as well as for the Ashmead Channel, from January 2016 to October 2018 (32 to 35 readings at each site) are shown in Figure 4-13. Counts at Site 4 (the Bongani outflow) were consistently high, although several *E. coli* spikes in excess of 10,000 CFU/100 mℓ were measured in the Ashmead Channel and in outflows from the CBD (Sites 11, 12 and 13). Values of 30,000 CFU/100 mℓ correspond to an upper viable counting limit of 300 colonies on a plate, after the first two steps in a ten-fold serial dilution. Reported values of 30,000 CFU/100 mℓ may, therefore, be higher. At such elevated E. coli concentrations, it is not necessary to determine the value with a higher accuracy, as the values are two orders of magnitude higher than safe limits. Figure 4-14 shows the same data, with the outliers excluded.

Table 4-5 shows the mean, 90th and 95th percentile *E. coli* values for each site. Six of the sites were located at outflows to the estuary, and one in the Ashmead Channel, and therefore compliance with the guidelines for recreational use in marine waters was assessed (DEA, 2012). All sites were categorized as ‘poor / unacceptable’ as the 90th percentile values exceed 500 CFU/100 mℓ. At all sites except the KADA drain and the Salt River, the 90th percentile values were significantly higher than the suggested limit of 500 CFU/100 mℓ. Mean values can be skewed by *E. coli* spikes, however only 28% of the measured values at the Bongani outflow, and 37% at the Ashmead Channel, were less than 500 CFU/100 mℓ. This indicates that *E. coli* pollution in these areas is a chronic, rather than an intermittent problem. The median values at all other sites were less than 200 CFU/100 mℓ. The 95th percentile values at all sites exceeded the Blue Flag (2018) beach criteria by a considerable margin (*E. coli* limits of 250 and 500 CFU/100 mℓ for coastal and inland waters respectively). Recommended water quality objectives for the Knysna River and Knysna Estuary were recently published in the Government Gazette for public comment (DWS, 2018d). The quality objectives were set in order to maintain the Knysna Estuary at its present ecological state. Whilst not directly applicable to the smaller rivers draining to the estuary, the objectives can be used as guideline for these rivers. 95th percentile *E. coli* measurements at all sites were very high when compared to the recommended water quality objectives for the Knysna River (130 CFU/100 mℓ).

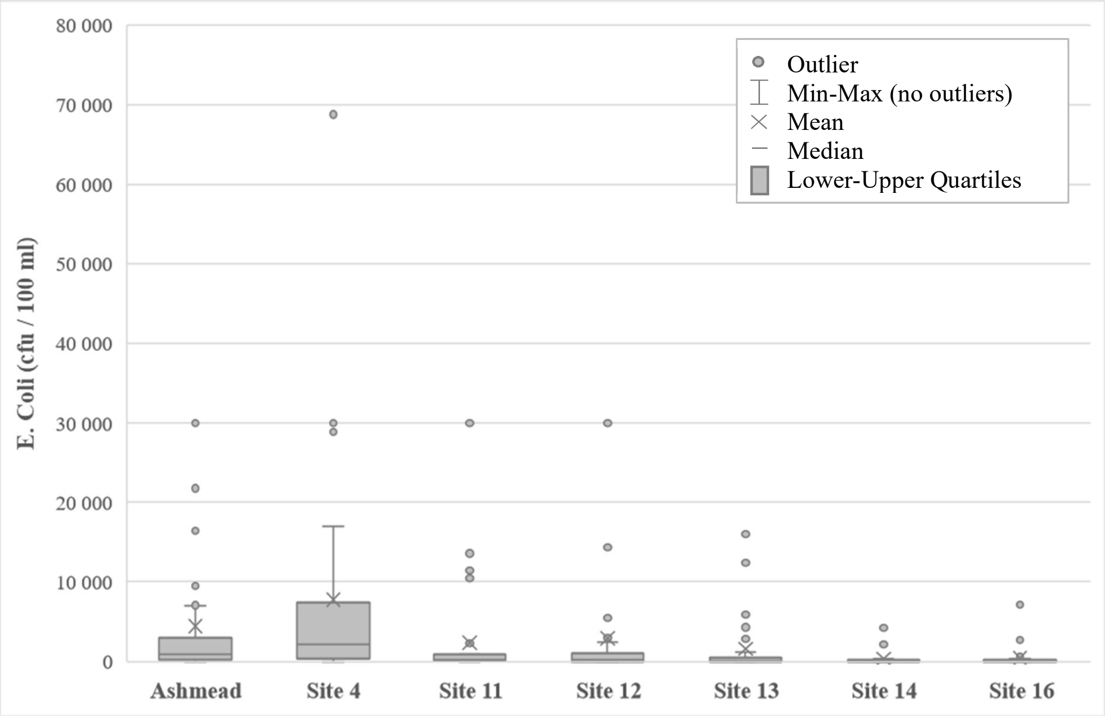


Figure 4-13: *E. coli* comparison across monitored sites

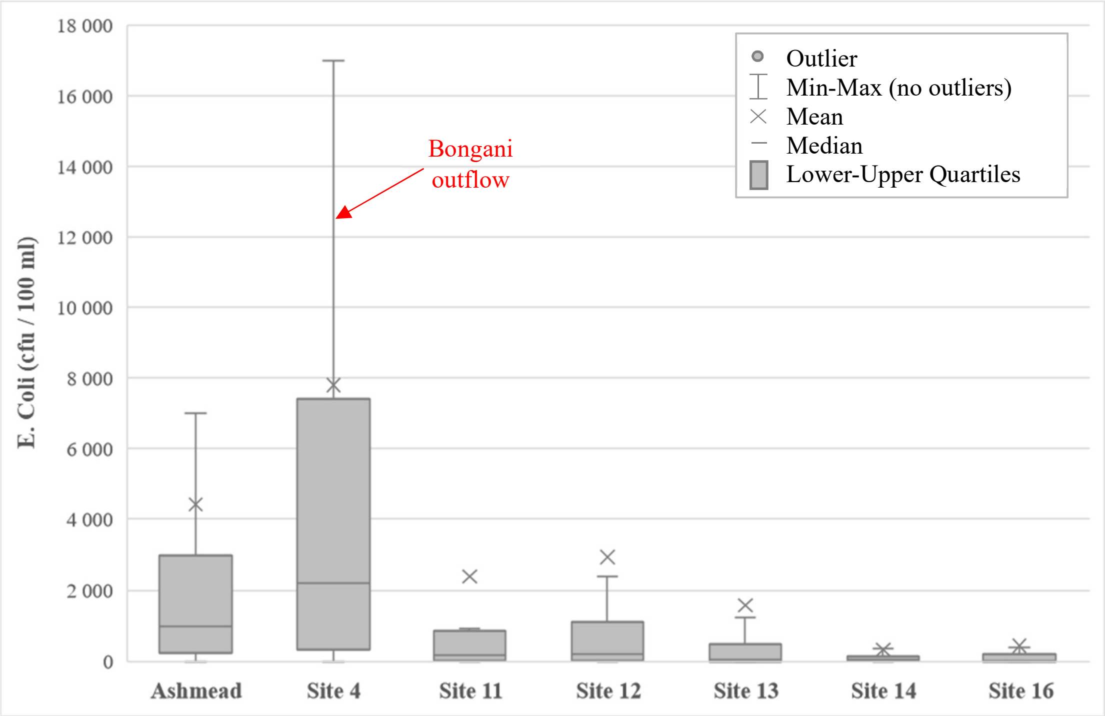


Figure 4-14: *E. coli* comparison across monitored sites excluding outliers

Table 4-5: ***E. coli*** **results from the Knysna Municipality**

Site	Description	Mean	90th percentile	95th percentile	DEA Category*	<= 500 CFU /100 mℓ
		CFU/100 mℓ	CFU/100 mℓ	CFU/100 mℓ		%
Ashmead	Ashmead Channel	4554	19100	30000	Poor	37%
Site 4	Bongani River outflow	8053	29780	45520	Poor	28%
Site 11	CBD: Queen St Drain	2461	11300	20160	Poor	69%
Site 12	CBD: Long St Drain	2931	11730	30000	Poor	63%
Site 13	CBD: Station Drain	1586	5340	13480	Poor	76%
Site 14	CBD: KADA Drain	345	1814	3048	Poor	88%
Site 16	Salt River mouth	456	1274	4494	Poor	84%

*DEA (2012), 90th percentile > 500 = poor, 90th percentile < 500 & 95th percentile > 500 = fair

4.1.2.7 Summary

Elevated TSS data was recorded for the Knysna Golf Course (Site 3), sites below the hospital (Sites 8 and 9), the Salt River (Site 16) and the stream outflow at Point (Site 18). Elevated turbidity data was also recorded for Sites 8 and 9, and additionally for Site 12 (Long Street Drain). Increased turbidity and TSS measurements were observed during or immediately after storms. The mean value of TSS data recorded between 1991 and 1994 was higher than data measured in this study for the Salt and Bongani Catchments. TSS concentrations measured between 1996 and 1999 were significantly higher than concentrations measured in this study at the Salt River, Bongani River, and Long Street Drain. The Simola Golf Course failure in 1996 mobilised significant sediment loads to the Salt River, and flooding in 1996 may have also elevated TSS concentrations.

It is difficult to draw conclusions from the nutrient data for the 18 monitoring sites, due to concerns regarding the validity of test results from the MWTW. Assuming that the relative nutrient concentrations are valid, elevated nutrients were measured at Sites 8 and 9 (below the hospital), the Bongani Catchment, and the Salt River.

No *E. coli* testing was undertaken for the 18 monitoring points as part of this study. Assessment of data obtained from the Knysna Municipality shows that the Bongani River and the Ashmead Channel consistently experience unacceptably high *E. coli* counts, with median values of 2700 and 1190 CFU/100 mℓ respectively. Only 28% and 37% of samples for the Bongani River and Ashmead Channel sites respectively were below the recommended target value for recreational use (DEA, 2012). Sites in the Knysna CBD and Salt River experience occasional extremely high *E. coli* counts, and were all categorized as 'poor' according to the guidelines for recreational use (DEA, 2012). 95th percentile counts at all sites were considerably higher than the Blue Flag criteria, as well as the water quality objectives for the Knysna River.

Sites 8 and 9 were not monitored further as part of this study, as they were deemed to have relatively low flows, and would therefore contribute lower pollutant loads, however it is recommended that elevated TSS and nutrients at these sites be investigated as part of on-going monitoring. The Long Street Drain was also not investigated further, although further research may seek to investigate the cause of elevated sediment loads in a predominantly urbanised catchment. Sites 16 and 18 are likely to generate the highest sediment loads to the estuary, and on-going monitoring at these sites is recommended. The Salt River, Bongani River and Bichai River were identified for further monitoring as part of this study.

4.2 Phase 2: Revised sampling points

4.2.1 Location and sampling regime

Problematic catchments were identified during the initial sampling and from February 2018 sample locations were revised accordingly. Descriptions of all monitoring sites are detailed in Appendix A, and described in Sections 3.3.2 to 3.3.3.4. The Bongani, Bigai and Salt catchments were the primary focus of the revised monitoring.

4.2.2 Results

4.2.2.1 Assessing validity

The validity of the results obtained from the KBP was not checked with confirmatory testing. The validity of the tests can therefore only be assessed by indirect comparison with the testing undertaken at UCT, the test results from the MWTW and historical data. No TSS testing was undertaken by the KBP. Turbidity measurements were assessed at the MWTW for samples collected between September 2017 and February 2018, and at the KBP laboratory for samples collected between July and November 2018. A comparison of the results obtained from the two laboratories is shown in Figure 4-15. The mean and maximum turbidity results obtained from the KBP laboratory were substantially higher than those measured at the MWTW for Sites 1d, 4 and 16c. Turbidity results can be strongly influenced by storms, and high values measured during storm events can skew the mean significantly. A large storm was experienced on the 14th of July, which resulted in elevated turbidity readings at the KBP laboratory for Sites 1d, 4, 5 and 16c. The single results measured by the KBP at Sites 11 and 18 were also taken during this storm. A storm on the 21st of November also resulted in elevated turbidity values at Sites 4 and 5. The elevated maximum and mean values were therefore reasonable. The median results from the KBP were significantly higher than the MWTW data for Sites 4 and 16c, however for Site 16c only one sample was tested at the MWTW and two at the KBP, one of which was taken after the large storm. For Site 4, the median value was also impacted by the two storm events, and non-storm event data was similar to that measured by the MWTW.

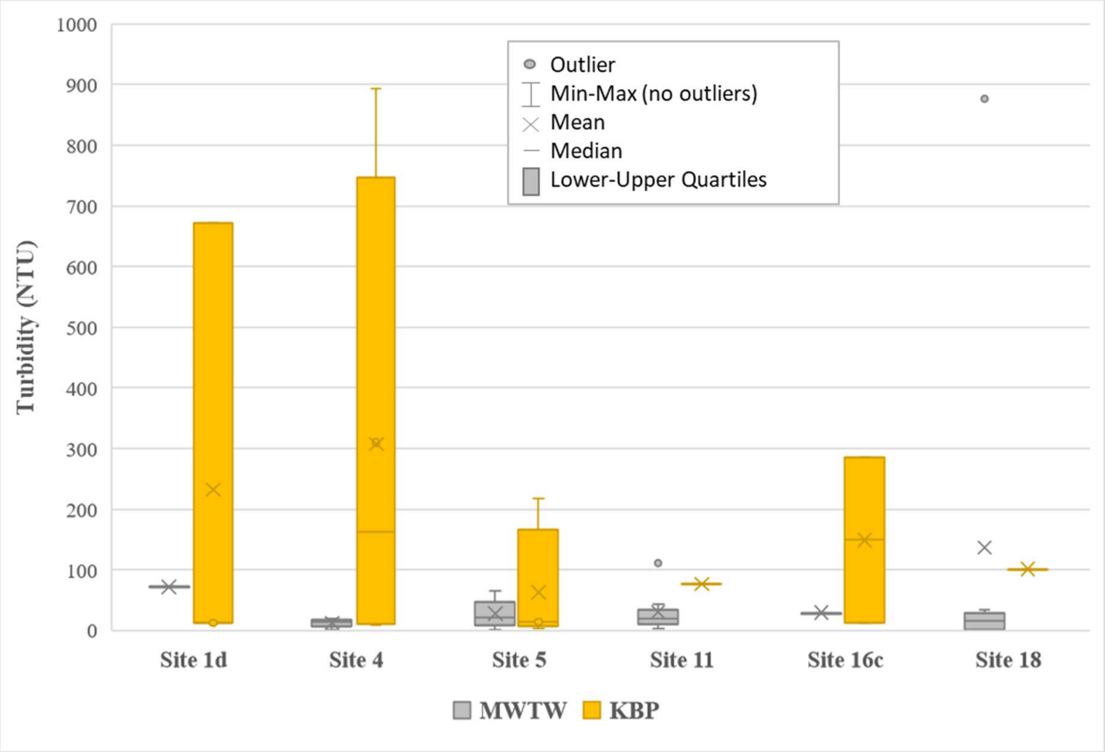


Figure 4-15: Comparison of turbidity measured at the MWTW and KBP

The pH values measured at the KBP laboratory showed a much lower variability than those measured at the MWTW, as discussed in Section 4.1.2.3 The range of pH values measured at the KBP laboratory were comparable to the values measured at UCT, particularly given the changes in season between the UCT testing and the KBP testing.

No confirmatory testing was conducted to confirm the results of the nutrient testing at the KBP laboratory, but the results can be compared to data tested at UCT for the same sites. In March and April 2018 samples were taken at Sites 1c and 4b, as discussed in Section 4.1.2.1. The samples were tested at UCT for TAN, NO_2, NO_3 and TP. The samples were transported a considerable distance and temperature and time factors may have affected the results. As discussed in Section 4.1.2.1, the testing of a sample of known concentration at UCT showed maximum errors of -15.7%, 82% and 23% for TAN, NO_2N and NO_3N respectively. Whilst the error for NO_2N was unacceptably high, the results corresponded closely with results obtained from the MWTW, and the error may be the result of inaccuracies in the preparation of the sample, as the NO_2N concentrations were extremely low. In this dissertation Total Inorganic Nitrogen results are presented, and NO_2N and NO_3N typically contributed only 0 – 2%, and 9 – 47% of TIN respectively, across all sites. The only exception was Site 14c, where a concentration of 0 mg/ℓ was measured for TAN for a single sample.

The range and mean values obtained for these Sites 1c and 4b were compared to the range of values obtained at UCT, and the results are presented in Table 4-6. Mean values that exceed the UCT range are shown in bold. At Site 1c, the mean NO_2N and NO_3N concentrations measured at the KBP exceeded the range measured at UCT. At Site 4b only the mean TAN concentration fell outside the range measured at UCT, by a small margin. Values measured by the KBP and at UCT were comparable for TAN, which typically makes up 52 – 91% of TIN. For the KBP testing interference levels were considered, in particular for salinity. None of the revised sampling sites were expected to be influenced by high salinity values (not impacted by tidal movement). The results for NO_2N may be impacted by the presence of NO_3N, however NO_2N makes up only 1 – 2% of TIN. Where results exceeded the test limits, samples were diluted until the results fell within the acceptable range for the tests. Comparison to historical data is discussed in Section 4.2.2.4.

Table 4-6: Comparison of UCT test results and KBP test results

	TAN		**NO_2N**		**NO_3N**	
Site	**UCT range***	**KBP range, mean***	**UCT range***	**KBP range, mean***	**UCT range***	**KBP range, mean***
	mg/ℓ					
Site 1c	0.1 – 9.2	3 – 14, 7	0.00 – 0.04	0.01 – 0.14, **0.08**	0.1 – 0.8	0.6 – 4.3, **2.6**
Site 4b	8.3 – 11.8	6 - 13, **8**	0.03 – 0.22	0.03 – 0.24, 0.14	0.6 – 5.9	1.4 – 4.2, 2.4

* Data is for different sampling events so comparison is indicative only

No direct comparison of SRP results is possible, as the testing at UCT and the MWTW was for TP, and the KBP reported SRP values. SRP is a measure of the phosphorus that is soluble and chemically available for uptake by plants. TP is a measure of total phosphorus, which includes both SRP, condensed phosphates and the phosphorus that is present in plant and animal matter in the water. TP will therefore always be higher than SRP. Only one sampling event was tested for TP at UCT. Testing of TP at UCT gave errors of 3.7% to -2.6% for the sample of known concentration. The mean SRP values measured at the KBP laboratory for Sites 1c, and 4b exceeded the range of values measured for TP at UCT. SRP values should be less than or equal to TP values. No conclusions can be drawn from this data as there was considerable range in SRP values, and the comparison is based on only one sampling event. The TP values measured at the MWTW typically had a wider range of values than the SRP values measured at the KBP. Mean and maximum TP values were higher than the SRP values, with the exception of Sites 1c and 4b (if sites with only one TP reading are excluded). Sites 1c and 4b frequently experienced very high nutrient loading (Section 4.2.2.4), with a significant range in the nutrient values measured. The comparison shows that the results for most sites were as expected (TP higher than SRP) but it is not possible to reach a definite conclusion about the accuracy of the testing. It is recommended that testing be undertaken to confirm the validity of SRP results for future monitoring.

No confirmatory testing of the *E. coli* results was undertaken, however the testing was performed at a SANAS accredited laboratory. For all pollutants, data obtained as part of this study is compared to historical and literature data, where this is available, in Sections Total Suspended Solids 4.1.2.2 to 4.1.2.5.

4.2.2.2 Turbidity

No testing for TSS was undertaken at the KBP laboratory. Samples collected monthly from July to November were tested for turbidity by the KBP. Four sample sets were tested (no data was obtained for October). Comparison of the data at all the revised sampling sites is shown in Figure 4-16. Two storm events occurred shortly before or during sampling, on the 14th of July (38 mm of rainfall) and the 21st of November 2018 (25 mm). The two storms generated a marked response in turbidity readings, as shown in Figure 4-17. For sampling events not associated with a storm the turbidity readings were all below 100 NTU. For the storm in July, in particular, turbidity readings increased substantially, with 68% of the readings above 200 NTU.

In the Bigai Catchment, particularly high turbidity readings were measured on the tributary stream (1b), and in Hornlee (1c and 1d). In the Bongani Catchment particularly high readings were measured at the Bongani outflow (4) and at one site in the Bongani headwaters (1e). The Bongani River adjacent to the industrial area (4b) and the tributary stream (4g), as well as a second site in the Bongani headwaters (4d) all also showed increased turbidity values in response to storms. For the larger storm (July) the turbidity reading at the Bongani outflow (4) was substantially higher than either of the contributing streams (4b and 4e). This could indicate a local source of sediments. Increased turbidity readings were also measured at Site 5 (where the WWTW discharges), indicating that this site receives stormwater runoff as well as the WWTW discharge. Of the CBD catchments, the Rawson Street Drain (14b) turbidity reading for the large storm was particularly high, but was diluted with clearer water originating at the Pledge Nature Reserve, as measured at the monitoring site immediately downstream. The Salt River experienced a marked increase in turbidity in response to storms (16a), and there may be some dilution effect from the Simola Golf course tributary (16b), before reaching 16c.

The increase in turbidity in response to a storm can be seen in Figure 4-18. The two photos show typical base flow turbidity in March, and increased turbidity the day after a large storm (140 mm of rainfall) in September. New sand deposits were noted in the channel after the September storm, and large sand heaps dredged from the channel were visible on the river bank (Figure 4-19). Based on the size of the heaps, the volume of sediment mobilised from the catchment after a storm is significant.

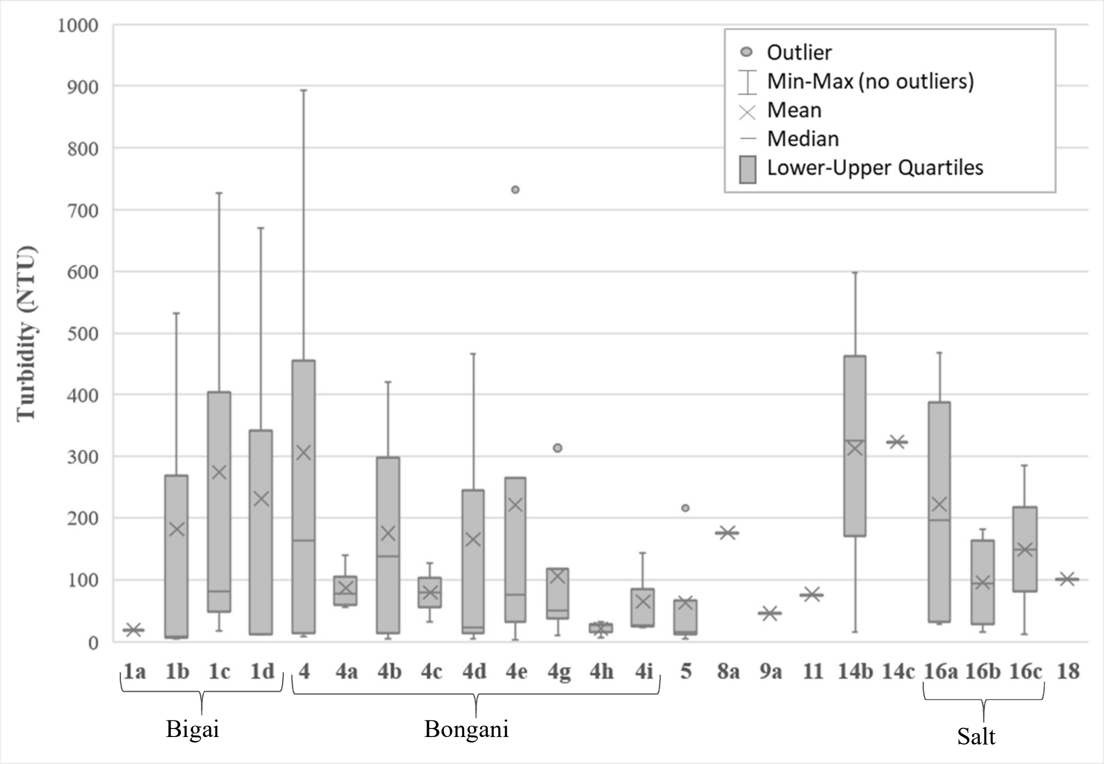


Figure 4-16: Turbidity comparison for the revised monitoring points

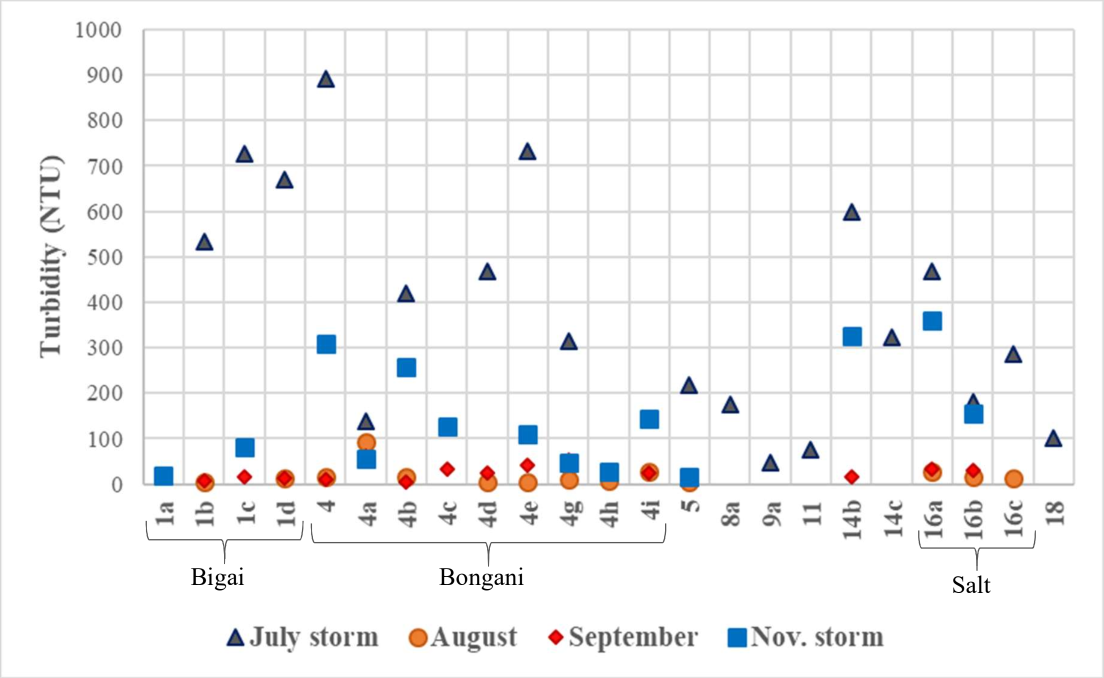


Figure 4-17: Turbidity readings for four sampling events

Figure 4-18: Bongani River turbidity, March (left) and September (right) 2018

Figure 4-19: Sand heaps next to the Bongani River

4.2.2.3 pH

The pH values measured by the KBP for sampling events between June and November 2018 are shown in Figure 4-20. The variability in pH values was much lower than those measured by the MWTW, as discussed in Section 4.1.2.3. All pH measurements at all sites ranged between 6 and 7.5, for both winter and summer measurements. This is typical of South African rivers, which range between pH values of 6 and 8, although pH values can be lower where fynbos vegetation is present and can vary due to photosynthetic activity

(DWAF, 1996a). These pH values were used in the calculation of un-ionized ammonia concentrations (discussed in Section 4.2.2.4).

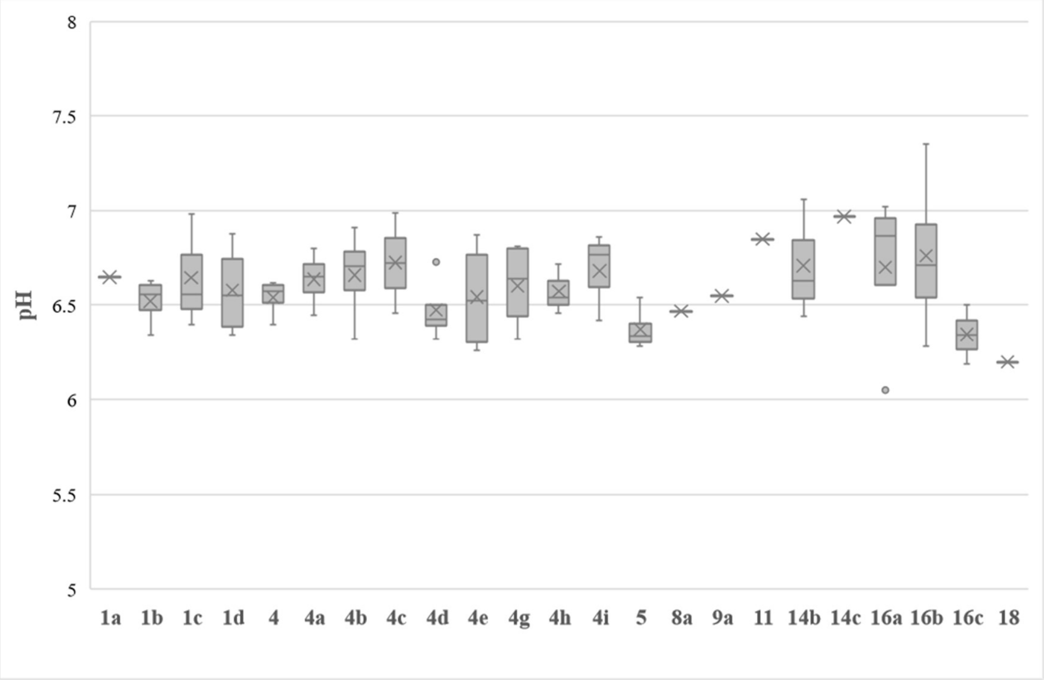


Figure 4-20: pH comparison for the revised monitoring points

4.2.2.4 Nutrients

The Total Inorganic Nitrogen (TIN) test results for the 23 revised monitoring sites for data collected monthly from June 2018 to November 2018, are presented in Figure 4-21. The results for discharge from the WWTW for January 2013 to June 2017, as obtained from the WWTW, are also shown. In the Bigai Catchment the TIN concentrations recorded at Site 1c (Bigai River in Hornlee) were particularly high, and markedly higher than concentrations at Site 1d, approximately 430 m upstream. TIN concentrations for the Bongani Catchment were particularly high at Sites 4 (Bongani outflow) and 4b (Bongani River adjacent to the Industrial area). Very high TIN concentrations were recorded at the WWTW. Particularly high TIN concentrations were also measured at Site 5, which is the culvert on George Rex Drive which receives the WWTW discharge. It should be noted that the TIN concentrations at Site 5 and the WWTW were measured during different time periods. No distinct seasonal trends were noted in TIN concentrations.

The TIN test results are also presented in Table 4-8. The proposed water quality objectives for the Knysna River were recently gazetted for public comment, and include the requirement that median TIN values be less than 0.7 mg/ℓ (DWS, 2018d). The Median TIN concentrations at all sites except Site 14c exceeded this recommended water quality objective for the Knysna River. The trophic state for each site, based on the TIN results, is also shown. The trophic state is based on the relevant table in the DWAF water quality guidelines for aquatic ecosystems (DWAF, 1996a). The typical environmental effects of different trophic states '*if all other nutrients and environmental conditions are within favourable ranges for the organisms concerned*' (DWAF, 1996b, Nitrogen (inorganic) p. 3) are reproduced in Table 4-7. All sites were classified as Eutrophic, except for Sites 4, 4b and 5 (Hypertrophic), and Site 14c (Mesotrophic). Only one sample was taken at Site 14c. The TIN concentrations at 14c appear to be considerably lower than Site 14b, immediately upstream. The improvement in water quality could be the result of dilution with good quality water originating at the Pledge Nature Reserve (the Brickelbos Stream). More data would be required to confirm this supposition.

The DWAF guidelines also note that '*(i)n unimpacted, well-oxygenated…waters, most (> 80 %) of the inorganic nitrogen should be present as nitrate; typically, ammonia concentrations will be below 0.1 mg N/ℓ, or less than 20% of the inorganic nitrogen present*' (DWAF, 1996b, Nitrogen (inorganic) p. 3). Based on the data presented in Table 4-8, it is evident that the ammonium concentrations made up a disproportionate amount of the TIN readings, with all sites except 14c exceeding 20%, and many sites exceeding 70%. This indicates that none of the sites were in an unimpacted condition, with the possible exception of the area draining to 14c (however only one reading was taken at Site 14c).

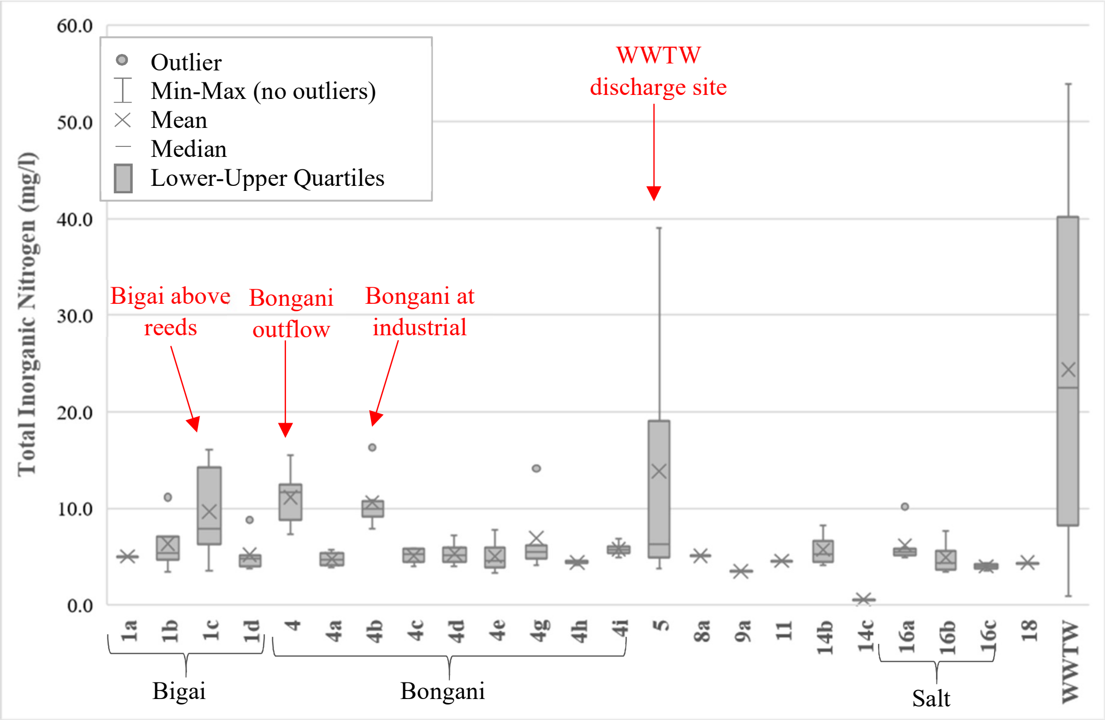


Figure 4-21: TIN comparison for the revised monitoring points

Table 4-7: Environmental effects of trophic states (after DWAF, 1996a)

Trophic State	Effects
Oligotrophic	usually moderate levels of species diversity; usually low productivity systems with rapid nutrient cycling; no nuisance growth of aquatic plants or the 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 seldom toxic.
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 very highly productive systems; nuisance growth of aquatic plants and blooms of blue-green algae, often including species which are toxic to man, livestock and wildlife.

Table 4-8: Total Inorganic Nitrogen results

Site	Description	No. Samples	Trophic state based on TIN	TAN as % of TIN	Mean TIN	Median TIN
					mg/ℓ	mg/ℓ
Site 1a	Bigai at Howard Street Culvert	1	Eutrophic*	60%	5.0	5.0
Site 1b	Bigai tributary near Hope Street	4	Eutrophic	67%	6.4	5.4
Site 1c	Bigai, Hornlee lower	5	Eutrophic	71%	9.7	7.9
Site 1d	Bigai, Hornlee upper	6	Eutrophic	68%	5.2	4.8
Site 4	Bongani River outflow	6	Hypertrophic	66%	11.1	11.7
Site 4a	Vigilance Drive Drain lower	6	Eutrophic	77%	4.8	4.7
Site 4b	Bongani adjacent to industrial area	6	Hypertrophic	76%	10.7	10.0
Site 4c	Khayalethu Stream, Khayalethu Clinic	4	Eutrophic	70%	5.1	5.3
Site 4d	Bongani River, Judah Square	6	Eutrophic	67%	5.4	5.2
Site 4e	Bongani River, Bongani	6	Eutrophic	73%	5.1	4.6
Site 4g	Bongani Tributary – Upper Old Place	6	Eutrophic	69%	6.5	5.2
Site 4h	Vigilance Drive north pipe	4	Eutrophic	74%	4.9	4.6
Site 4i	Vigilance Drive east pipe	3	Eutrophic	76%	5.8	5.5
Site 5	George Rex - Knysna WWTW discharge	6	Hypertrophic	84%	13.9	6.3
Site 8a	At N2 below Knysna Hospital - east	1	Eutrophic*	78%	5.1	5.1
Site 9a	At N2 below Knysna Hospital - west	1	Eutrophic*	85%	3.5	3.5
Site 11	CBD: Queen Street Drain	1	Eutrophic*	87%	4.6	4.6
Site 14b	Channel at Stepping Stones – Rawson St.	4	Eutrophic	52%	5.8	5.3
Site 14c	Channel at Stepping Stones – Trotter St.	1	Mesotrophic*	0%	0.6	0.6
Site 16a	Salt at Old Cape Road Culvert	6	Eutrophic	72%	6.2	5.6
Site 16b	Salt tributary from Simola - Old Cape Rd	4	Eutrophic	68%	4.9	4.3
Site 16c	Salt 200 m upstream of mouth	2	Eutrophic*	87%	4.0	4.0
Site 18	West Point at stream mouth	1	Eutrophic*	91%	4.4	4.4

*Trophic state should be based on more data

The results of Soluble Reactive Phosphorus (SRP) are shown in Figure 4-22. The results for discharge from the WWTW for January 2013 to June 2017 are also shown. Median SRP concentration at all sites exceeded the recommended water quality objectives for the Knysna River (DWS, 2018d). In the Bigai Catchment particularly high SRP concentrations were recorded at Site 1c (above the reed beds). In the Bongani Catchment, Sites 4 (Bongani River outflow), 4b (adjacent to the industrial area), 4g (tributary at Upper Old Place), and 4i (industrial area) showed particularly high SRP values. Elevated SRP concentrations were also recorded at Site 5 (WWTW discharge at George Rex Drive) and the WWTW. A reduction in SRP concentrations was evident between Sites 14b and 14c. This improvement in water quality could be the result of dilution with good quality runoff originating at the Pledge Nature Reserve, although more data would be required to confirm this.

The trophic state for each site, based on the SRP results, are shown in Table 4-9. The trophic state is based on the relevant table in the DWAF water quality guidelines for aquatic ecosystems (DWAF, 1996a). It is important to note that the classification in the guideline is based on Total Inorganic Phosphorus (TIP, which includes both SRP and condensed phosphates) and so the trophic state in the table is indicative only. Since the TIP concentration can only be the same as, or higher than SRP, the trophic state can only stay the same or worsen. All sites were classified as hypertrophic, with the anticipated effects detailed in Table 4-7.

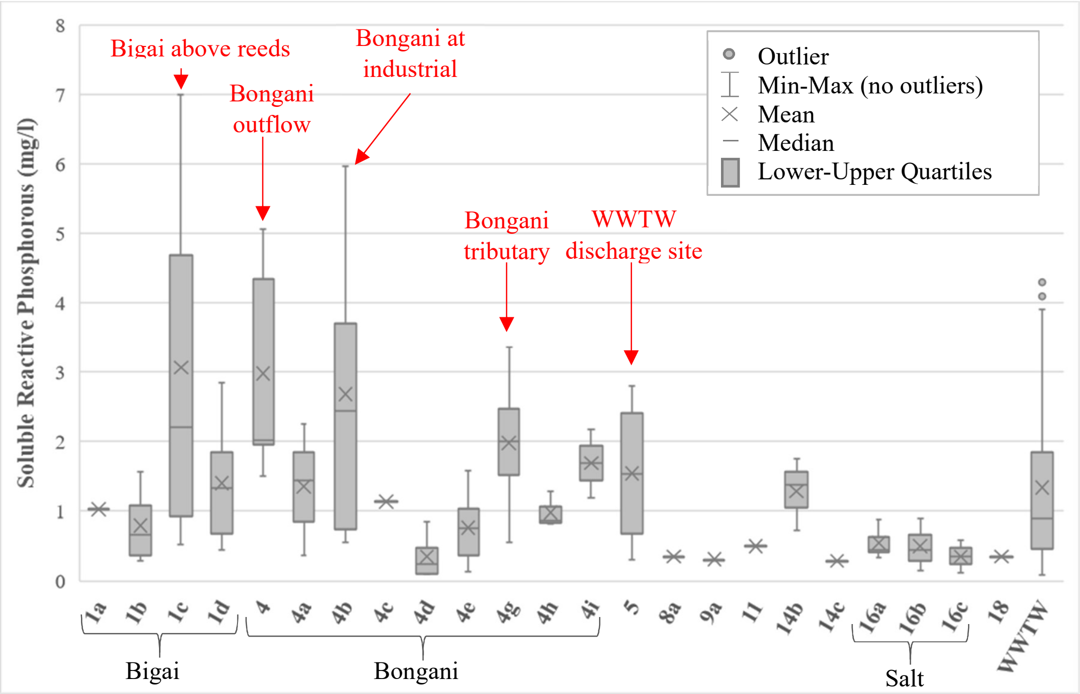


Figure 4-22: SRP comparison for the revised monitoring points

The trophic state is dependent on the presence of both elevated nitrogen, and elevated phosphorus, and the ratio between these two. Table 4-8 indicates that sufficient nitrogen was present to create eutrophic or hypertrophic conditions at almost all sites, and Table 4-9 indicates there was sufficient phosphorus for hypertrophic conditions. The ratio of TIN to SRP is also shown in Table 4-9. In unimpacted streams ratios of TIN:TIP of 25-40:1 are typical, whilst ratios of less than 10:1 are indicative of eutrophic or hypertrophic conditions (DWAF, 1996a). Only sites with three or more readings were calculated. All sites except Site 4d (Bongani River tributary in Khayalethu) and Site 16a (Salt River) had ratios conducive to hypertrophic conditions. The ratio should be based on TIP but since TIP can only be the same or higher than SRP the trophic state can only stay the same or worsen with the inclusion of TIP data.

Table 4-9: Soluble Reactive Phosphorus/ Orthophosphate results

Site	Description	No. Samples	Trophic state based on SRP**	TIN : SRP***	Mean SRP	Median SRP
				mg/ℓ : mg/ℓ	mg/ℓ	mg/ℓ
Site 1a	Bigai at Howard Street Culvert	1	Hypertrophic*		1.0	1.0
Site 1b	Bigai tributary near Hope Street	4	Hypertrophic	8.0 : 1	0.8	0.7
Site 1c	Bigai, Hornlee lower	5	Hypertrophic	3.1 : 1	3.1	2.2
Site 1d	Bigai, Hornlee upper	6	Hypertrophic	3.7 : 1	1.4	1.3
Site 4	Bongani River outflow	5	Hypertrophic	3.7 : 1	3.0	2.0
Site 4a	Vigilance Drive Drain lower	6	Hypertrophic	3.5 : 1	1.4	1.4
Site 4b	Bongani adjacent to industrial area	5	Hypertrophic	4.0 : 1	2.7	2.4
Site 4c	Khayalethu Stream, Khayalethu Clinic	1	Hypertrophic*		1.1	1.1
Site 4d	Bongani River, Judah Square	4	Hypertrophic	15.1 : 1	0.4	0.2
Site 4e	Bongani River, Bongani	6	Hypertrophic	6.6 : 1	0.8	0.8
Site 4g	Bongani Tributary – Upper Old Place	4	Hypertrophic	3.3 : 1	2.0	2.0
Site 4h	Vigilance Drive north pipe	3	Hypertrophic	4.9 : 1	1.0	0.9
Site 4i	Vigilance Drive east pipe	2	Hypertrophic*		1.7	1.7
Site 5	George Rex - Knysna WWTW discharge	4	Hypertrophic	9.0 : 1	1.5	1.5
Site 8a	At N2 below Knysna Hospital - east	1	Hypertrophic*		0.4	0.4
Site 9a	At N2 below Knysna Hospital - west	1	Hypertrophic*		0.3	0.3
Site 11	CBD: Queen Street Drain	1	Hypertrophic*		0.5	0.5
Site 14b	Channel at Stepping Stones – Rawson St.	3	Hypertrophic		1.3	1.4
Site 14c	Channel at Stepping Stones – Trotter St.	1	Hypertrophic*		0.3	0.3
Site 16a	Salt at Old Cape Road Culvert	5	Hypertrophic	11.4 : 1	0.5	0.5
Site 16b	Salt tributary from Simola - Old Cape Rd	3	Hypertrophic	9.9 : 1	0.5	0.4
Site 16c	Salt 200 m upstream of mouth	2	Hypertrophic*		0.4	0.4
Site 18	West Point at stream mouth	1	Hypertrophic*		0.4	0.4

*Trophic state should be based on more data

**NB: Trophic state should be based on Total Inorganic Phosphorus, however the state can only stay the same or worsen if TIP data is used

***Should be Ratio of TIN:TIP, however ratio can only decrease with the inclusion of TIP

To understand which of the sites was the most impacted by high nutrients two approaches were taken, sites were ranked based on mean nutrient values, and student t tests were used to compare selected sites. To account for both elevated TIN and SRP a ranking (from 1 to 23) was assigned to each site and then the TIN and SRP ranks were added together to give a combined ranking. The poorest water quality based on this ranking was measured at Sites 4, 1c, 4b, 5 and 4g (in order). Three of these sites are within the Bongani Catchment area (at the outflow, adjacent to the industrial area and at the tributary at Upper Old Place). The least impacted sites were 14c, 9a, 18 and 16c (in order of least impacted), although this is based on a single sample at three of these sites.

Student t tests with an alpha value of 0.05 were used to determine whether the differences between sites were due to chance or if data was statistically significantly different. At independent sites (for example sites on different rivers) a two-sample t test assuming unequal variances was used. At dependent sites such as upstream and downstream locations on the same river on the same day, a paired t test was used. The results are presented in Table 4-10.

The following is concluded from the data comparison across catchments:

- Although there was no statistically significant difference between SRP values for any of the sites tested, it can be seen in Figure 4-22 that one site on the Bigai River (Site 1c), and two sites on the Bongani River (Sites 4 and 4b) frequently experienced elevated SRP values. The sites were not statistically different because the variance at each of these sites was reasonably high. Table 4-9 showed that SRP values at all sites were sufficient to create conditions conducive to hypertrophic states. It is recommended that confirmatory testing be conducted to confirm the accuracy of the SRP testing. Should the test results be confirmed it is recommended that further research be conducted to determine the source of the elevated SRP values.
- TIN results at Site 4b were significantly higher than Sites 16a and 16b but not significantly different to Site 1c. This indicates that TIN concentrations in outflow from the Bongani Catchment were significantly higher than concentrations in flows from the Salt catchments.
- There was no significant difference between TIN concentrations in the lower Bongani (4b), the Bongani tributary (4g), and the Upper Bigai (1c) with measurements at George Rex Drive adjacent to the WWTW outflow (5). As can be seen in Figure 4-21, the readings at Site 5 are likely to have undergone some dilution when compared to the WWTW outflow, or the TAN testing issue at the MWTW may be exaggerating TIN concentrations at the WWTW. The WWTW has been non-compliant with the conditions of the special licence (DWS, 2014) for several years and was issued with a directive from the DWS to address these issues in 2018. Even accounting for some dilution at Site 5, this data indicates that water quality in the Bongani River, and Upper Old Place tributary, and the Upper Bigai were extremely poor, and also need to be urgently addressed. Sampling below the reed beds on the Bigai is recommended, to determine if the reed beds have a significant impact on water quality in the Bigai Catchment.

For the Bigai Catchment, the following was concluded:

- Despite having different mean values, there was no significant difference between TIN values at Sites 1c and 1d, both above the reed beds. This is discussed in more detail in Section 4.2.2.4.

The following was concluded for the Bongani River:

- TIN concentrations in the lower Bongani River (4b) were significantly higher than TIN concentrations in the Vigilance Drive Drain, which receives runoff from the industrial area and formal housing (4a).
- There was no significant difference between TIN concentrations in runoff generated from the industrial area and formal housing (4a) when compared with concentrations in runoff from catchments where a substantial proportion of the catchment was semi-formal housing (measured against the site with the highest mean value, 4d). It is recommended that additional monitoring be established downstream of the entire semi-formal development to determine whether this holds true.
- TIN concentrations in the lower Bongani River (4b) were significantly higher than concentrations in the semi-formal development in the headwaters (4c, 4d, 4e). This indicates that there is a significant source of nutrients between the monitoring points. Periodic major sewage leakages have been noted on the sewage pipe that crosses the middle reaches of the Bongani River. Sites 4c, 4d and 4e only measure runoff from the upper portions of the semi-formal area and it is recommended that additional monitoring be put in place downstream of the development but upstream of the sewage line. This may assist in isolating the source of elevated nutrients.
- TIN concentrations in the lower Bongani River (4b) were not significantly different from concentrations on the eastern tributary, which flows through Upper Old Place (4g). It should, however, be cautioned that the results at 4g were perhaps overly skewed by a single high reading, and on-going monitoring should be continued to establish if this trend is valid. Land use in the catchments was similar, with high proportions of undeveloped land (61% and 71% respectively), although the Bongani had a higher proportion of grass and a lower proportion of forest (27% and 34% forest and grass in the Bongani relative to 60% and 11% in the tributary catchment). Semi-formal development comprised 30% and 26% of the Bongani and tributary catchments respectively. Three possible sources of elevated nutrients have been identified in the tributary catchment:
    - Periodic major sewage leakages have been noted on the sewage pipe that crosses the middle reaches of the tributary river, over several years
    - the Knysna organic waste dump is located within the catchment
    - semiformal-housing developments in the catchment headwaters

  As for the Bongani Catchment, should nutrient concentrations remain high, it is recommended that additional monitoring be put in place. Additional sampling points should be located downstream of the semi-formal development but upstream of the sewage line. Monitoring is also recommended downstream of the organic waste dump. This may assist in isolating the source of elevated nutrients.
- The drain that received runoff from formal housing and the industrial area (4i) had significantly higher TIN concentrations than the drain that only received runoff from a small portion of the formal housing area (4h).

For the Salt River Catchment, the following is concluded:

- The TIN concentrations at the Salt River, and Simola tributary were not significantly different, despite having quite different land uses.

Table 4-10: T test comparing different sites

Site compared	Dates & (No. Samples) TIN	Dates & (No. Samples) SRP	Significance (p = 0.05)	
			TIN	SRP
1C : 1D	06/2018-11/2018 (5)	06/2018-11/2018 (5)	NS	NS
1C : 4B	06/2018-11/2018 (5)	06/2018-11/2018 (4)	NS	NS
1C : 5	06/2018-11/2018 (5)	06/2018-10/2018 (4)	NS	NS
4A : 4D	06/2018-11/2018 (6)	06/2018-09/2018 (4)	NS	NS
4B : 4A	06/2018-11/2018 (6)	06/2018-11/2018 (5)	S 4A < 4B	NS
4B : 4C	06/2018-11/2018 (4)	N/A	S 4C < 4B	N/A*
4B : 4D	06/2018-11/2018 (6)	06/2018-09/2018 (4)	S 4D < 4B	NS
4B : 4E	06/2018-11/2018 (6)	06/2018-11/2018 (5)	S 4E < 4B	NS
4B : 4G	07/2018-10/2018 (4)	07/2018-11/2018 (4)	NS	NS
4B : 5	06/2018-11/2018 (6)	06/2018-09/2018 (4)	NS	NS
4G : 5	07/2018-10/2018 (4)	06/2018-11/2018 (4)	NS	NS
4B: 16A	06/2018-10/2018 (5)	06/2018-11/2018 (5)	S 16A < 4B	NS
4B: 16B	07/2018-11/2018 (4)	07/2018-09/2018 (3)	S 16B < 4B	NS
4H : 4I	08/2018-11/2018 (4)	N/A	S 4H < 4I	N/A*
16A : 16B	07/2018-09/2018 (3)	07/2018-09/2018 (3)	NS	NS

*insufficient data

Water Quality data was obtained from the DWS for eight monitoring sites at stream or stormwater channel outflows to the estuary. Two of the monitoring sites (Kl05, KL04) corresponded with KBP monitoring sites (4 and 5 respectively). In addition, one site, KL10, was located at the mouth of the Salt River. T tests were used to determine whether water quality at the three sites has changed over time. The water quality at the mouth of the Salt River was not measured as part of the revised monitoring for this study. Direct comparison between historical data at the mouth of the Salt River, with data from this study was therefore not possible. Historical data for the mouth of the Salt River was compared with data obtained as part of this study for two upstream monitoring points, to give an indication of water quality changes over time. The results are presented in Table 4-11. The analysis shows that TIN and SRP concentrations at the Bongani Outflow (Site 4) have increased significantly since the 2010-2013 data was taken. Neither TIN nor SRP concentrations for the WWTW discharge have changed significantly since 2011. TIN concentrations at Sites 16a and 16b on the Salt River were significantly higher than readings at the Salt River mouth in 2010 to 2013. SRP concentrations were significantly higher at Site 16a, but not at Site 16b, when compared to the earlier data. Results for the Salt are indicative only as it is not known what influence the tide had on readings at the Salt River mouth during the 2010-2013 sampling.

Table 4-11: T test for TIN and SRP changes over time

Site	DWS Dates & (No. Samples)	KBP Dates & (No. Samples) TIN	KBP Dates & (No. Samples) SRP	Significance (p = 0.05)	
				TIN	SRP
Site 4 (KL05)	08/2010-10/2013 (15)	06/2018-11/2018 (6)	06/2018-11/2018 (5)	S DWS < KBP	S DWS < KBP
Site 5 (KL04)	08/2010-11/2011 (5)	06/2018-11/2018 (6)	06/2018-09/2018 (4)	NS	NS
Site 16 (KL10) vs 16a	08/2010-10/2013 (12)	06/2018-10/2018 (5)	06/2018-10/2018 (5)	S* DWS < KBP	S* DWS < KBP
Site 16 (KL10) vs 16b	08/2010-10/2013 (12)	07/2018-10/2018 (4)	07/2018-9/2018 (3)	S* DWS < KBP	NS*

*Sites cannot be directly compared so results are indicative only

4.2.2.5 Ammonia

As discussed in Section 4.1.2.5, Ammonia is toxic to aquatic fauna when present as un-ionized ammonia. Ammonium is converted to un-ionized ammonia at elevated temperatures and high pH values. In-situ temperature and pH data was collected during site visits in March and April 2018. Unfortunately, these in-situ readings correspond with TAN testing at the MWTW. TAN testing at the MWTW has been shown to be inaccurate (Section 4.1.2.1) and therefore this data cannot be used to calculate estimated un-ionized ammonia concentrations. No in-situ temperature data was collected for the period during which water quality testing was conducted at the KBP. pH data was measured at the KBP laboratory for all samples. Temperatures between 14° C and 25° C were measured for the March and April sampling events. For assumed temperatures of 15° C and 25° C, the percentage of ammonium that would be present as un-ionized ammonia was calculated from the relevant table in the DWAF guideline for aquatic ecosystems

(DWAF, 1996a). The percentage of un-ionized ammonia was then multiplied by the TAN concentrations measured at the KBP laboratory to estimate un-ionized ammonia concentrations. The concentrations were then compared to the target, chronic and acute limits reported in the guideline for aquatic ecosystems (DWAF, 1996a). None of the values were above the acute limit. Values below the target water quality limit, above the target water quality but below the chronic range, and in the chronic range are shown in Table 4-12. The guideline notes that single un-ionized ammonium concentrations are of limited use (DWAF, 1996a), and therefore only sites with four or more readings are reported in the table.

At a temperature of 15° C, un-ionized ammonia concentrations in the chronic range were calculated for Sites 1c (Upper Bigai), 4b (Lower Bongani), 5 (WWTW) and 16a (Salt River). At 25° C, un-ionized ammonia concentrations in the chronic range were also calculated for Sites 4 (Bongani outflow), 4c (Upper Bongani), 4g (Bongani tributary), 14b (Knysna CBD) and Site 16b (Salt River tributary). At elevated temperatures 75% of samples at the lower Bongani River (Site 4b), and the Salt River (Site 16a) were estimated to fall within the chronic range for in-ionized ammonia. It is clear that in-ionized ammonia concentrations were elevated at many sites. On-going in situ monitoring of temperature is recommended to establish a database of typical seasonal water temperatures at all sites. As temperature and pH values are in constant flux it is recommended that the TAN levels be managed to prevent ecological damage caused by the presence of un-ionized ammonia. At the outflow from the catchments to the estuary higher salinity levels, combined with a dilution effect, will reduce the concentrations of un-ionized ammonia.

Table 4-12: Estimated un-ionized ammonia compared to target ranges

Site	Description	Temperature of 15°			Temperature of 25°		
		<=TWQ	> TWQ	Chronic	TWQ	> TWQ	Chronic
Site 1b	Bigai tributary near Hope Street	100%	0%	0%	25%	75%	0%
Site 1c	Bigai, Hornlee lower	67%	0%	33%	33%	33%	33%
Site 1d	Bigai, Hornlee upper	100%	0%	0%	75%	25%	0%
Site 4	Bongani River outflow	50%	50%	0%	25%	25%	50%
Site 4a	Vigilance Drive Drain lower	100%	0%	0%	0%	100%	0%
Site 4b	Bongani adjacent to industrial area	25%	25%	50%	0%	25%	75%
Site 4c	Khayalethu Stream, Khayalethu Clinic	50%	50%	0%	50%	0%	50%
Site 4d	Bongani River, Judah Square	100%	0%	0%	75%	25%	0%
Site 4e	Bongani River, Bongani	100%	0%	0%	50%	50%	0%
Site 4g	Bongani Tributary – Upper Old Place	75%	25%	0%	25%	50%	25%
Site 5	George Rex - Knysna WWTW discharge	75%	0%	25%	50%	25%	25%
Site 14b	Channel at Stepping Stones – Rawson St.	67%	33%	0%	33%	33%	33%
Site 16a	Salt at Old Cape Road Culvert	25%	50%	25%	25%	0%	75%
Site 16b	Salt tributary from Simola - Old Cape Rd	50%	50%	0%	25%	25%	50%

4.2.2.6 Coliform bacteria

The KBP collected samples twice in October and once in November 2018, and had the samples tested for *E. coli* at a SANAS accredited laboratory (Figure 4-23). The limited number of tests means it is difficult to form conclusions about the data. High *E. coli* spikes of over 30,000 CFU/100 mℓ were measured at Sites 1c (Bigai in Hornlee) and 4c (Khayalethu) in early October.

In the Bongani Catchment a high *E. coli* spike of over 30,000 CFU/100 mℓ was measured in Khayalethu in the Upper Headwaters (Site 4c) in early October. All sites in the Bongani Catchment, with the exception of 4a, had counts of over 30,000 CFU/100 mℓ for November. The *E. coli* spike at 4c in early October was not reflected in downstream measurements at Site 4b, however this is likely due to dilution effects, as 4c is a small stream in the upper headwaters. Elevated *E. coli* counts at Sites 4a, 4h and 4i indicate that there is sewage contamination in the industrial area or the urban area upstream of the industrial area. High *E. coli* counts for this area were also recorded in the 2012 monitoring (SSI, 2012).

Sites 4b and 4c (Bongani at industrial area and Khayalethu) had counts above the recommended limit of 400 CFU/100 mℓ for all three sampling events. All other sites in the Bongani Catchment had counts above the recommended limit for two of the sampling events. Elevated TIN concentrations in the Bongani Catchment corresponded with elevated *E. coli* counts in this catchment, although TIN and *E. coli* didn't necessarily correspond at individual sites. Of the 23 samples collected in 2018 in the Bongani Catchment, only four were below the recommended *E. coli* count. This is reflected in the municipal database, with only 25% compliance to the limit at Site 4, and a mean count of 8053 CFU/100 mℓ. None of the sampling points measured in the Bongani Catchment in 2012 fell below the recommended limit, with 6 of the 11 sites exceeding counts of 2000 CFU/100 mℓ (SSI, 2012).

In the Bigai Catchment a high *E. coli* spike of over 30,000 CFU/100 mℓ was measured in Hornlee, at Site 1c, in early October. Both sites in the Upper Bigai (Sites 1c and 1d) had counts above the recommended limit for all three sampling events. The elevated *E. coli* counts at Site 1c corresponded with the elevated TIN data that identifies point 1c as a monitoring point of concern. Although Site 1d is only approximately 430 m upstream of 1c, a small stream and at least 2 km of stormwater pipe discharge to the Bigai River between the two points. The t test for TIN and SRP concentrations at Sites 1d and 1c showed no statistically significant difference, however both mean and median values for TIN and SRP were considerably higher at Site 1c. Similarly, in the *E. coli* data the spike at Site 1c in the beginning of October was not reflected at Site 1d. It is not possible to compare the sites for November because the dilution series for 1c was limited to 3000 CFU/100 mℓ. The nutrient and *E. coli* data would seem to indicate that there was a nutrient source, likely a sewage leak, in the catchment between these two points. On-going monitoring will help to confirm this supposition.

Sampling on the Bigai River in Hornlee in 2012 also showed elevated *E. coli* counts of 687 CFU/100 mℓ at Site LR2.5 (upstream of 1d), >2420 CFU/100 mℓ on the side stream between Sites 1c and 1d, and at Site LR2.3 downstream of Site 1c (SSI, 2012). The same study noted the regular occurrence of blockages and sewage overflows in the Hornlee area, with an average of two incidents reported daily.

There is insufficient data at present to test whether there is a significant difference between nutrient levels at Sites 1c (Bigai above the reed beds) and 1a (within the reed beds on the Bigai). The *E. coli* spike at Site 1c in early October (> 30,000 CFU/100 mℓ) was not reflected at Site 1a (220 CFU/100 mℓ). *E. coli* testing in 2012 also found a reduction between the two points, with *E. coli* counts of > 2420 CFU/100 mℓ above the reed beds, 970 CFU/100 mℓ within the reed beds (Howard Street), and 228 CFU/100 mℓ at

Wilson Street, in the lower portion of the reed beds (SSI, 2012). This effect could be due to dilution or to the positive effect of the reed beds. On-going data is required to confirm whether this improvement is consistent.

Elevated *E. coli* concentrations at the WWTW outflow in late October and November 2018 are of serious concern as they could indicate inadequate treatment at the WWTW.

No *E. coli* sampling was undertaken in the Salt River catchment, however data collected in 2012 showed that although some elevated *E. coli* was measured in the upper Salt, low *E. coli* counts for the lower Salt River were recorded (4 CFU/100 mℓ). The municipal database (Table 4-5) also reveals that the Salt River was less problematic than the Bongani, with 81% compliance with the recommended limit and a mean count of 456 CFU/100 mℓ.

No additional *E. coli* sampling in the Knysna CBD was undertaken by the KBP, as the municipal database has a high degree of information for this area. The database shows 63%, 63%, 73% and 88% compliance with the *E. coli* limit at the Queen, Long, Station and KADA monitoring points (Table 4-5). Monitoring in 2012 found only 10% compliance at the 18 monitoring points tested, with half of the samples exceeding 2420 CFU/100 mℓ (SSI, 2012).

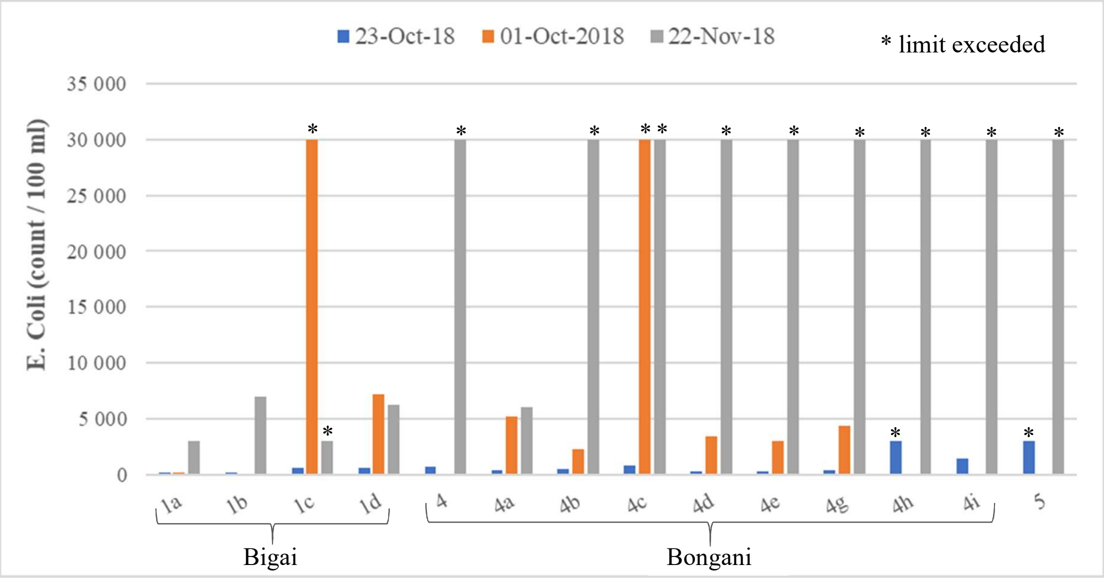


Figure 4-23: *E. coli* comparison for the revised monitoring points

4.2.2.7 Summary

Turbidity measurements, as well as site observations, indicate that turbidity increases at most sites due to storm events. Following a storm event turbidity was particularly high in the upper Bigai Catchment, in the lower Bongani River and some sites in the Upper Bongani River, at the Rawson Street Drain and in the middle reaches of the Salt River. Personal observations of high sediment loads deposited in the Bongani River adjacent to the industrial area are cause for concern.

At most sites in the Bongani, Bigai, Salt and CBD catchments, TIN and SRP concentrations were high enough to be conducive to eutrophic or hypertrophic conditions. TIN concentrations measured in the lower Bongani were significantly higher than those measured in the Salt catchment but not significantly higher than the TIN measured in the upper Bigai. No significant difference was found for SRP at any of the analysed sites. TIN and SRP concentrations in the Bongani Catchment at the outflow (Site 4) and adjacent to the industrial area (Site 4b) were particularly high. TIN concentrations in the lower Bongani River (4b) were significantly higher than concentrations in the semi-formal development in the headwaters (4c, 4d, 4e) but not significantly higher than monitoring in Upper Old Place (4g). Additional monitoring to determine the source of elevated nutrients in the two catchments is recommended. T test comparison with DWS data shows that TIN and SRP concentrations at the Bongani outflow (Site 4) have increased significantly since 2010-2013. Toxic un-ionized ammonia concentrations in the chronic range were estimated for many sites. Un-ionized ammonia concentrations are impacted by temperature and pH values, which are in constant flux. It is recommended that the TAN levels be managed to prevent ecological damage caused by the presence of toxic un-ionized ammonia.

In the Bigai Catchment, particularly high TIN and SRP concentrations were measured at Site 1c in Hornlee, above the reed beds. This site did not have significantly different concentrations to Site 4b (lower Bongani River) and Site 5 (WWTW). Additional sampling below the reed beds on the Bigai is recommended, to determine if the reed beds have a significant impact on water quality in the Bigai Catchment.

High TIN concentrations were also recorded for the WWTW discharge at George Rex Drive (Site 5). There was no significant difference between TIN concentrations in the lower Bongani (Site 4b) and the Bongani tributary (Site 4g) with measurements at the WWTW outflow (Site 5), indicating that water quality in the Bongani Riverwas extremely poor. Priority should be given to addressing water quality concerns at the WWTW and the Bongani Catchment. Neither TIN or SRP concentrations for the WWTW discharge (Site 5) have changed significantly since 2011.

The TIN concentrations at the Salt River, and Simola tributary were not significantly different, despite having quite different land uses. TIN concentrations at Sites 16a and 16b on the Salt River were significantly higher than readings at the Salt River mouth in 2010 to 2013, but results are indicative only as it is not known what influence the tide had on readings at the Salt River mouth during the 2010-2013 sampling.

Based on data from the Knysna Municipality database, unacceptably high *E. coli* counts were frequently measured in the Knysna CBD and Bongani Catchments, and in the Ashmead Channel. Compliance with the recommended limit is lowest at the Bongani River outflow (25%) and the Ashmead Channel (37%). Additional monitoring in 2018 showed very high *E. coli* spikes in the Bigai and Bongani headwaters (Sites 1c and 4c) in October, and throughout the Bongani Catchment in November. Of the 23 samples collected in 2018 in the Bongani Catchment, only 4 were below the recommended *E. coli* count. Historical data from 2012 shows similar findings. A considerable reduction in *E. coli* readings downstream of the reed beds on the Bigai was found both in data in this study, and in the 2012 study. Additional monitoring is recommended to confirm the hypothesised improvement in water quality due to the reed beds.

In conclusion, no TSS data was available but elevated turbidity data in the Bongani, Bigai and Salt catchments after storms may be cause for concern; elevated nutrient concentrations, conducive to eutrophic or hypertrophic conditions, were measured at most monitoring sites; and *E. coli* and nutrient concentrations were particularly high in the Bongani Catchment.

4.3 Waste Water Treatment Works

The Knysna Waste Water Treatment Works (WWTW) receives sewage from most neighbourhoods in Knysna. The WWTW is only designed to treat sewage, however studies have shown that stormwater runoff, groundwater ingress, and tidal flows are contributing to the influent to the WWTW (SSI, 2011). Stormwater ingress, in particular, could lead to excessive influent during high rainfall events, and consequent over-burdening of the WWTW. Monthly water quality data from January 2013 to June 2017 for the WWTW was supplied by the Knysna Municipality and was compiled from monthly data testing at a SANAS accredited laboratory. A water use licence was granted to the WWTW in 2014. Compliance with the licence conditions (DWS, 2014) is shown in Table 4-13 for the period January 2015 to June 2017.

Table 4-13: WWTW compliance with licence conditions

Parameter	Licence limit	Percentage compliance	Mean
Residual Chlorine (mg/ℓ)	0	0%	1.6
pH	5.5 - 7.5	100%	7.4
COD (mg/ℓ)	30	0%	93.1
TAN (mg/ℓ)	1	0%	35.5
NO_xN (mg/ℓ)	1.5*	90%	1.0
TSS (mg/ℓ)	10	14%	24.1
SRP (mg/ℓ)	1	55%	1.3

*Licence conditions actually refer to nitrates

Assuming that the pollutant concentrations were typical for the month, a basic pollutant load can be calculated by multiplying the concentrations by the volume of treated effluent. Mean pollutant loads were calculated as 115, 9, 107 and 8 kg/day for TAN, NO_xN, TSS and SRP respectively. These values can be compared to the 27 kg/day Total Inorganic Nitrogen (TAN + NO_xN) for the Knysna River estimated by Petermann *et al.* (2018). Based on these calculations the TIN contribution of the WWTW to the estuary was 4.5 times higher than the contribution of the Knysna River. Nutrient load estimates for the Knysna River vary, however, with Allanson *et al.* (2000) noting values of 0 - 140 kg/day for NO_xN and 0 - 12 kg/day for SRP for the Knysna River during flooding in 1996. The authors note that the upper limits of these ranges may be higher, as the flood peaks were not captured. Nevertheless, sustained pollutant loads of these magnitudes are of serious concern for the health of the estuary.

Lemley *et al.* (2014) provided nutrient load estimates for seven WWTW in the Gouritz Water Management Area, including the Knysna WWTW. The monitoring periods for the seven WWTW varied but typically data was from 2004 to 2013. Operational daily flows varied from 0.09 to 8.03 Mℓ/day. The Knysna WWTW treated the third highest effluent flows, and contributed the third highest TIN loads, and fourth highest SRP loads.

The authors calculated the estimated nutrient loads from the Knysna WWTW effluent using median concentration values for the period 2004 to 2013. The mean effluent flows for this period were approximately 5% lower than the mean from 2013 to 2017. The resultant SRP load of 14 kg/day was nearly

75% higher than the SRP load calculated for this study (8 kg/day). Conversely, the 42 kg/day TIN load calculated by Lemley *et al.* (2014) is nearly three times smaller than the load calculated as part of this study (124 kg/day). The changes in nutrient concentration in the WWTW effluent over time were assessed using a Kendall correlation analysis for a data set from 2004 to 2017. The analysis indicates a significant positive (increasing) trend in TAN and TIN, and a significant negative (declining) trend in NO_x and SRP in the WWTW effluent. The TAN concentrations in the WWTW effluent are shown in Figure 4-24.

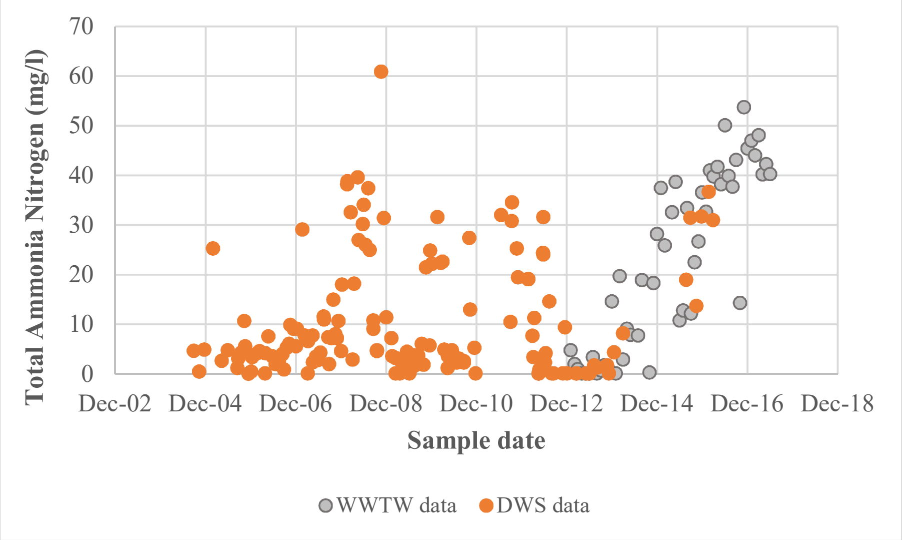


Figure 4-24: TAN concentrations in the WWTW effluent over time

TSS concentrations in the WWTW discharge were low when compared to other sites (Figure 4-6). Due to the sustained flows at the estuary, TSS loading is still a concern. Figure 4-21 and Figure 4-22 show that TIN and SRP concentrations at the WWTW were of concern when compared to other sites. A t test was used to compare concentrations at Site 5 in 2018, with the WWTW measurements in 2017. Site 5 is located where the WWTW outflow reaches George Rex Drive. TIN concentrations from the WWTW were significantly higher (mean of 43.8 mg/ℓ) than Site 5 (mean of 13.9 mg/ℓ). SRP concentrations at the WWTW were not significantly higher than Site 5 (means of 1.5 and 2.1 mg/ℓ respectively). The reduction may be:

- a result of dilution (although the similar SRP results seem to exclude this)
- indicative of a significant reduction in TIN concentrations since 2017 (however TIN concentrations were shown to be statistically similar to readings in 2010-2011), or
- a measurement error (however the testing is conducted at a SANAS accredited laboratory).

Using the KBP data, Site 5 still had the highest mean TIN concentrations of all the sites measured, and the 6th highest mean SRP concentrations.

At high temperatures and high pH values, ammonium is converted to un-ionized ammonia, which can be toxic to aquatic organisms. The proportion of un-ionized ammonia is also impacted by other factors such as CO_2, dissolved oxygen and the presence of other toxic substances (DWAF, 1996a), none of which information is available for this study. The WWTW water quality database includes pH values but not temperature values. For data between January 2013 and June 2017, pH values ranged from 6.8 to 7.9. Assuming temperatures between 15° and 25°, the concentration of un-ionized ammonia was calculated using the relevant table in the water quality guidelines for aquatic ecosystems (DWAF, 1996a). At a temperature of 15°, 20% of the data fell within the chronic range, and 65% of the estimated concentrations were above the acute limit for toxic un-ionized ammonia. At a temperature of 25°, 13% fell within the chronic range, but 76% were estimated to exceed the acute limit for toxic un-ionized ammonia. A dilution effect will occur when the effluent is discharged to the estuary, and at higher salinities ammonia concentrations will reduce, however, the estimated levels of un-ionized ammonia in the WWTW effluent are of serious concern.

The WWTW showed a very low compliance rate with its licence conditions, particularly for TIN, SRP and TSS. Elevated concentrations, combined with sustained high flows, lead to high nutrient and TSS loads to the estuary. The high concentrations of un-ionized ammonia could lead to negative impacts on ecosystems, and it is recommended that the high TAN levels in the WWTW effluent be managed. Elevated *E. coli* counts at the site where the WWTW drains under George Rex Drive (Site 5) could indicate inadequate treatment at the WWTW. Water quality concerns at the WWTW need to be urgently addressed.

4.4 Assumptions and limitations

Water quality data was limited to grab sampling. Grab samples only represent the situation at a particular point in time and may not be representative of the average or poorest water quality. If funding is available for continuous sampling, this should be considered for future research.

As part of this project nine water quality indicators were assessed. The research team selected these indicators as likely to give the best overall indication of water quality at a reasonably low cost. There may, however, be other significant contaminants that were not identified through this monitoring, such as heavy metals and hydrocarbons. The impact of salinity, and tidal flows on the initial monitoring sites has not been fully assessed. The data analysis conducted in this dissertation is based on a limited data set and on-going monitoring and analysis is recommended. Only outflows to the estuary from the northern and eastern catchments to the estuary were included in the initial water quality sampling. Impacts from Thesen Island, Leisure Isle, and the southern and western catchments have not been monitored.

5. Hydrological modelling

5.1 Detailed discussion of input parameters

The methods of sourcing rainfall, soils and flow level data are discussed in Section 3.4. For each of these parameters a more detailed analysis of the data itself is justified, and is discussed in this section.

5.1.1 Rainfall data

Rainfall data was obtained from the South African Weather Service (SAWS) for five rainfall stations in the Knysna Area, as shown in Figure 5-2. Two of the stations, Knysna-TNK (0014063W) and Concordia (00300900) had long daily rainfall records of 118 years and 108 years respectively. The other three rainfall stations have rainfall records of 22 to 31 years of data. The Knysna-TNK gauge is located on Thesen Island, whilst the Concordia gauge is located in the headwaters of the primary catchment of interest. According to the SAWS co-ordinates the Knysna Meer gauge is located in the tidal zone on the Southern side of the estuary. The Knysna gauge is located at the WWTW and the Kruisfontein gauge is located to the south east of the Bongani Catchment.

Figure 5-1 shows the cumulative rainfall for the two rainfall stations with long records (Knysna TNK and Concordia) for the period where both were operational. The graph shows how rainfall can be spatially distributed. The two stations are located only 3.5 km apart but the rainfall record for Concordia shows significantly higher rainfall when compared to rainfall recorded at Knysna-TNK. This is also demonstrated in the significant difference in Mean Annual Precipitation (MAP) for the Concordia and Knysna-TNK stations (936 and 748 mm respectively).

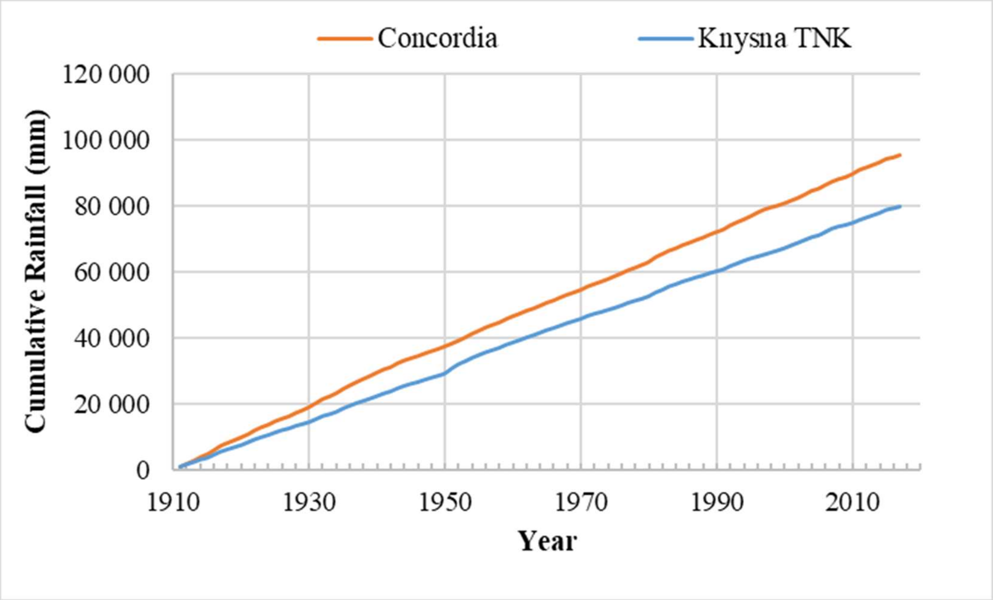
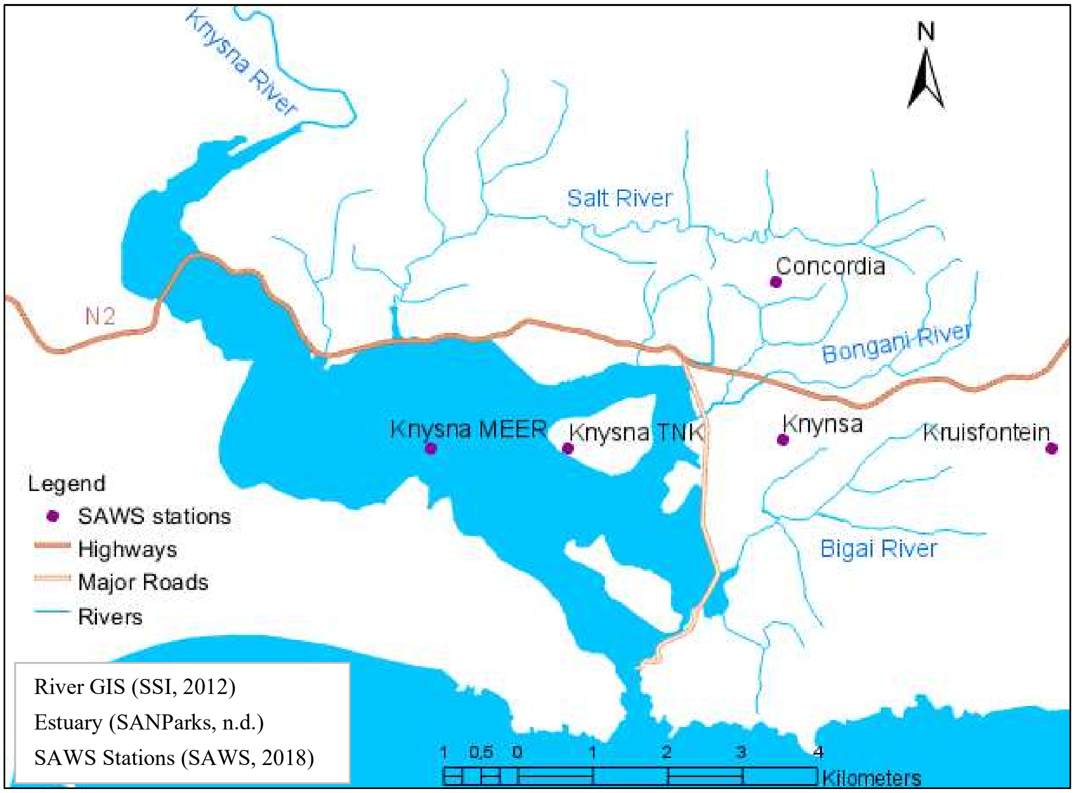


Figure 5-1: Cumulative Rainfall for two stations 1910-2017



River GIS (SSI, 2012)
Estuary (SANParks, n.d.)
SAWS Stations (SAWS, 2018)

Figure 5-2: Location of SAWS rainfall stations

An assessment was made of the reliability of the rainfall data for the two gauges. For Knysna-TNK, rainfall data for the period from 1901 to 2001 was obtained from the daily rainfall database (Lynch, 2004). Data extracted from the database includes patched data, in these instances data from nearby stations was used to supplement missing data. The degree of patching was 18% for this period. Data for the period 2001 to 2018 was obtained directly from the SAWS and does not include patched data. For this period there was no missing data but for 2% of the record (143 days), data was not taken on the day but was accumulated with the next reading. A mass plot is a common technique for assessing the consistency, and therefore reliability, of a rainfall station. The closer the mass plot is to a straight line the more consistent the historical rainfall record is. The mass plot for the Knysna-TNK gauge is shown in Figure 5-3. A linear trendline fitted to the data gives a high correlation coefficient (0.9997), indicating that the gauge is consistent for the length of record.

Similarly, the mass plot for the Concordia gauge has a high correlation coefficient (Figure 5-4). It should, however, be noted that post-1990 the daily Concordia data is unreliable, with rainfall data not recorded every day and significant rainfall accumulation before readings were taken. The results of this assessment indicated that both stations were consistent, with long records of reasonably reliable data. Data recorded at the Concordia gauge post-1990 could not be used for sub-monthly rainfall data.

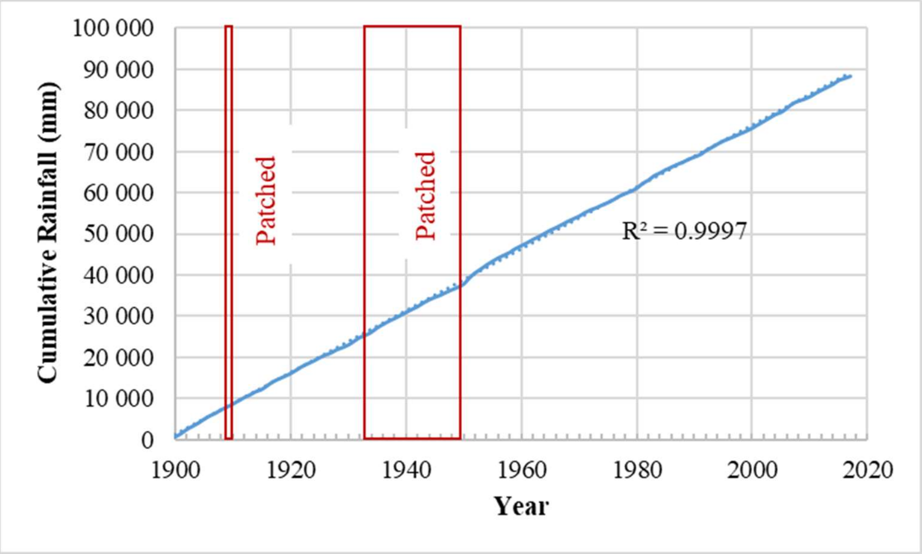


Figure 5-3: Rainfall Mass Plot for Knysna-TNK rainfall station

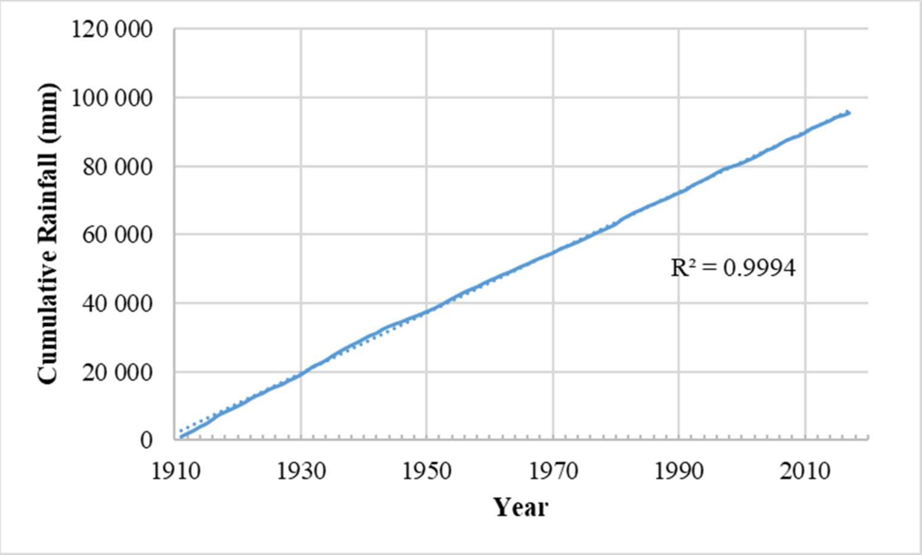


Figure 5-4: Rainfall Mass Plot for Concordia rainfall station

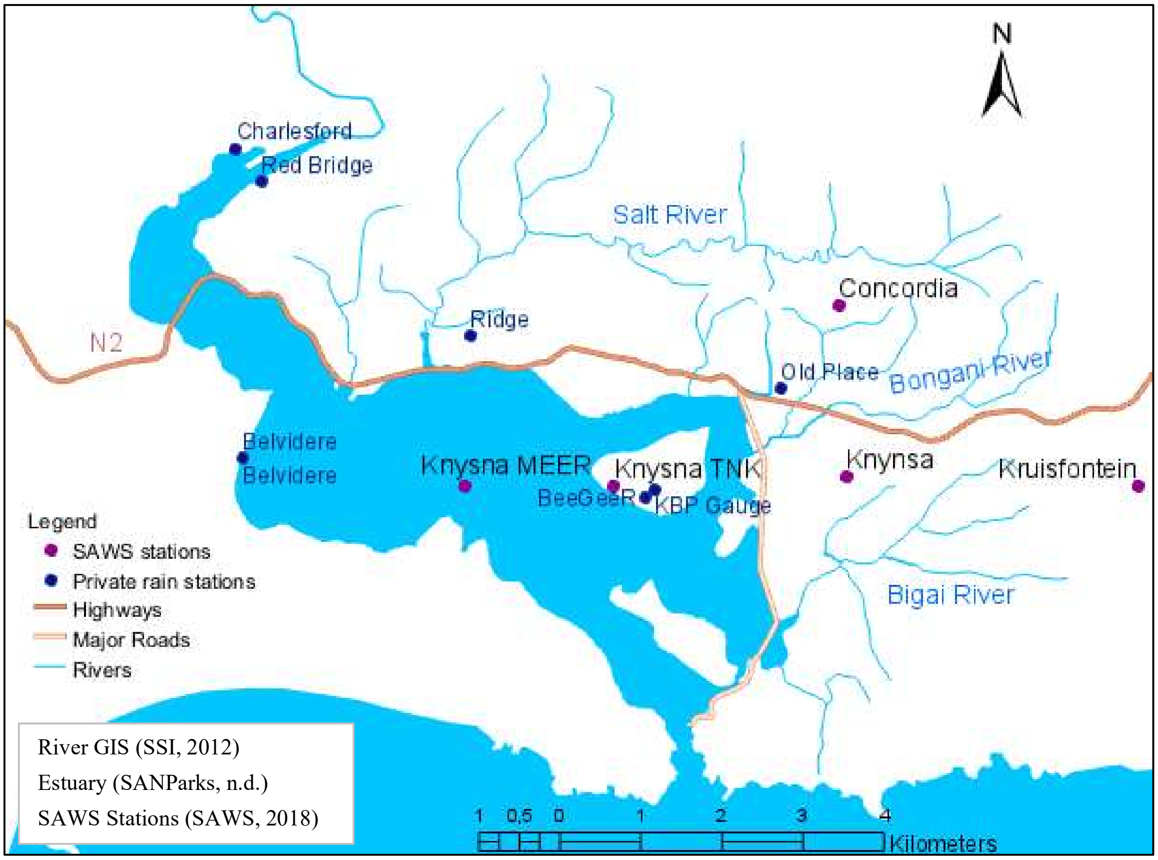
Rainfall data was required as an input to the hydrological model. During calibration of the model measured flow depths were compared to modelled flow depths in order to review and revise model assumptions. For the model calibration phase accurate and reliable rainfall data is required, but a short data period may be acceptable. The model was calibrated against flow level monitoring data collected between April and August 2018 and therefore reliable rainfall data was required for this period. The rainfall time step should ideally be significantly less than the catchment time of concentration (Ormsbee, 1989), and Berne *et al.* (2004) suggest that time intervals of 3 minutes and 5 minutes be used for catchments of 100 to 1000 ha respectively (both as cited by Fisher-Jeffes (2015)). The times of concentration for the two catchments that were used for model calibration were calculated using the SCS and Kerby equations. The times of concentration were calculated as 17 minutes and 70 minutes. One catchment is 40 ha, whilst the other is 360 ha. Ideally the rainfall interval should then be 5 minutes or less.

Only one of the rainfall stations for which data was supplied by the SAWS records sub-daily rainfall. Hourly rainfall data was available for a 22-year record for the Knysna gauge (0014123). Five-minute rainfall was available from the KBP, for a gauge located on Thesen Island. To supplement this data, requests for rainfall data were placed in local newspapers and on the KBP's website. Data from seven private rainfall stations was obtained, and the approximate locations of these gauges are shown in Figure 5-5. One of these gauges recorded monthly data, three recorded daily data, one had hourly data, one 20-minute records and one recorded five-minute data. Of these gauges the most relevant in terms of proximity, appropriate time span and sub-daily rainfall were the SAWS Knysna and the KBP gauges. Data for the other stations was useful in helping to assess the reliability of these two gauges, and the degree of spatial variability of the rainfall across the catchment area. The details regarding the rainfall stations are supplied in Table 5-1.

Table 5-1: Rainfall data summary

Station Name	**Source**	**Location**	**Proximity***	**Record Duration**	**Start Date**	**End Date**	**Recording interval**	**MAP**
			km	**years**				**mm**
Kruisfontein (BOS)	SAWS	Kruisfontein	1.6 – 5.0	31	1987	2018	Daily	925
Concordia (BOS)	SAWS	Concordia	0.0 – 3.0	108	1911	2018	Daily but post 1990 unreliable daily	936
Knysna	SAWS	Fisher Haven	0.1 – 3.6	22	1996	2018	Hourly	847
Knysna (TNK)	SAWS	Thesen Island	1.8 – 6.2	99 years, Patched 118 years	1900	2018	Daily	748
Knysna (MEER)	SAWS	Lake Brenton	3.6 – 7.9	26	1989	2015	Monthly	656
KBP Gauge	KBP	Thesen Island	1.3 – 5.7	3	2015	2018	Hourly, 5 min from April 2018	497
Belvidere	Private	Belvidere	6.2 – 10.6	< 1 year	2018	2018	5 min	/
Ridge	Private	Paradise	3.5 – 7.5	< 1 year	2018	2018	20 min	/
BeeGeeR	Private	Thesen Island	1.4 – 5.8	1.5	2015	2018	Daily	321
Red Bridge	Private	Red Bridge	6.4 – 10.2	10	1994	2003	Monthly	691
Belvidere	Private	Belvidere	6.2 – 10.6	5	2012	2017	Daily	780
Old Place	Private	Old Place	0.1 – 3.8	1	2017	2018	Daily	659
Charlesford	Private	Charlesford Weir	7.0 – 10.7	5	2013	2018	Hourly	/

* Distance between the gauge and the closest and furthest points of the Bongani Catchment



River GIS (SSI, 2012)
Estuary (SANParks, n.d.)
SAWS Stations (SAWS, 2018)

Figure 5-5: Location of SAWS and private rainfall stations

Given the short records for the sub-daily rainfall stations it was difficult to use measures like mass plots or an assessment of MAP to assess the reliability of the gauges. Instead Figure 5-6 shows the cumulative monthly rainfall for seven gauges for the period where data was available for the KBP gauge (from January 2015). As for the longer record, the Concordia rainfall station shows higher rainfall than the Knysna TNK gauge. Of concern is the relatively low rainfall recorded at the KBP gauge for this period, particularly as it is situated in very close proximity to the Knysna-TNK gauge.

Flow level measurements used for the model calibration were measured between April and August 2018. Rainfall data for the calibration period was only recorded at five of the rainfall stations shown in Table 5-1. The cumulative rainfall for the five stations for the calibration period is shown in Figure 5-7. For this period the KBP rainfall data was comparable with adjacent rainfall stations. Four of the stations fell within a 1.4 km radius, with only the Kruisfontein gauge located further away. Within this 1.4 km radius, over the four-month period the cumulative rainfall varied from 130 mm measured at the Knysna gauge, to 160 mm measured in Upper Old Place, indicating the degree of spatial variability associated with short rainfall events.

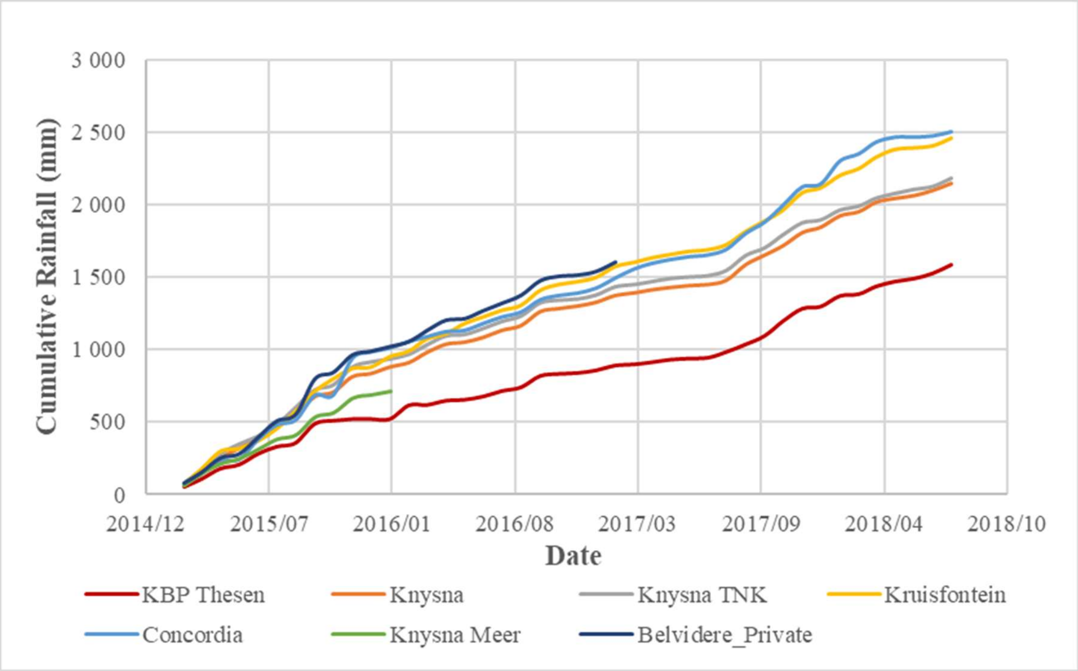


Figure 5-6: Cumulative monthly rainfall for multiple stations 2014-2018

Of these five rainfall stations, three recorded rainfall daily, the Knysna gauge was measured hourly, and only the KBP data was available at a 5-minute recording interval. The KBP gauge has relatively low cumulative rainfall for the early part of the record, as shown in Figure 5-6, however for the model calibration period the rainfall data is comparable with other stations in close proximity as shown in Figure 5-7. The gauge is unfortunately not situated within the Bongani Catchment. The rainfall gauge is located 1.3 km from the Bongani River outflow, and 5.7 km from the furthest point, in the upper headwaters. The Kruisfontein gauge is located closest to the upper headwaters of the Bongani River, and Figure 5-6 shows that measurements at this gauge were comparable to the Concordia gauge, which is located in the upper headwaters. The difference in rainfall patterns between Thesen Island and the upper headwaters of the Bongani River can therefore be estimated by looking at the KBP and Kruisfontein gauges for the calibration period. The cumulative rainfall at the Kruisfontein gauge (164 mm) was higher than the KBP gauge (150 mm), and the rainfall patterns showed rainfall on the same dates, but of different magnitudes. Rainfall data at the KBP gauge is therefore not an ideal measurement of the rainfall experienced in the upper headwaters of the Bongani River, however the gauge has 5-minute data, is relatively close to the site, and is comparable with gauges in close proximity. Rainfall data recorded at the KBP gauge was therefore used for the model calibration.

5.1.2 Soils

Soil types were obtained from the ARC land type maps (Land Type Survey Staff, 2006a). The three land types present in the Bongani Catchment are DB26 (Duplex Soils on Mid-slopes), GA2 (Fixed Dunes) and IA39 (Alluvial Valley Deposits). The area classified as DB26 only makes up 5% of the Bongani Catchment area, to the north of the N2 highway. The land type in the lower reaches of the catchment is classified as IA39 and makes up 13% of the catchment. The remaining 82% of the catchment is classified as Fixed Dunes (GA2). Texture classes for land use types are shown in Table 5-2.

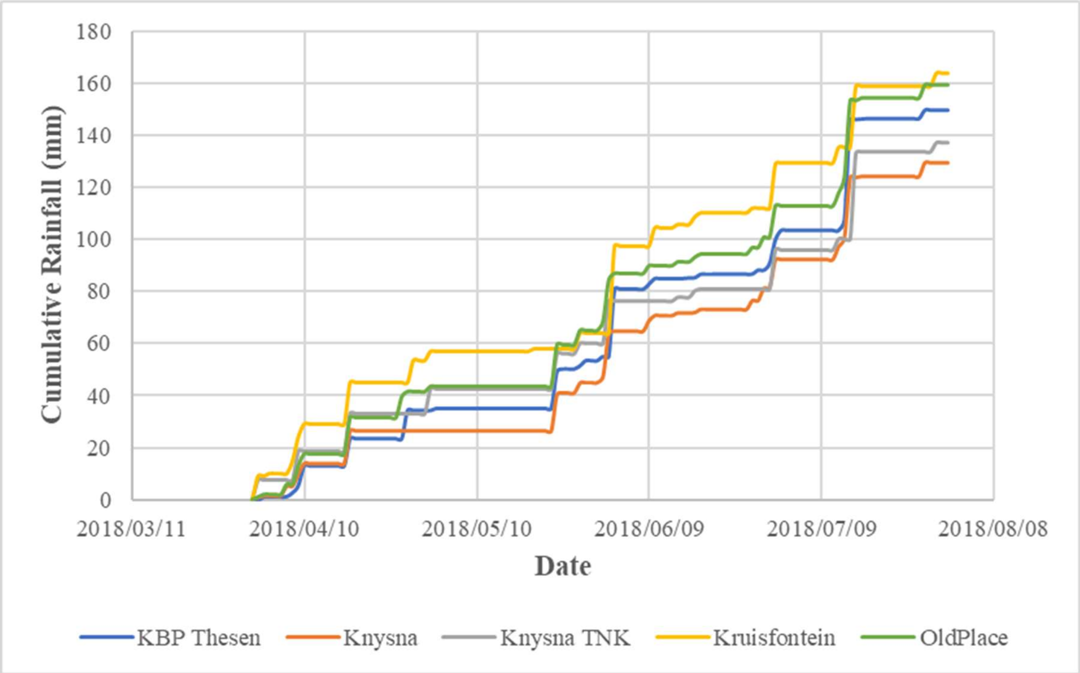


Figure 5-7: Cumulative daily rainfall for the calibration period

Table 5-2: 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	32.0%	fine/ medium Sand - Sandy Clayey Loam	45%	medium Sand	66.4%
Loam fine Sand - Sandy Loam	20.0%	fine/ medium Sand - Loamy Sand	24%	Loam fine/ medium Sand - Sandy Loam	16.1%
medium Sand	15.0%	Loam fine/medium Sand - Loam	11%	medium Sand - Loamy Sand	6.4%
Loam medium Sand - Sandy Clayey Loam	10.0%	Loam fine/medium Sand - Sandy Loam	6%	Loam medium Sand - Sandy Loam	4.0%
fine/medium Sand	9.0%	fine Sandy Loam - Clayey Loam	4%	fine/medium Sand - Loamy Sand	2.7%
fine Sand - Loamy Sand	8.0%	Clayey Loam - Clay	3%	fine Sand - Sandy Loam	2.4%
medium Sand	3.0%	Rocks	4%	Loam fine Sand - Sandy Loam	2.0%
Streams	3.0%	medium Sand	2%		
		Loam fine Sand - Sandy Loam	1%		

Green-Ampt parameters were assigned for the different texture classes and weighted averages were then calculated for each land type. The weighted average values for each of the soil types are shown in Table 5-3. Parameters obtained using the classification from WR2012 (Bailey & Pitman, 2015b) for the whole Knysna area are included.

According to the ARC classification shown in Table 5-2, the dominant textures are Loamy Sand – Sandy Loam, Sand – Sandy Clayey Loam and Sand for land types IA39, DB26 and GA2 respectively. In contrast the WR2012 classification for the whole of Knysna is ‘moderate to deep Clayey Loam’. Clayey Loam has a finer particle grading and higher clay component than any of the dominant soil types classified by ARC. Soils with finer particle gradings and higher clay components typically have higher suction heads and lower conductivity and initial soil moisture deficits. It therefore follows that the WR2012 suction head is higher, and the conductivity and initial deficit are lower than those calculated for all ARC land use types (Table 5-3). Higher suction heads and lower conductivities and initial deficits will lead to lower infiltration rates, and consequently higher runoff, as demonstrated in the sensitivity analysis (Section 5.2.1)

Land use types identified in each catchment were used to calculate weighted average Green-Ampt parameters for each catchment. The ARC parameters generated no run-off from pervious surfaces for any of the modelled events and therefore for the model sensitivity analysis the WR2012 values were input as the starting parameters, in order to understand the sensitivity of the model to these parameters (if no runoff is generated then the model will be completely insensitive to these parameters). The WR2012 parameters were also used as the starting input parameters for model calibration, so that combined impervious and pervious runoff could be calibrated against observed flow data.

Table 5-3: Green-Ampt parameters for different land use types

Source	Land use type	Description	Suction head	Conductivity	Initial Deficit
			mm	mm/h	
ARC	IA39	Alluvial Valley Deposits	96.6	99.8	0.279
ARC	DB26	Duplex Soils on Mid-slopes	107.8	105.7	0.265
ARC	GA2	Fixed Dunes	58.8	182.0	0.328
WR2012	All Knysna	Moderate to deep Clayey Loam	208.8	2.0	0.146

5.1.3 Flow level data

5.1.3.1 Automated sensors

The automated sensors measured flow depths to the nearest 10 mm. Sources of uncertainty included the level of noise associated with the sensors, and a daily measurement fluctuation. Figure 5-8 shows both the raw measurement data and a half hour moving average for the Vigilance Drive sensor for three dry days. The half hour moving average has been applied to reduce the noise associated with the data.

The source of the daily fluctuation was not identified. In a previous study the automated sensors were found to be sensitive to temperature and therefore a temperature correction was included. A temperature sensor inside the junction box measured temperature and corrected the water level readings accordingly. For this study the data transmitted to the server already had this temperature correction applied. The temperature data and uncorrected data were not transmitted. Ambient air temperature data was available for the KBP gauge, which was located approximately 1.7 and 1.9 km from Sites 4a and 4b respectively. Figure 5-9 and Figure 5-10 show the ambient temperature measurements and water level measurements over a number of dry days for the Vigilance Drive Drain and Bongani River sensors respectively.

There was a possible correlation between temperature data and the flow depth fluctuation but other factors may also have affected the flow depth fluctuation. If the daily flow depth fluctuation was a result of temperature changes then the temperature correction already applied was insufficient. This could be due to the location of the temperature sensor within the junction box, which was likely to be more insulated and therefore experienced lower temperature fluctuations than the ambient temperature. It was not possible to confirm this supposition as temperature data within the box was not transmitted to the server. Due to the uncertainty in the temperature and water level correlation, and the fact that a temperature correction was already applied, no additional correction factor was used. For both the Vigilance Drive and the Bongani River sensors, the daily fluctuation range for dry days was approximately 3 cm. This was considered to be well within the accuracy range of the study, given the considerably sources of uncertainty.

All flow level data mentioned henceforth in this dissertation refers to a half hour moving average of the raw data. No correction factor was applied to account for the daily fluctuations, and the dry weather flow depths (base flow) were calculated based on mean dry weather flows. It was not possible to determine any seasonal fluctuation in base flows within the accuracy of the measurement equipment, and therefore constant base flows were assigned for each channel. The base flows were calculated from the mean of the measurements recorded over 18 dry weather days for the Bongani sensor and seven dry weather days for the Vigilance Drive sensor. There was less fluctuation in the Vigilance Drive Drain water levels, and therefore a shorter period was considered representative. There was considerable uncertainty associated with both estimates, as bed roughness and errors in flow depth measurement have a much more significant effect for such low flows than for high flows. In addition, at very low flows the flow might not extend across the full channel section, and calculations based on flow depth would not be accurate. The source of the base flows is not known but could be groundwater recharge. A high-level calculation of potential average groundwater recharge indicated that the calculated base flows were likely too high. The base flows could therefore not be used in load calculations, as they would likely overestimate pollutant loads.

At the Vigilance Drive Drain observed flow responses preceded rainfall events, which is clearly not feasible. The source of this measurement error was not established, although it was likely an error in the recording of the correct time data for the observed flow depths. A time correction was therefore applied to the observed water level data so that flow responses matched rainfall data.

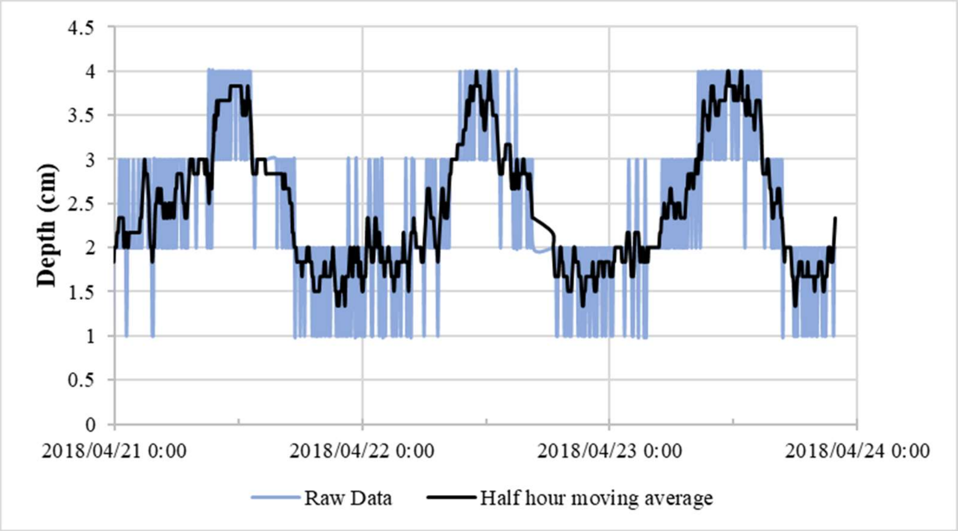


Figure 5-8: Vigilance Drive Drain water level measurement – no rainfall

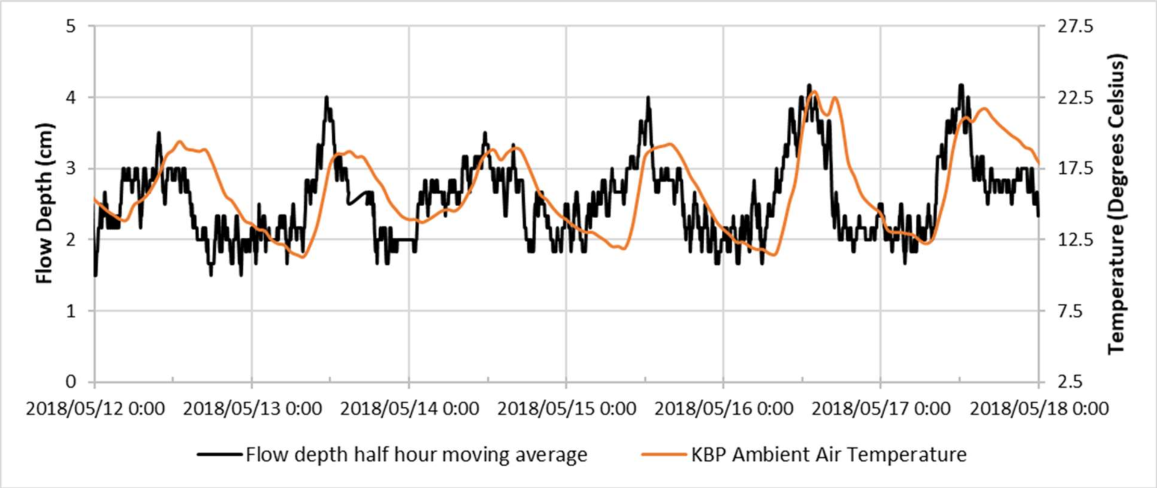


Figure 5-9: Vigilance Drive Drain flow depths and ambient temperatures

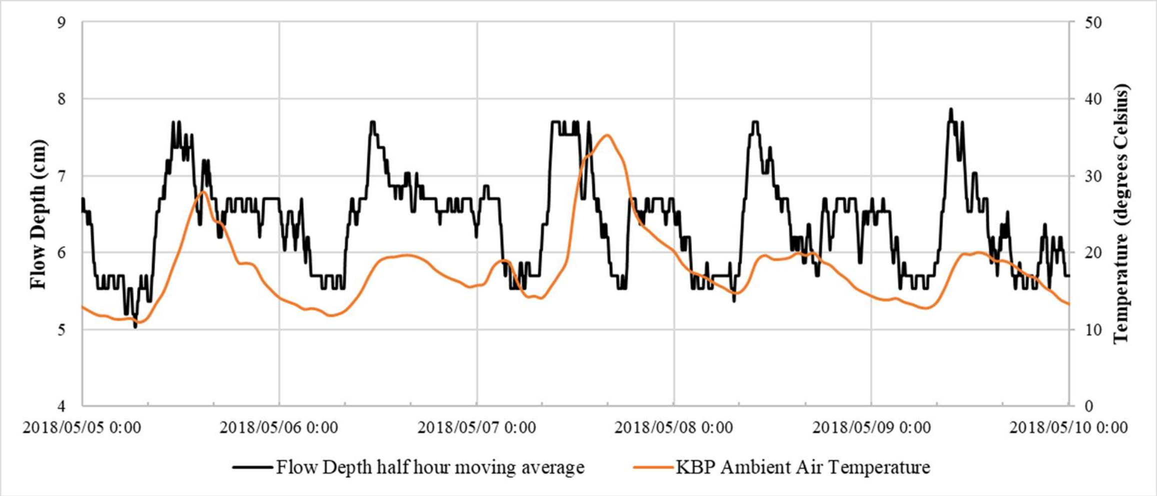


Figure 5-10: Bongani River flow depths and ambient temperatures

5.1.3.2 Chalk sticks

The chalk sticks provided useful data for the Vigilance Drive Drain when the automated sensors were not functioning. The depth of flow at the Vigilance Drive Drain response was measured with both the flow level device and the chalk stick for three rainfall events. The measured highest flow depth could then be compared for these three events. For one of the events (measured 27th of July 2018), the chalk stick reading was unrealistically high (420 mm flow depth for the 38 mm rainfall event), and the maximum depth measured on the automated sensor was more feasible (170 mm). There was a reasonable correlation between maximum water level depths measured using the chalk sticks and the automated sensors for the other two rainfall events. The depths measured using the chalk sticks were 17% and 18% (or 20 and 25 mm) higher than those measured with the automated sensor. There was some uncertainty in the measurement of the distance between the base of the chalk stick and the channel base, and all the chalk stick measurements were reduced by 20 mm so that the flow depths corresponded more closely for these two events.

The chalk stick could only be read to an accuracy of 10 mm. In some cases, the chalk washed off in a distinct line that allowed the measurement to be easily read off, in other cases the depth was less easy to accurately determine. The sticks were simple, effective and reasonably reliable, although in some instances the sticks were stolen. These measurement devices required manual effort as the KBP was required to go to site and read the high-water mark between storms, and recoat the sticks with chalk.

5.2 Model results

5.2.1 Sensitivity analysis

A sensitivity analysis was undertaken for monitoring stations at Vigilance Drive and the Bongani River. Two of the calibration storms were assessed for each location, one small storm that did not generate modelled runoff or generated little modelled runoff from pervious areas, and one larger storm that included the impacts of changes in pervious surface parameters. For each site and storm the impact of varying the input parameters by - 50% / +50% was assessed. The parameters varied were catchment width, catchment slope, percentage imperviousness, Manning's *n* (N) and depression storage (D) for impervious and pervious surfaces, and percentage of the impervious area that has no depression storage. Routing between impervious and pervious surfaces was simulated using the '% routed parameter', which also formed part of the sensitivity analysis. The final three parameters assessed were the Green-Ampt soil parameters of suction head, conductivity and initial deficit. Sensitive model parameters were identified through the sensitivity analysis, and were the focus of the calibration effort. Model calibration against observed data is essential to reduce the uncertainty associated with hydrological modelling.

5.2.1.1 Bongani River

For the Bongani River the sensitivity results of the small storm (3 mm rainfall) are shown in Figure 5-11 and Figure 5-12 for the peak flow and flow volume respectively. Figure 5-13 and Figure 5-14 show the impacts of a larger storm (25 mm rainfall) on peak flow and flow volume respectively. Sensitivity is expressed as the change in value from the base value, divided by the base value. For the small storm, both peak and volume were insensitive to changes in the pervious area inputs, as well as the Green-Ampt parameters. This was expected, as no modelled runoff was generated off pervious surfaces for this storm. The peak flow was most sensitive to percentage imperviousness, impervious depression storage and percentage routed. Peak volume demonstrated a similar sensitivity, but percentage routed and fraction of zero impervious surfaces were equally sensitive.

Neither peak flows or volumes were particularly sensitive to catchment width, slope or Manning's roughness. These findings are generally in line with the findings of Krebs *et al.* (2014); Fisher-Jeffes (2015) and Lee *et al.* (2017), with the exception of the insensitivity of pervious factors. The relative insensitivity of flow peaks and volume to changes in catchment width and slope are supported by similar finding of Krebs *et al.* (2014) and Lee *et al.* (2017). Fisher-Jeffes (2015) found that peak flows were affected by changes in catchment width. For this catchment, peak flows were found to be relatively insensitive to changes in Manning's roughness for impervious surfaces, which is contradictory to the findings of both Krebs *et al.* (2014) and Fisher-Jeffes (2015). Generally, flow volume was found to be less sensitive than peak flows.

For the larger storm the model was found to be particularly sensitive to changes in the Green-Ampt parameters, followed by percentage imperviousness and pervious depression storage. Impervious depression storage, percentage routing and fraction of impervious area with no depression storage were found to be relatively insensitive. Both peak flows and volumes were found to be sensitive to changes in catchment width and Manning's *n* for pervious areas. These findings can be explained by the substantial proportion of the catchment linked to this monitoring point (86%) that was classified as pervious areas.

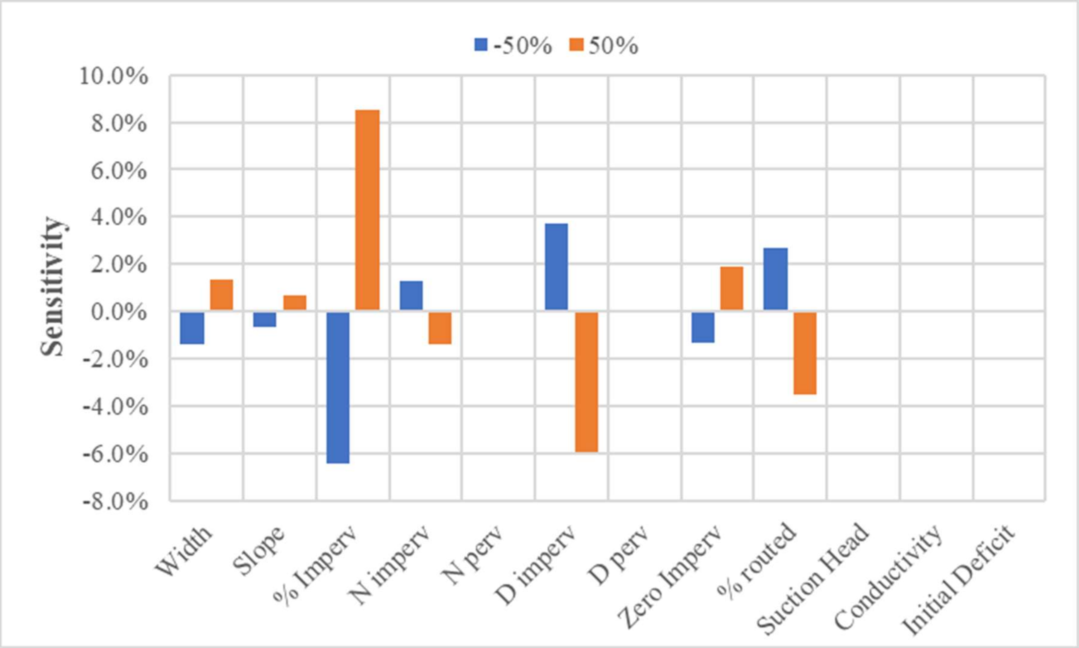


Figure 5-11: Bongani River peak flow sensitivity for a small storm

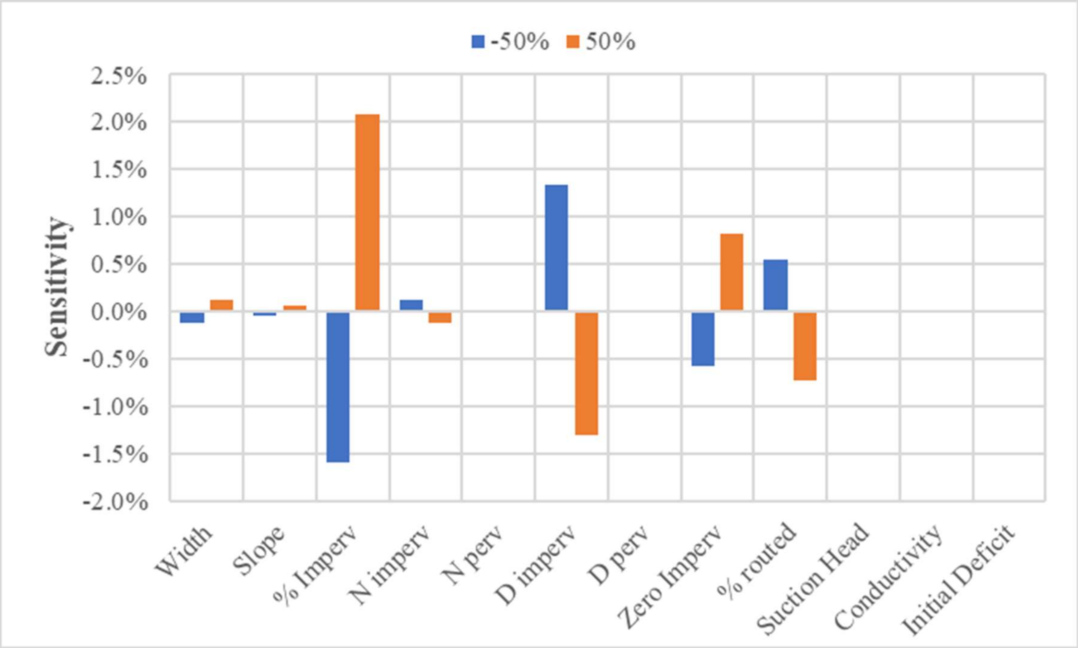


Figure 5-12: Bongani River flow volume sensitivity for a small storm

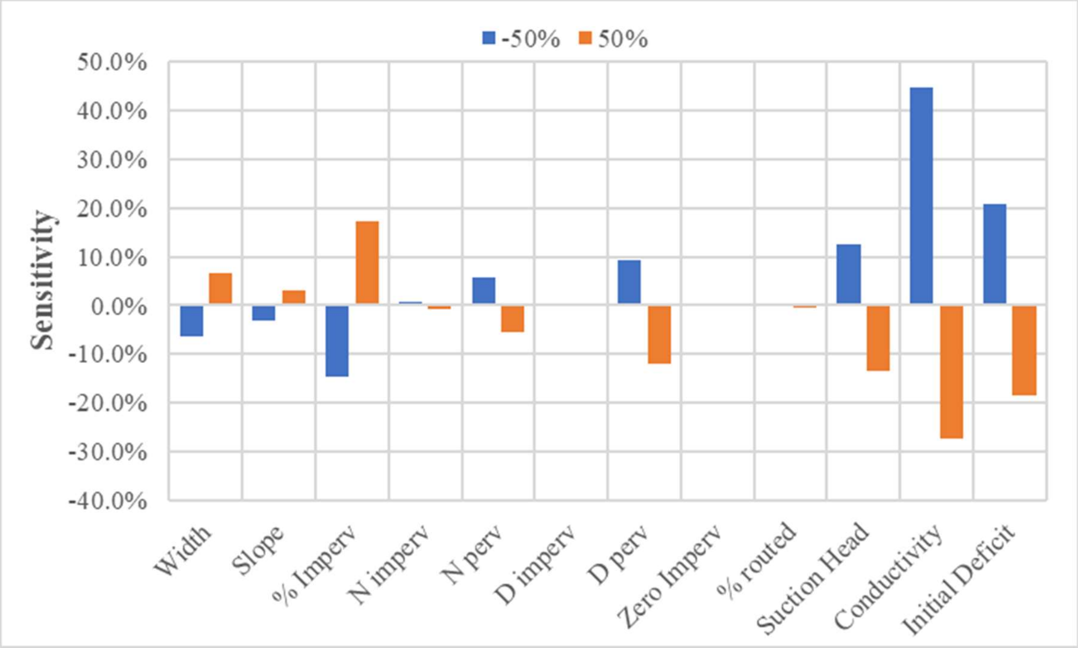


Figure 5-13: Bongani River peak flow sensitivity for a larger storm

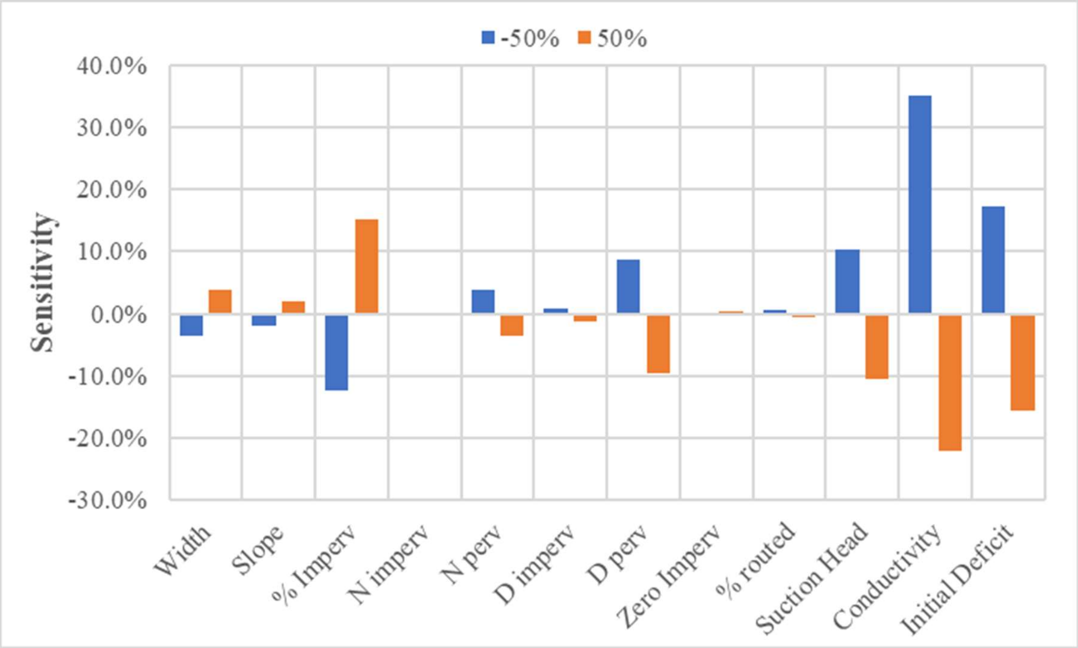


Figure 5-14: Bongani River flow volume sensitivity for a larger storm

5.2.1.2 Vigilance Drive

A similar assessment was undertaken for the Vigilance Drive Drain with a relatively small storm (11 mm rainfall), which generated a small amount of pervious runoff, and a larger storm (38 mm rainfall). The results are shown in Figures 5-15 to 5-18. The sensitivity analyses for both peak flows and volumes for the small storm were dominated by sensitivity to percentage imperviousness. Part of this extreme sensitivity to imperviousness may be attributed to the sensitivity analysis method. The Vigilance Drive catchment had a significantly higher proportion of imperviousness (57%) and therefore changing this value by - 50% / +50% results in values of 29% / 86%. The percentage imperviousness for the Bongani Catchment was only 14%, which results in values of 7% to 21%, and therefore the effect of changing this parameter was less extreme.

Green-Ampt parameters, catchment width and impervious depression storage were found to be the next most sensitive parameters for peak flows. Flow volumes were most sensitive to percentage routed, Green-Ampt parameters, and impervious depression storage.

A similar sensitivity was evident for the larger storm for Vigilance Drive, with percentage imperviousness, conductivity and flow width the most sensitive parameters for peak flows. The sensitivity to catchment width is supported by the findings of Fisher-Jeffes (2015) but contrary to the findings of Krebs *et al.* (2014), and may be the result of the smaller and more responsive catchment. For larger storms the peak flow was more sensitive to Manning's roughness for impervious areas (supporting the findings of Fisher Jeffes and Krebs) and was insensitive to depression storage and the fraction of the impervious area that has no depression storage. The catchment was small, with a large impervious surface area and thus would have a quick response to rainfall. During large storms, the depression storage should become a negligible factor in determining peak flows. Flow volumes were primarily impacted by the percentage imperviousness and the Green-Ampt parameters. The sensitivity to Green-Ampt parameters shows the impact that pervious areas can have on flood peaks and volumes for larger storms, even where the catchment has a high impervious fraction.

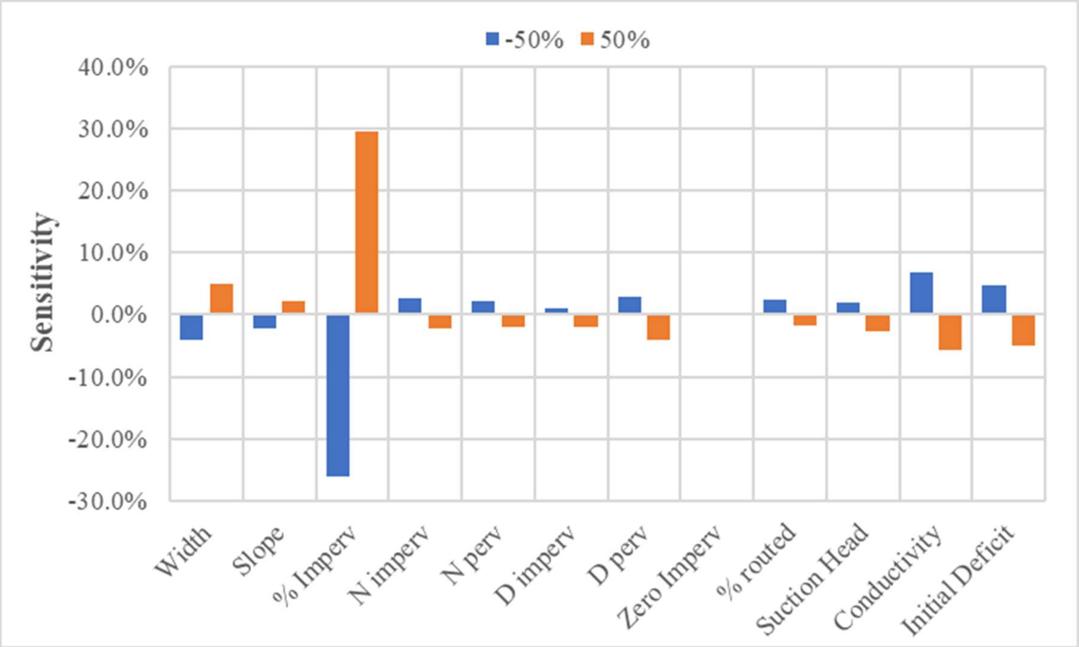


Figure 5-15: Vigilance Drive Drain peak flow sensitivity for a small storm

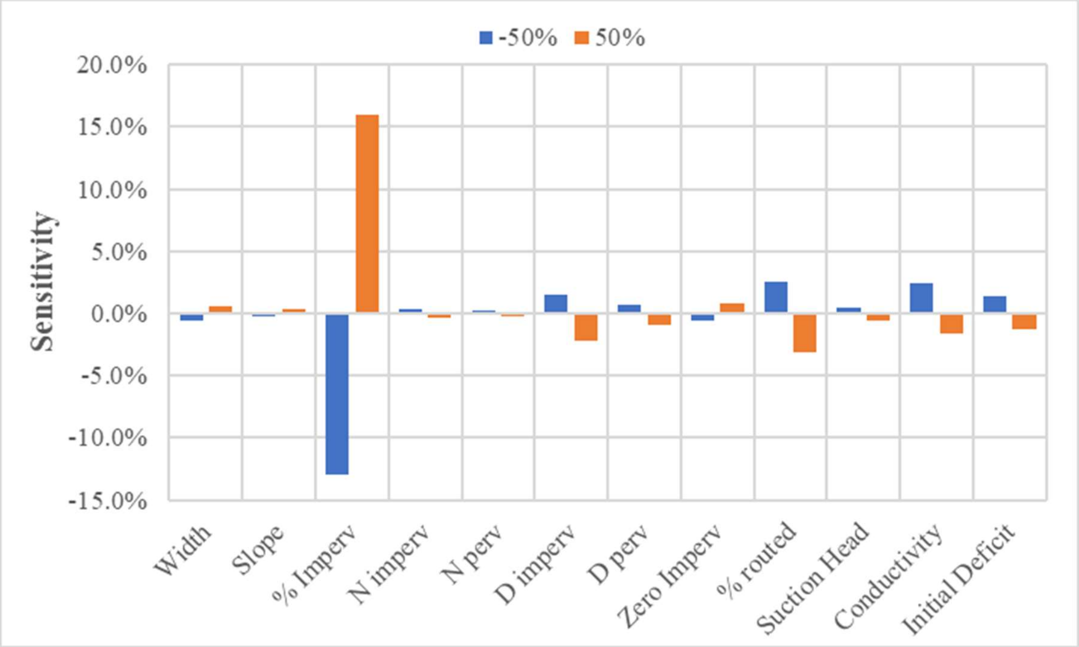


Figure 5-16: Vigilance Drive Drain flow volume sensitivity for a small storm

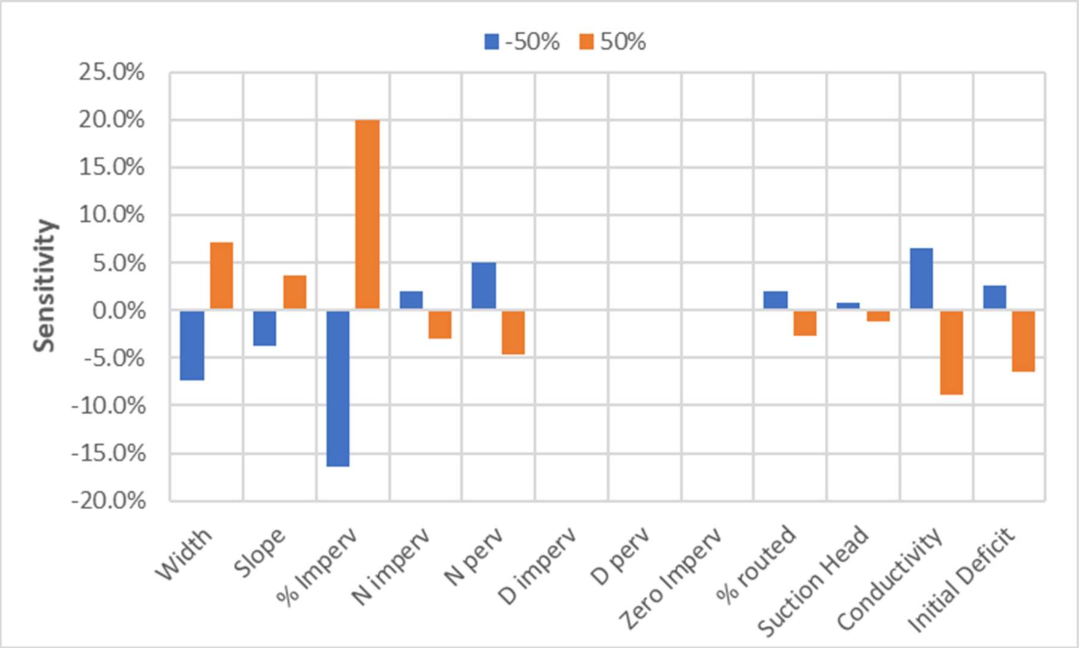


Figure 5-17: Vigilance Drive Drain peak flow sensitivity for a larger storm

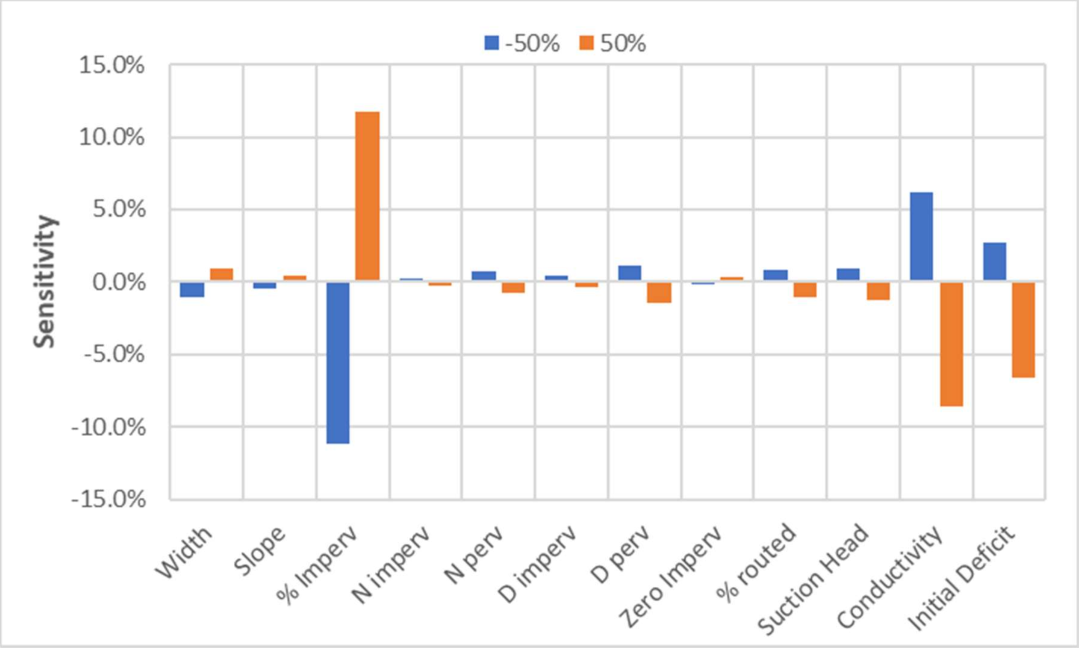


Figure 5-18: Vigilance Drive Drain flow volume sensitivity for a larger storm

5.2.2 Calibration and validation

For model calibration and validation the PCSWMM model was run for a continuous simulation and then modelled response to particular events was compared to the observed data. The model was run for at least seven days preceding the rainfall events used for calibration and validation, to minimise the impacts of assumptions regarding antecedent conditions.

The SRTC tool in PCSWMM was used to assist in model calibration. The tool allows the user to move toggle buttons to assess the impact that changes in input parameters will have on modelled flows. A manual calibration was then undertaken where input parameters were varied in accordance with the guidance from the SRTC tool. The input parameters were limited by realistic boundary values, as determined from the literature review. The same parameters selected for the model sensitivity analysis were varied during model calibration, and typically the parameters identified as most sensitive were the focus of calibration effort.

The modelled response to the selected rainfall events was compared to the observed flow data. For each calibration/validation event the modelled performance was assessed in terms of the six performance functions that PCSWMM provides, as well as peak flow and flow volume comparisons. The model performance as assessed by three of the performance functions is reported in this dissertation: Integrated Squared Error (ISE), Nash-Sutcliffe Efficiency (NSE) and coefficient of determination (r^2). ISE is a measure of the difference between modelled and observed data, and therefore the closer the ISE value is to zero, the better the correlation between modelled and observed data. NSE values can vary from $-\infty$ to 1. NSE values of less than zero indicate that using the mean value of the observed data would give a better approximation than using the modelled flows. The closer an NSE value is to 1, the better the modelled and observed data correlate. The coefficient of determination is a measure of the variance of modelled flows from observed flows, and the closer the r^2 is to 1, the better the correlation between the flows. All the performance measures were used as an indication of the acceptability of the model calibration, and therefore the degree of uncertainty associated with the modelling.

5.2.2.1 Vigilance Drive

The flow depth response to rainfall in the Vigilance catchment was measured for 13 rainfall events, with some larger storms (38 mm, 26 mm and 18 mm). Unfortunately, the large storm on the 7th - 8th of September 2018 (140 mm of rainfall) was not captured due to an equipment fault, and theft of the chalk stick. Runoff response to three of the rainfall events was measured with both the flow level device and the chalk stick, four were measured only with the chalk sticks and the remaining six were measured only with the flow level device. An attempt was made to ensure that both the calibration and validation events had high and low rainfall events, and events measured using both the chalk sticks and the automated sensors. The data was split with approximately 2/3 of the data used for calibration, and 1/3 for validation.

Eight rainfall events were used for model calibration, with the remaining five used for validation. The rainfall events and measured rainfall are recorded in

Table 5-4 for calibration events, and Table 5-5 for validation events. The chalk sticks only record the highest water level for any given storm, which was converted to a peak flow using Manning's equation.

The results of the model calibration and validation are presented in

Table 5-4 and Table 5-5 respectively. For low rainfall events (4 mm or less) the model calibration and validation were both very poor. For these low rainfall events the observed flow response was significantly higher than the modelled response. Attempts to increase the catchment response for low rainfall events resulted in unrealistic peaks for higher rainfall events. The model inputs that primarily affect low or early runoff, for example storage, were varied but a successful calibration was not achieved. If the model is to be used for modelling of very low flow events then this discrepancy will need to be further investigated as part of future research.

The calibration for larger events was acceptable with Integrated Square Errors (ISE) rated as 'very good' or 'excellent' and coefficients of determination of 0.66 to 0.83. The Nash-Sutcliffe Efficiency (NSE) values were particularly low for the low rainfall events and for the largest storm (14th of July). The poor NSE rating for the large storm is the result of higher modelled peak values, and the fact that a second peak recorded in the rainfall record was not reflected in the observed runoff. The observed and modelled runoff for the larger rainfall calibration events are shown in Figure 5-21. The mean peak flow error for the larger storm events was +5%. The Vigilance Drive Catchment is relatively small with a high impervious fraction, which led to quick response times. The half hour moving average used on the observed data therefore had a damping effect on peaks, which could lead to an underestimation of peak flows in the model. The damping effect was not an issue for the chalk stick readings. A comparison of the observed and modelled peaks flows is shown in Figure 5-19.

The volume errors were particularly high for the low rainfall events. The model also underestimated event flow volumes for larger events, with a mean error of -14%. For all events the runoff response to lower rainfall (before or after the main peak flows) is typically underestimated in the model. A comparison of the observed and modelled flow volumes is shown in Figure 5-20. The model validation showed very similar trends to the calibration, with mean peak flow and volume errors for the larger events of and -12% and -10% respectively. The peak flow error was strongly influenced by a chalk stick reading error of -56%, which could be due to an equipment fault. Calibrated input data is provided in Appendix B.

The PCSWMM runoff and routing errors were -0.2% and -0.3% respectively for the Vigilance Drive model, and were deemed to be acceptable.

For the calibrated model no runoff was generated from pervious areas, including for the largest storm. This result was unexpected for the large storm, however the high infiltration capacity of the catchment, and the relatively dry period preceding the storm could account for no runoff from pervious areas. This meant calibration of the soil parameters was not possible, other than to note that the soil infiltration parameters indicated a soil with a infiltration capacity at least equal to that of silt loam (as determined from Table A2 in Krebs *et al.* (2014), reproduced from Rawls *et al.* (1992); Oram (2012)). This corresponded with the ARC soil parameters for the Vigilance Drive Catchment, which have a high infiltration capacity. Additional observed data, in particular for larger storms, would be required to confirm this finding. For future research it would also add value if a gauge location could be found to monitor runoff generated from pervious areas.

Table 5-4: Results of calibration at Vigilance Drive Canal

Event date	Rainfall	Integral Squared Error (ISE)	Nash-Sutcliffe Efficiency (NSE)	Coefficient of determination (R^2)	Peak Flow Error	Volume Error
	mm				%	%
24/05/2018	14.3	n/a*	n/a*	n/a*	-20%	n/a*
29/05/2018	3.2	n/a*	n/a*	n/a*	-78%	n/a*
27/06/2018	1.6	very good (5.34)	-0.15	0.3	-75%	-37%
30/06/2018	2.6	very good (3.20)	0.36	0.90	-61%	-30%
01/07/2018	11.0	excellent (1.73)	0.61	0.69	2%	-20%
14/07/2018	38.3	very good (4.14)	0.25	0.66	27%**	-5%
07/08/2018	9.0	excellent (1.19)	0.77	0.79	-3%	-9%
10/08/2018	17.6	excellent (1.95)	0.75	0.83	-5%	-20%

* Chalk stick reading does not allow for assessment of performance functions, or calculation of volume errors

**Peak could be higher, 15 min of data missing

Table 5-5: Results of validation at Vigilance Drive Canal

Event date	Rainfall	Integral Squared Error (ISE)	Nash-Sutcliffe Efficiency (NSE)	Coefficient of determination (R^2)	Peak Flow Error	Volume Error
	mm				%	%
18/04/2018	10.4	n/a*	n/a*	n/a*	-56%	n/a*
28/04/2018	10.8	n/a*	n/a*	n/a*	18%	n/a*
03/06/2018	25.8	excellent (2.43)	0.72	0.83	0%	-12%
10/06/2018	4.0	excellent (2.94)	-0.10	0.47	-51%	-38%
19/09/2018	16.0	very good (3.01)	0.84	0.90	-8%	-9%

*Chalk stick reading does not allow for assessment of performance functions, or calculation of volume errors

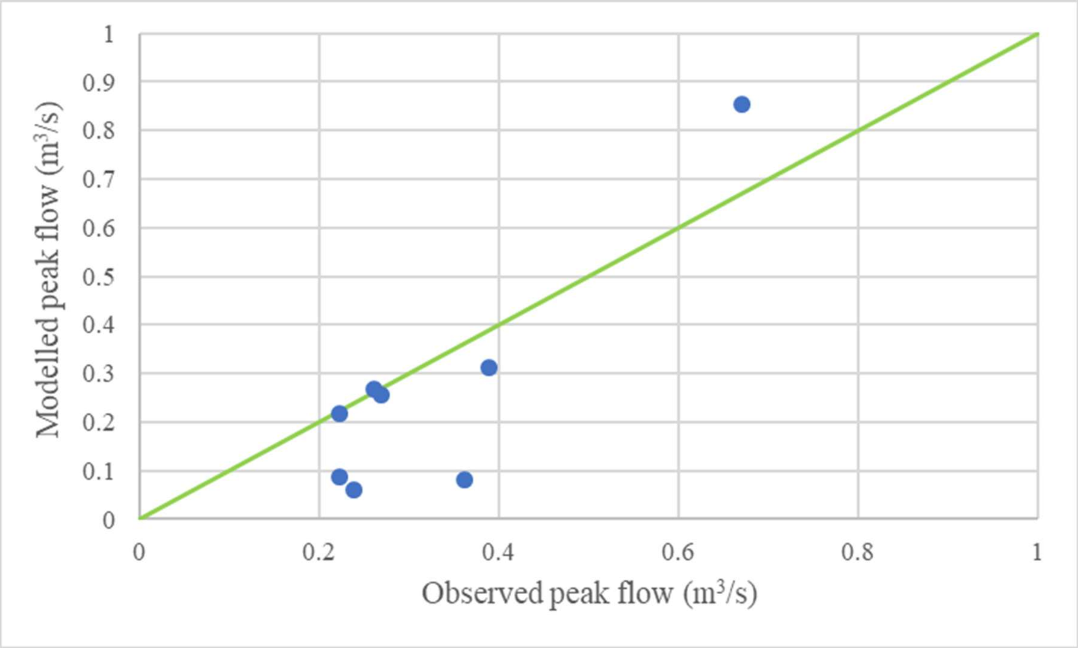


Figure 5-19: Vigilance Drive: comparison of observed and modelled peak flows

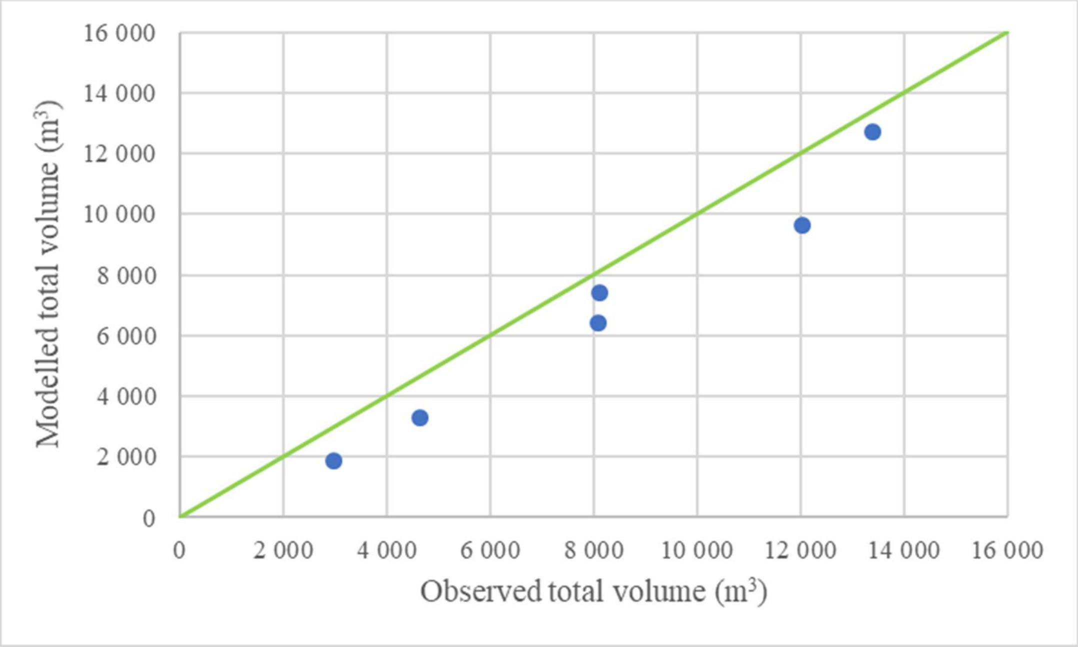


Figure 5-20: Vigilance Drive: comparison of observed and modelled flow volumes

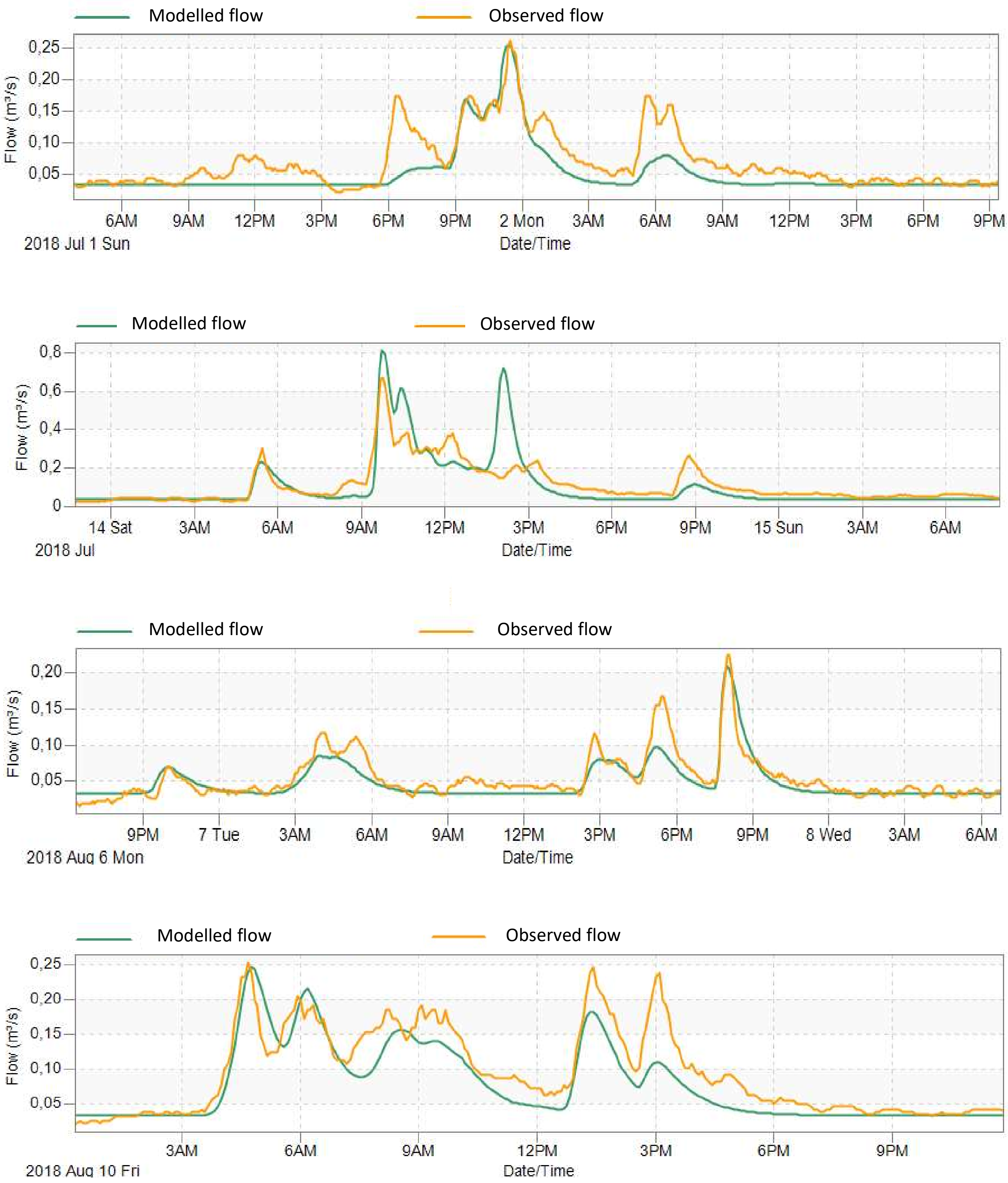


Figure 5-21: Vigilance Drive Drain: observed and modelled flow

5.2.2.2 Bongani River

The water level in the Bongani River was measured for six rainfall events. Unfortunately, large storms on the 14th of July 2018 (38 mm of rainfall) and the 7th - 8th of September 2018 (140 mm of rainfall) were not captured due to flow-measuring equipment failure. The largest rainfall event for which flow was measured was 26 mm of rainfall on the 3rd of June. The other 5 storms were relatively small (15, 11, 9, 3, and 2.6 mm). As an indication, the one day 1:2 year storm for the Knysna TNK gauge is 56 mm, and the 1:20 year one day storm is 127 mm (SAWS daily design rainfall database after Smithers & Schulze (2000)). 2/3 of the data was used for calibration and 1/3 was used to validate the modelled response. Only the 26 mm storm generated modelled pervious runoff and was used to calibrate pervious factors.

The model calibration and validation results for the Bongani River are presented in

Table 5-6 and Table 5-7 respectively. The calibration gave excellent Integrated Squared Errors (ISE) when compared to measured flows. The NSE values were also high (0.75 – 0.89) and the coefficient of determination values showed good correlation with the measured data (0.86 – 0.96). All three performance functions therefore indicated a good correlation between the measured and modelled flows. The peak flow errors show a larger discrepancy, with the model overestimating two peak flows by 16% and 24%, and underestimating the peak flows from two rainfall events (-12% and -27%). The mean peak flow error for the calibration period was 0%. Due to the larger catchment and slower response times, the half hour moving average had a negligible impact on observed peak flows. The model typically underestimated total storm flow volumes, with a mean volume error of -7%. Observed and modelled flows for the four calibration events are shown in Figure 5-24. The peak flows and total flow volumes are compared to observed data in Figure 5-22 and Figure 5-23.

The model validation also gave excellent ISE ratings and high coefficient of determination values (0.85 and 0.87), but showed poor correlation with the measured flows when assessed using NSE (values of 0.5 and -0.62). The peak flow error was particularly high for the small storm event on the 30th of June (-43%), and volume errors were also reasonably high (27% and -29%). For the small storm on the 30th of June the observed flow shows an increased base flow both before and after the storm, which may be the result of measurement inaccuracies.

The PCSWMM runoff and routing errors were both -0.2% for the Bongani River model, and were deemed to be acceptable. Calibrated model inputs are provided in Appendix B.

For the calibrated model, only the largest storm generated modelled runoff from pervious areas, and the runoff had a negligible effect on runoff peaks or volumes. Calibration of the soil parameters was therefore not possible, other than to note that the soil infiltration parameters indicate a soil with a infiltration capacity at least equal to that of silt loam (as determined from Table A2 in Krebs *et al.* (2014), reproduced from Rawls *et al.* (1992); Oram (2012)). This corresponds with the ARC soil parameters for the Bongani Catchment, which have a high infiltration capacity. Additional observed data, in particular for larger storms, would be required to confirm this finding.

Table 5-6: Results of calibration at Bongani River

Event date	Rainfall	Integral Squared Error (ISE)	Nash-Sutcliffe Efficiency (NSE)	Coefficient of determination (R^2)	Peak flow Error	Volume Error
	mm				%	%
24/05/2018	15.0	excellent (1.28)	0.87	0.96	24%	5%
29/05/2018	3.0	excellent (0.86)	0.75	0.86	-27%	-8%
03/06/2018	25.0	excellent (1.27)	0.89	0.93	16%	-6%
01/07/2018	11.0	excellent (1.16)	0.78	0.91	-12%	-18%

Table 5-7: Results of validation at Bongani River

Event date	Rainfall	Integral Squared Error (ISE)	Nash-Sutcliffe Efficiency (NSE)	Coefficient of determination (R^2)	Peak flow Error	Volume Error
	mm				%	%
28/04/2018	9.0	excellent (2.74)	0.50	0.87	15%	27%
30/06/2018	2.6	excellent (1.40)	-0.62	0.85	-43%	-29%

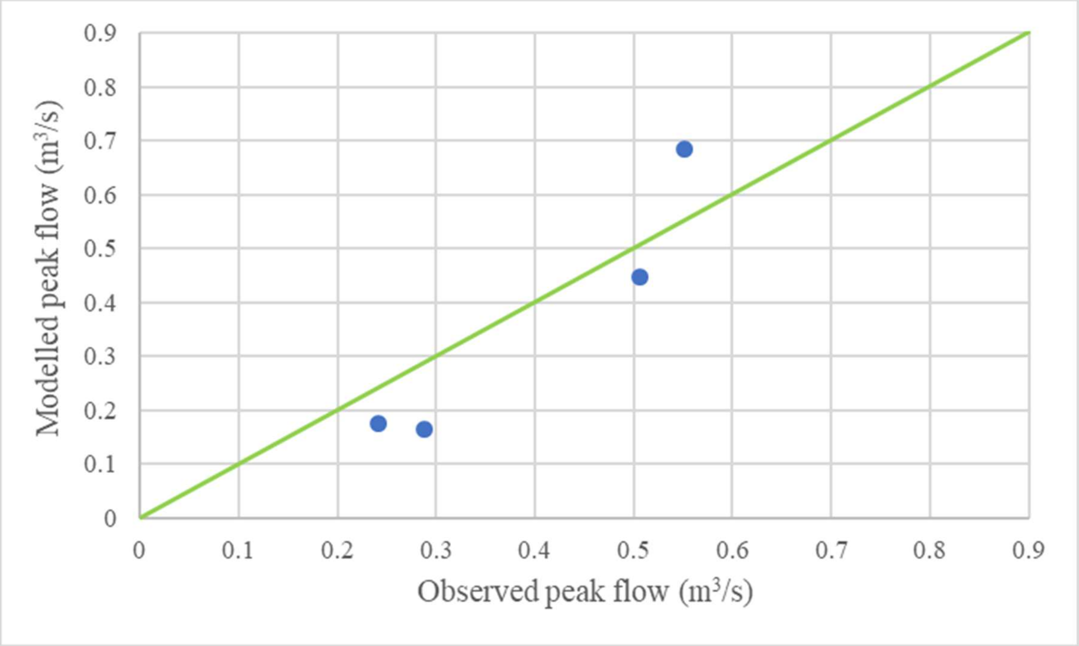


Figure 5-22: Bongani River: comparison of observed and modelled peak flows

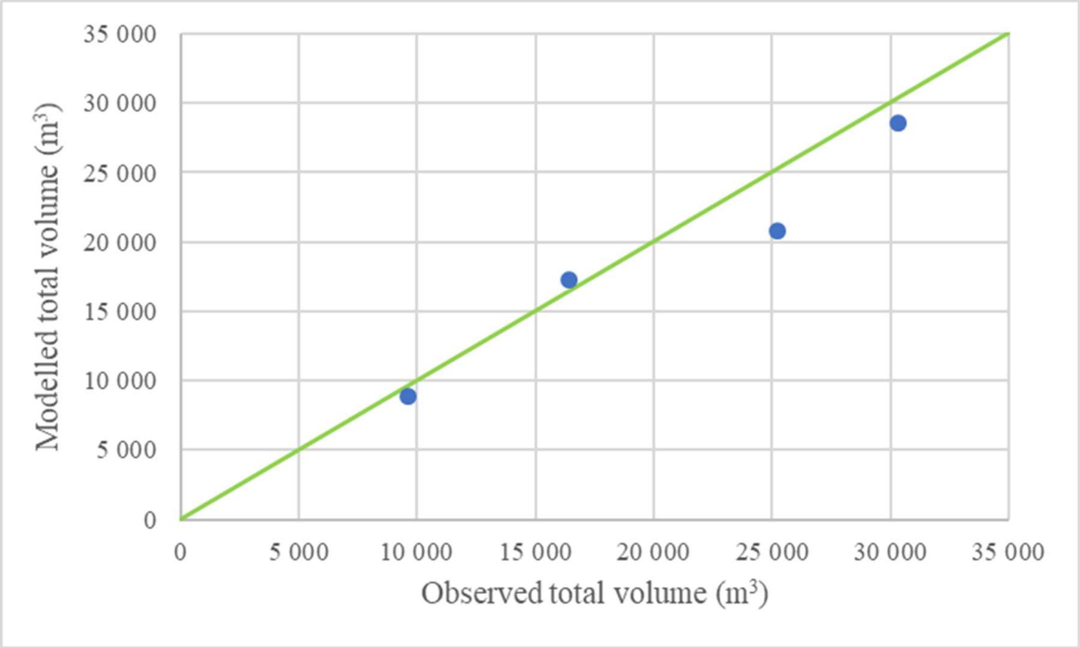
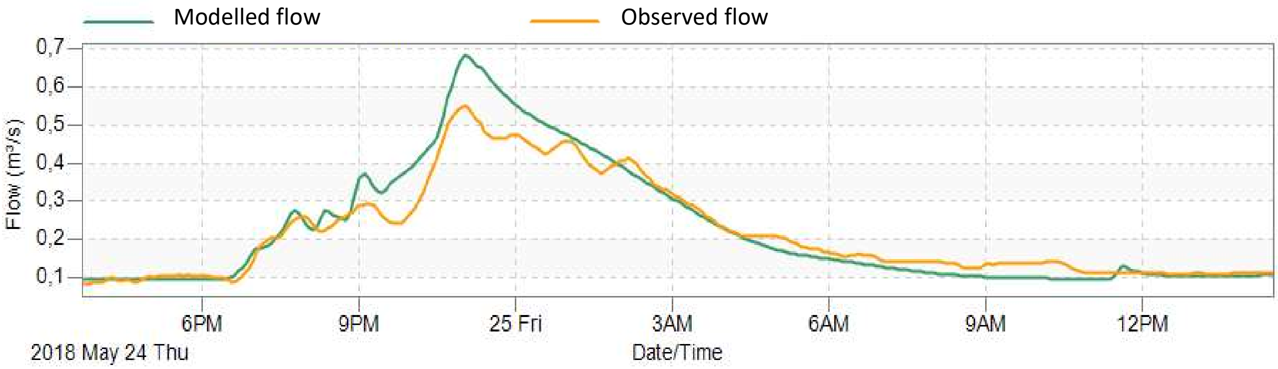
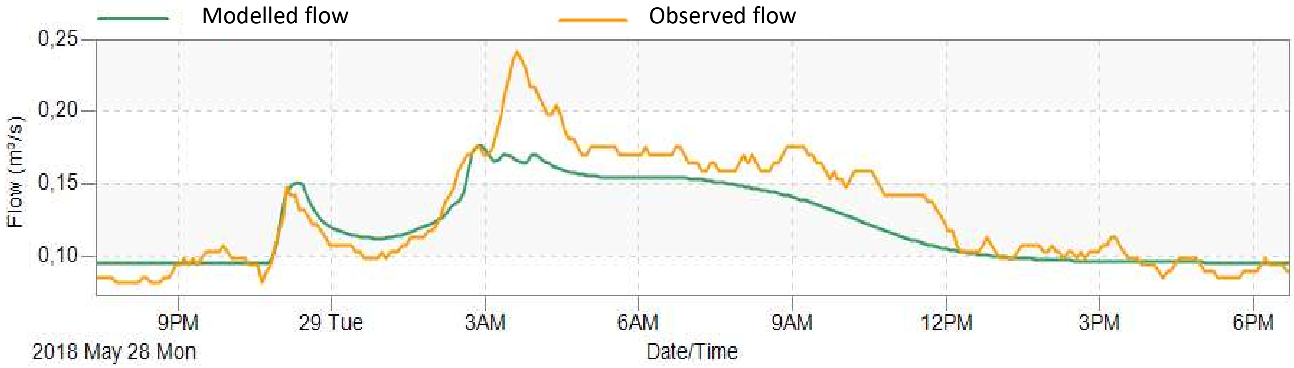


Figure 5-23: Bongani River: comparison of observed and modelled flow volumes





Modelled flow

Observed flow

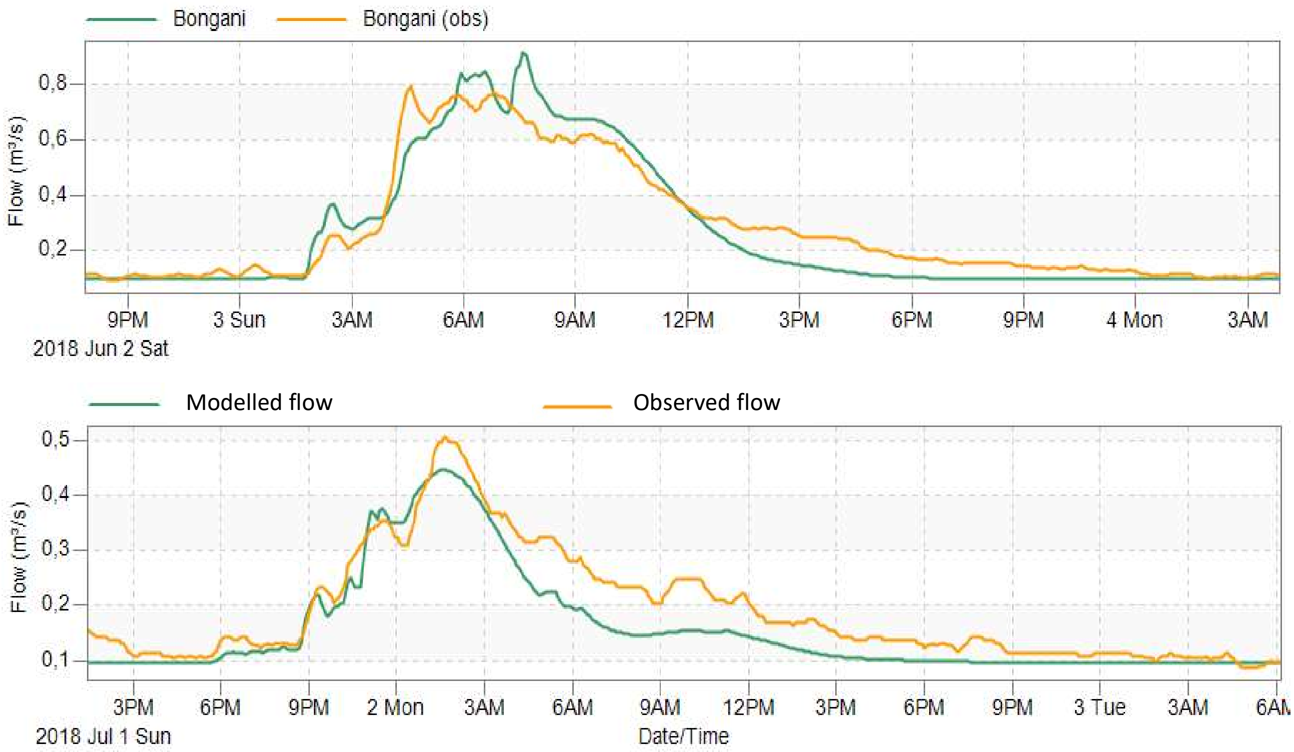


Figure 5-24: Bongani River: observed and modelled flow

5.3 Findings

The modelling exercise established a reasonable calibration for the Bongani River and Vigilance Drive monitoring sites. The model input parameters calibrated for these two sites were used to model the entire Bongani Catchment. On-going flow monitoring, and calibration of the model for larger storm events is recommended. It was not possible to accurately determine base flows for the two sites due to limitations of the flow measuring equipment, and the source of these sustained base flows was not investigated. If reliable base flows can be determined then the water quality measurements can be used to calculate sustained pollutant loads to the estuary.

A large storm (140 mm of rainfall) was measured at the KBP rain gauge on the 7th - 8th of September 2018. The KBP rainfall station recorded 116 mm of rainfall over the first 18 hours, and 123 mm in the first 24 hours. This is equivalent to a 1:20 year one day storm (127 mm as reported for the Knysna TNK station in the SAWS daily design rainfall database after Smithers & Schulze (2000)). No observed data was measured from this storm, but site observations on the 10th of September indicated that the magnitude of flows in the Bongani River was sufficient to flatten reeds, scour sections of the channel, and deposit significant sediment in other sections of the channel. The hydrological model calculated peak flows for this storm event of 2.1 and 1.2 m^3/s for the Bongani River and Vigilance Drive Channel respectively. The modelled peak velocity was 0.88 m/s on the Bongani River, at the monitoring station, but 1.44 m/s immediately upstream of the monitoring section, where sediment scour was observed. The maximum modelled velocity in the Vigilance Drive Channel was 2.09 m/s. Modelled storm flow volumes for the Bongani River and the Vigilance Drive Channel for this storm were 126,900 m^3 and 39,680 m^3 respectively.

Figure 5-25: Flattened reeds in the Bongani River

At the Bongani flow monitoring site TIN concentrations measured during storm events were not markedly different from concentrations measured during dry periods. Assuming that the mean TIN concentration was representative of the entire storm, and using the modelled flow volumes for storms, pollutant loads can be calculated by multiplying the concentrations by the storm volumes. A similar approach was used to calculate SRP and NO_xN loads, as reported in Table 5-8 for two storms. SRP concentrations seemed to be somewhat lower for storms and this calculation could overestimate SRP loading. The NO_xN concentrations seemed to rise with storms, and the load calculation may underestimate NO_xN loading. The calculated NO_xN and SRP loads are on the upper end, or above, the loads measured in the Knysna River during flooding in 1996, where NO_xN was reported to vary from 0 to 140 kg/day and SRP from 0 to 12 kg/day (Allanson *et al.*, 2000). The researchers noted that concentrations and flows were measured only for the onset of the flooding, and not for the entire flooding event. TSS concentrations were shown to change substantially during storms (Section 4.1.2.2), and therefore no TSS load estimates were attempted.

For the WWTW the mean pollutant loads were calculated as 122, 9 and 8 kg/day for TIN, NO_xN and SRP respectively (Section 4.3). The calculated pollutant loads for the two storms for the Bongani outflow are therefore 6 to 8 times higher than sustained loads at the WWTW for TIN, 42 to 51 times higher for NO_xN, and 11 to 17 times higher for SRP. The WWTW loads are sustained loads, whilst those in the Bongani River are for isolated storms, however the calculation highlights that both the WWTW effluent and the Bongani River need to be managed to limit nutrient loading to the estuary. There is considerable uncertainty associated with these load estimates, as uncertainty in the flow modelling is compounded by uncertainty in the pollutant concentrations, and the assumption of steady concentrations for large storms may not be valid. To more accurately calculate the pollutant loads continuous water quality monitoring, and further calibration of the hydrological model, would be required. The calculations still demonstrate the magnitude of the pollutant loading originating from the Bongani River Catchment.

Table 5-8: Estimated loads for two storms

Site	Event	Pollutant	Storm load	Storm duration	Load
			kg	hours	kg/day
Site 4b: Bongani River at industrial area	14/07/2018	TIN	330	25	320
		NO_xN	70		70
		SRP	20		20
	07/09/2018	TIN	1360	59	550
		NO_xN	330		130
		SRP	70		30
Site 4: Bongani River outflow	14/07/2018	TIN	730	25	700
		NO_xN	470		460
		SRP	95		90
	07/09/2018	TIN	2440	59	990
		NO_xN	920		370
		SRP	330		140

5.4 Assumptions and limitations

Runoff models are only as accurate as the data input. For this study there is uncertainty in rainfall data (see Section 5.1.1), in rainfall-runoff modelling processes, and finally uncertainty in input parameters based on data availability (see sub-sections under Section 3.4). Only one rainfall gauge has been used for the catchment as no rainfall data was available higher up in the catchment. Rainfall data is highly spatially and temporally variable and this could lead to inaccuracies in the model calibration. For this model the Hargreave's method has been used to estimate evapotranspiration. The evapotranspiration was not calibrated against measured data, and no crop factors were applied for different land uses.

The low spatial resolution of the land use data, and assumptions regarding the disaggregation of land use types, introduces model uncertainty. The approach of using weighted averages, particularly where different land uses overlie different sub-soils, may lead to some inaccuracies. There are a very limited number of sub-catchments where different land uses overlie different sub-soils. Sub-soils were based on high resolution GIS mapping but the use of weighted averages may not give a true representation of the infiltration capacity of different soil types. The relationship between impervious and pervious areas is complex and the simplistic approach used in this model may lead to inaccuracies.

Node elevations, catchment slopes and irregular channel cross-sections have all been extracted from DEM data, which is limited to a 5 m grid accuracy. Sizes for the stormwater drains were obtained from the GIS information supplied by the municipality. These sizes were only assessed on site at a few locations and further site visits would be required to confirm the accuracy of this information.

Modelling uncertainties include the use of the simplistic Manning's equation to model channel and river response. The selection of Manning's roughness coefficients can be subjective and should strictly be a function of flow velocity. The Manning's roughness assumptions used to convert observed water level data to flow data had a significant impact on the observed flows. Additional calibration, particularly for larger storm events, is recommended to assess the validity of the roughness assumptions. Base flows were calculated using the Manning's equation and average flow depths on dry days. There is considerable uncertainty associated with base flows and very low flow events, as the impact of channel roughness is particularly high for low flow events. A high-level calculation of potential groundwater recharge indicated that the calculated base flows for both channels was too high (if the source of the base flow is groundwater). These flows make up a relatively small proportion of the peak flows for storm events.

The low rainfall storms used for model calibration mean that there is still considerable uncertainty about soil and pervious parameters. These parameters could have a significant impact on large storm peaks, particularly on the Bongani River. It is recommended that the model be calibrated with higher rainfall events. No groundwater modelling was undertaken as part of this model.

A scarcity of flow data limited the accurate calibration of the model. In addition, the model was calibrated based on only two flow level gauges. The gauge on Vigilance Drive has a catchment of 40.7 ha with relatively high imperviousness (57%). Almost all the drainage paths are constructed stormwater drains. The monitoring site has a simple rectangular geometry with relatively uniform roughness (concrete sides and base). The degree of uncertainty related to this site is therefore lower than for the gauge on the Bongani River. Some uncertainty is introduced by changes in slope near the monitoring site, with the concrete broken and therefore introducing small steps at two locations. The channel widened downstream of the monitoring site, which was not accounted for in the model. The calibration was particularly poor for low rainfall events. The assumption of a moving average for observed flow data led to a damping on observed peak flows, which could lead to the underestimation of peak flows in the model. If the model is to be used for further research it is recommended that a better representation of observed data is sought, which both accounts for the noise in the data and does not damp peaks. The possible errors introduced by noise and daily fluctuations in the measured data have not been quantified but will be more significant for low flow events.

The gauge on the Bongani River has a much larger catchment area of 357.6 ha with a low imperviousness (14%). Most of the drainage paths are natural streams. There are some stormwater channels in the headwaters of the stream in Khayalethu, and adjacent to the industrial area. The monitoring site is less well defined, with a trapezoidal shape. Both the roughness and slope are less regular than Vigilance Drive due to the uneven deposition of sands and rocks, as well as plant growth in some sections of the channel. Sediment build-up downstream of the monitored section could have led to a back-water effect, which would lead to higher flow levels, and could exaggerate flow peaks, particularly for low flows. Uncertainty in the calculation of flows is relatively high at the gauging site, particularly for small storms. The possible errors introduced by noise and daily fluctuations in the measured data have not been quantified but will be more significant for low flow events.

The pollutant load calculations are based on concentrations obtained from monthly grab sampling, and are therefore not necessarily accurate for storm events. Continuous water quality monitoring would be required to more accurately determine the pollutant concentrations during storm events. The pollutant load calculations are also dependent on the accuracy of flow modelling, the limitations of which have been discussed.

6. Stakeholder engagement and Mauri Model

6.1 Stakeholder engagement process

An interview process was used to engage with stakeholders. Seventeen stakeholders were interviewed, some in their professional or organizational capacity and others in their private capacity. Six stakeholders were private residents from Khayalethu, Upper Old Place and Lower Old Place. Five stakeholders represented four different environmental organisations (SANParks, Knysna Basin Project, Biowise, and the Knysna Environmental Forum). Two municipal representatives were interviewed, although permission for use of the data for one interview was not obtained and this data has not been used. Additional stakeholders included representatives of the Knysna Residents' Association, the House of Judah Rastafarian community, and the local Xhosa initiation school, as well as a participant from the forestry industry. Twelve of the participants were single participants in the interview process, three private residents were interviewed together, and one private resident and one SANParks employee were interviewed together.

Each stakeholder was assigned a random number identifier to protect their identity. Three of the participants were interviewed together and completed the world view together and have therefore been assigned a single identifier. Participants who represented their organisations did so to the best of their ability but were not necessarily able to express the views of the entire organisation, and in some cases private opinions were expressed. Based on the world view assessment (see Section 6.2.1), the environmental world view is possibly over-represented in this group of participants. This is likely to be as a result of the author's personal inclination, the author's primary contacts being environmental organisations, and the people most willing to participate in this study.

Participants in the study were generally found to be cognizant of water management issues and some of the impacts of these on human health and the environment. Many stakeholders had been involved in the water or environmental space in either a formal or informal capacity. Two of the private residents who were interviewed separately approached the researcher during sampling or river investigations. Both of these residents had previously addressed water management concerns to the municipality. Typically, the topic of water management was therefore easy to broach, and most stakeholders were found to have strong opinions in this regard. It is recognized that a broader stakeholder engagement would be required to get a more comprehensive view of water management in Knysna. In particular it is recommended that community groups in Khayalethu, women / women's representatives, vulnerable groups, players in the industrial space, as well as business owners, be included in any future stakeholder engagement.

Engagement with stakeholders can add considerable value in helping to determine pollution sources, to understand the value that stakeholders place on environmental, social, cultural and economic indicators, and how these are being impacted by pollution, and to inform possible solutions.

6.1.1 Water management challenges

The key water management challenges discussed in this chapter are based on the stakeholder engagement process as well as site visits and issues raised at some pollution committee meetings. The issues raised by stakeholders may be perceived issues, the result of personal experience, anecdotal evidence or information gleaned from research, publications or attendance at committee meetings. Data was extracted from interview recordings and has been paraphrased and grouped to assist in interpreting the issues raised. Key challenges have been selected based on the recurrence of an issue in multiple interviews. The full list of water management challenges raised by stakeholders is provided in Appendix E. Water management challenges raised by stakeholders can be used to inform solutions and also provide insight into how the lives and activities of stakeholders are being impacted by water pollution.

Stakeholders are concerned about pollution and water management concerns, and the impact these are having on the natural environment (Table 6-1). The following examples also indicate how pollution of Knysna's natural watercourses is affecting the social, cultural and economic well-being of stakeholders.

Two stakeholders discussed falling ill after watering their gardens with water extracted from streams. One of the stakeholders noted that due to health concerns his wife, who is a teacher, no longer takes school groups on a hike to a waterfall located on a tributary of the Bongani River. Two stakeholders expressed concern about the health of children who swim in the Bongani River or its tributaries. Two stakeholders water vegetable gardens with water extracted from streams, and the health of those consuming their produce is a concern, and could have indirect economic impacts. One stakeholder expressed concern about the health of initiates who drink and wash in water sourced from dams and streams, and noted that sometimes the initiation school is obliged to carry water to initiates (which has an indirect economic cost). One stakeholder noted that pollution, particularly in the form of litter, has an economic cost as it is a deterrent to tourism.

Each of these narratives is personal and subjective, and the stakeholder engagement was limited, however these examples serve to illustrate how poor water quality is currently impacting the lives of some of Knysna's residents who live close to natural water courses.

Table 6-1: Water Management concerns from stakeholder engagement

Category	Water management challenge	Stakeholders
Management	Problems are not addressed, there is a lack of / slow response to reported issues	1, 3, 6, 9, 10, 14
	Development, without sufficient supporting infrastructure, has and will negatively affect the receiving environment	4, 5, 7, 12, 13
	There are too many players and a lack of co-ordination between players in the water and environmental management sectors; there is no over-arching vision	6, 8, 9, 12
	There is a lack of implementation and enforcement of regulations	8, 9, 11, 12
	There are too many surveys, stakeholder engagements, strategy documents and meetings but insufficient action is being taken to address issues	2, 8, 9
	There is a lack of buy-in from the municipality on proposed environmental projects	10, 11
	Water security/ quality hasn't been well managed historically	7, 11
	Environmental issues need to be presented in a way that is relevant to the youth	10, 11
	Incompetence is an issue**	2, 7
	Water is treated as waste rather than as a resource	8, 12
	There is a general lack of respect for the natural environment and water within Knysna	5, 8
Pollution	Sewage leaks and manhole overflows are reporting to the environment	1, 2, 3, 4, 5, 6, 7, 9, 11, 13, 14, *
	Litter is a pollutant of concern	5, 6, 9, 11, 12, 13, *
	The WWTW capacity and/ or the quality of effluent at the WWTW is a concern	1, 4, 6, 7, 9, 13
	Siltation and sedimentation of streams and the estuary is concerning	1, 2, 9, 13, 14, *
	Nutrient enrichment and eutrophication of streams, the estuary and in particular the Ashmead Channel is concerning	2, 7, 9, 13
	Stormwater runoff from, and streams flowing through, informal areas is of poor quality	11, 12, 13
	Unpleasant smells indicate poor water quality	1, Resident, *
	Waste is being disposed of in rivers	10, 11, *
	There is a contamination risk to dams that supply drinking water (sabotage / pollution)	10, 11
General environmental and social concerns	Health concerns relating to exposure to contaminated water through direct contact or consumption of agricultural produce irrigated with river water, or consumption of fish	1, 3, 10, 11, 14
	There has been a decline in river water quality over time	1, 10
	There has been a decline in the health of the estuary over time but incremental changes are not always visible, particularly given the flushing effect	7, 9
	Flushing of the estuary carries pollutants out to sea	6, 7
	Lack of flushing of the Ashmead Channel has led to a pollutant build-up	6, 13

* Witnessed during site visits

**One stakeholder raised this issue with regards to the municipality and one for contractors employed by the municipality

6.1.2 Pollution sources

Pollution sources identified by stakeholders are listed in Table 6-2. The pollution sources are based on individual stakeholders' personal experience, perceptions, anecdotal evidence or information gleaned from research, publications or attendance at committee meetings.

Table 6-2: Pollution sources identified by stakeholders

Pollution sources	Stakeholders
Sewage leaks/ overflows*	1, 2, 3, 4, 5, 6, 7, 9, 11, 13, 14, **
Individuals disposing waste (e.g. litter) directly into water courses or storm drains	1, 5, 10, 11, 12, **
Companies within the industrial area – contaminated wash-down or direct disposal of waste to stormwater	1, 4, 7, 8, 13, **
Waste Water Treatment Works	1, 4, 6, 7, 9, 13
Small mechanics / back-yard mechanics and workshops	4, 8, 11, 12, 13
Destitute persons bring bags of rubbish down from town and sort them on the banks of the estuary, leading to litter issues	3, 6
Petrol Stations – fuel leak incident	4, 7, 8
Cows and other animals	10, 12, **
Businesses in CBD – e.g. lack of maintenance of grease traps, disposal of waste to stormwater drains	5, 8
Tourists dispose of litter and also indirectly pollute through oils/ hydrocarbons from motorboats	3

* Two stakeholders identified the sewage line near the organic waste dump as being particularly problematic
**Witnessed during site visits

6.1.3 Positive existing water management approaches

Positive existing water management approaches that were praised by stakeholders are listed in Table 6-3. Stakeholders 2, 4, 7, and 9 were very negative about current water management within the Knysna Basin catchments. These stakeholders, as well as Stakeholders 1, 3, 6 and 14 did not respond to this question with any positive current water management approaches. Positive water management approaches that are appreciated by stakeholders can be used to inform future pollution intervention solutions.

Table 6-3: Positive water management approaches praised by stakeholders

Positive water management approaches	Stakeholders
On-going water quality monitoring*	5, 6, 13
Estuary pollution committee and municipal transparency through this forum	7, 13
Improved legislation and FSC certification have improved environmental protection in the forestry industry	5
Municipal plans to upgrade the WWTW	5
Recent schemes to enhance water security (security of supply)	7
Praise for some municipal staff and the work that they are doing	7
Rapid response of the municipality to a fuel leak incident	7
Quality of water purification for municipal supply	10
Communication from the municipality**	10
Cape Nature – access to reserves for the youth	11
Some water recycling initiatives within communities	11
Community Works Programme – cleaning up litter within communities***	12
SANParks partnership to establish plant nurseries	12
Willingness of the municipal environmental department to investigate alternative ways of managing water and relevant training of staff****	8

* Refers to municipal water quality monitoring, although one stakeholder also mentioned the monitoring being carried out by the KBP and by the DWS.

** It was recommended that communication be broadcast on radio and in three languages.

*** Stakeholder 12 noted that the CWP do not clean the rivers, Stakeholder 11 expressed dissatisfaction with the quality of the work being carried out by the CWP.

**** Stakeholder 8 would like to see this thinking taken up more broadly within the municipality.

6.1.4 Proposed changes and solutions

Stakeholders were asked to discuss changes they would like to see in the way that water is managed in Knysna, or suggestions for future projects. The proposed changes are presented in Table 6-4. Proposed changes have been grouped with similar requests where possible. Proposed changes have been categorized as management, pollution minimization, water use/ alternative water sources, data collection or regulation measures. It is interesting to note that some measures proposed to address the same water quality problem (poor water quality in the Bongani River) are opposing. One stakeholder proposed that the lower Bongani River be cleared of vegetation and silt so that any sewage overflows or illegal discharges can be identified. Another stakeholder proposed that a wetland, with wetland vegetation, be established in the lower Bongani River to allow silts to settle and to provide treatment for pollutants such as nutrients. It is recommended that during the assessment of treatment alternatives unintended consequences should be considered (for example clearing of the Bongani River could have a negative impact on established ecosystems, while creating a wetland could cover sewage outlet pipes). It is recommended that an interactive public engagement process be followed for any proposed solutions.

Table 6-4: Water management changes or solutions proposed by stakeholders

Category	Proposed change or solution	Stakeholders
Management	Education/ awareness campaign, particularly for the youth	4, 9, 10, 11, 12
	Proactive management and faster response to water quality monitoring, focus on problematic areas	1, 4, 6, 13
	Faster/ more urgent reaction time on reported issues	1, 6
	Goal orientated, adaptive management with consequences for poor management	2
	Set targets and thresholds for environmental management	2
	Involve and keep stakeholders informed of water management issues and projects	1, 8, 12
	Construct a wetland on Bongani before George Rex Drive	8
	Open/ clear vegetation in Bongani, identify sewage overflows/ stormwater pipes	1
	Over-arching vision a regenerative economy	8
	Work with businesses so they become models of sustainability	8
	Adequately trained and qualified staff and political will is required	7
Minimize Pollution	Litter traps/ on-going river clean-ups/ 'Adopt a river' campaigns	4, 6, 9, 10, 11, 12
	WWTW must improve/ comply and be upgraded if necessary	1, 5, 6, 7, 13
	Stormwater, potable water and sewage maintenance & upgrades	6, 7, 9, 14
	Systematic removal of chemical pollutants	1, 4, 11
	Recycling bins and collection/ fashion show with recycling/ recycling initiatives	5, 10, 11
	Restrict access to dams and rivers to minimise the risk of pollution/ sabotage	10
	Identify and address high pollution sources	4
	Install silt traps	6
	Planning to manage all forms of waste resulting from increased development	5
	Manage impacts from golf courses	13
Water use/ Alternative water sources	Water saving (fixing broken or leaking taps), water recycling, rain water harvesting*	5, 8, 11, 12
	Address security of supply, possibly through another dam	7, 10
	Planning to sustainably supply water for increased development	5
	New developments should be decentralized and off-grid, residents allowed to go off-grid	8
	Use of 'fit for purpose' water (e.g. water used for gardens does not need to be potable)	5
	Improve water quality for use as irrigation for medicinal plant nursery and vegetables	12
Regulation	Address enforcement - fines or other penalties / by-laws that address enforcement	4, 8, 11
	More regulation and enforcement is required in the agricultural industry and for private properties - e.g. wetland and river delineation, management of alien invasive plants	5

Category	Proposed change or solution	Stakeholders
Data Collection	Focused sampling/ data collection to establish baseline data and problematic areas	1, 2, 6, 12
	Measure potable water use rather than only intake at the WWTW	8
	Understand wetlands, functionality, health	4

* One stakeholder noted that rain water harvesting could reduce the municipal water supply burden, capture the resource before it becomes contaminated, and help to ensure security of water supply.

6.1.5 Summary

The issues and proposed solutions discussed in this summary are focused on topics raised by multiple stakeholders, but the intention is not to minimize the valuable contribution of other stakeholders, particularly experts within their fields or contexts. Sewage leaks and sewage manhole overflows, as well as the quality of effluent discharge from the WWTW, were consistently identified by most stakeholders as pollutant sources. Many stakeholders raised concerns regarding the health impacts of pollution on people who could be exposed to contaminated water. Proposed intervention measures included more proactive management, faster response times to reported issues, and upgrades on the WWTW and sewage and stormwater infrastructure.

Litter and sediments were additional pollutants identified as a source for concern for multiple stakeholders. Suggestions to minimize litter that were favoured by six stakeholders were measures to clean-up litter and community awareness campaigns. Backyard mechanics and illegal discharge from the industrial area or other businesses are potential sources of hydrocarbons and heavy metals. Several stakeholders noted that they would support enforcement of regulations and fining of polluters, and some supported on-going water quality monitoring to identify pollution sources.

Four stakeholders raised concerns that water management in Knysna is fragmented, with a lack of co-ordination between players. Several stakeholders noted the negative impacts that development can have on the receiving environment if not properly managed and not supported by the necessary infrastructure. It is interesting to note that, though not the topic of this dissertation, measures to provide alternative water sources and address water security were raised by multiple stakeholders. The issues raised and solutions proposed are complex and cover broad topics, however sewage management concerns appear to be a consistent narrative.

6.2 Mauri Model

Stakeholders were asked to quantify their ‘world view’ by rating the relative importance of environmental, social, cultural and economic dimensions, as per the process described by Morgan *et al.* (2013). Stakeholders also assisted in the determination of indicators (or performance measures) that should be considered when assessing the relative performance of alternative solutions to address water pollution. Four possible solutions to address some water pollution issues were then assessed using the Mauri Model. The model allows the relative merits of the solutions to be compared, using the selected indicators. The quantified world views of stakeholders can then be superimposed on the outcomes, to help decision makers to understand how different stakeholders might view the solutions, and which solution is likely to be the most socially acceptable.

6.2.1 Stakeholder world views

Whilst some stakeholders easily quantified their world views, others struggled with the concept, critiqued it, or grappled with the task from several different angles. Critique of the model is discussed in Section 6.2.5. In Table 6-5 some of the more diverse normalised world views are presented, with the remainder presented in Appendix F. Dominant dimensions are shown in bold. The maximum percentage that can be achieved for any one dimension is 50%. Some stakeholders attempted to represent the views of their organisation but this is challenging, particularly where individuals within the organisation may have very different world views.

Stakeholder 8, who very strongly values the environment, made a compelling argument for why this should be the only world view, as all social, cultural and economic considerations cannot be sustained without the natural environment. This stakeholder stressed that a key part of the tool should be an agreed central principle or recognition that the environment is what sustains humanity. Stakeholder 11 expressed their passionate concern for the environment and an awareness of the impacts of environmental degradation on human health and well-being. At the same time the stakeholder, who is young, unemployed but running an NGO, expressed the opinion that the freedom to prioritize any dimension other than an economic one is a privilege of the wealthy. Basic needs must be met before other considerations can be assessed. These entrenched views clearly demonstrate the diversity of stakeholders and their experiences and lived realities within Knysna and how these affect their priorities.

Nine of the sixteen stakeholders valued the environmental dimension highest, two equally weighted environmental and economic concerns highest, four rated economic considerations highest and one valued social considerations the most. None of the stakeholders interviewed rated the cultural dimension highest.

Table 6-5: Selected stakeholder world views

Dimension	Environmental	Social	Cultural	Economic
SANParks official	42%	31%	3%	25%
Knysna Ratepayers Association	39%	19%	3%	39%
Environmental Department Municipality	50%	31%	11%	8%
Khayalethu Youth	17%	25%	8%	50%
Forester	31%	11%	28%	31%
Upper Old Place resident	36%	42%	14%	8%

6.2.2 Relevant indicators

The indicators (or performance measures) listed in Table 6-6 were determined from discussions with stakeholders. The stakeholders who listed the indicators of concern are shown in brackets. Some indicators were directly mentioned by stakeholders, some were identified by the researcher as possible indicators and proposed to stakeholders, and the importance of others was inferred from the water management discussions. Typically, only the indicators for the stakeholder's prioritised dimension were discussed, and therefore the number of people who identified indicators should not necessarily be used as a measure of the indicator's relative importance.

The Mauri Model requires that an equal number of indicators be selected in each field and that all indicators be equally weighted. Not all indicators that were mentioned by stakeholders have been included in this list, those that were mentioned by several stakeholders have been prioritized. This approach may have skewed the indicator selection to those originally identified by the researcher, and proposed to several stakeholders. Stakeholder engagement should be an iterative process and further stakeholder engagement is recommended if the tool is applied to the design of water management interventions. During the second round of stakeholder engagement, further indicators relevant to the particular solutions could be identified and stakeholders could be provided with the full list of indicators identified by all parties. The full list identified during this study is presented in Appendix G.

In this context indicators refer to the performance measures that will be used to assess the relative merits of different proposed solutions. Some of the stakeholders discussed the use of key indicator species, whose health/ abundance can be used as a proxy for the health of the system. For this project the assessment of indicators has been done qualitatively, and the assessment is only used as a demonstration of how the tool might be applied in this context. If the tool were to be applied in more detail, quantitative values would be assigned to most indicators, for example an *E. coli* count above 400 CFU/100 mℓ might be one measure of health, and the number of bags of litter might be one measure of litter. For the detailed model, the abundance or health of specific indicator species might well form the quantitative measure, for example areas of eelgrass might be a measure of aquatic plant health. The determination of these quantitative measures would need to be done in consultation with experts as the measures would need to be appropriate measures of the selected indicator, be sensitive to change, and be relatively easy to monitor or predict. Each quantitative measure would then be related back to a score, with scores from -2 (reducing sustainability, degrading value) to 2 (enhancing sustainability, restoring value). To ensure transparency and reproducibility the measures of each indicator should be detailed (i.e. the scores of -2 and 2 are clearly defined). Some indicators will be quantifiable whilst others will remain qualitative. The inclusion of stakeholders in the process to select indicators helps to ensure that the process is transparent and that the concerns of multiple stakeholders help to inform the selection of a preferred solution.

Table 6-6: Identified generic Mauri Model indicators for each of the four dimensions

Environmental	Social	Cultural	Economic
Water quality including siltation and nutrients (1, 2, 3, 4, 5, 6, 7, 8, 9, 13, 14)	Health when exposed to water (1, 2, 3, 9, 10, 11, 12, 14)	Spiritual/Cultural/Religious practices (10, 11, 12, 13)	Resources for personal use or for sale**** (1, 3, 4, 5, 10, 11, 12)
Aquatic fauna health, especially endemic species and fish (1, 2, 3, 4, 5, 6, 7, 9, 11, 12, 13)	Education/ research** (2, 3, 9, 11, 12)	Resource gathering for cultural practices (10, 11, 12)	Impact on tourism (5, 7, 8, 9, 11, 12)
Litter (5, 6, 9, 11, 12, 13)	Access to public space/ recreation (1, 5, 7, 9, 11)	Recognition, tolerance, awareness of different cultures (11, 12)	Abstraction/ use of river water, and the economic impacts of poor-quality water (1, 10, 11, 12, 14)
Biodiversity (2, 5, 6, 8, 9, 13)	Clean water and sanitation (7, 10, 11, 12)	Passing down of cultural knowledge (11, 12)	Capital cost (5, 7, 11)
Bird health (1, 2, 7, 9, 13)	Empowerment, co-creation and community involvement (2, 8, 12)	Pride/ show-casing of some cultural practices (11, 12)	Maintenance/ operational costs (5, 7, 11)
Aquatic plant health (2, 4, 5, 9, 13)	Smell (1, 9, Bichai resident)	Safe drinking/ washing water for initiates (10, 12)	Employment/ income opportunities (5, 11, 12)
Terrestrial plant health (4, 6, 11, 12)	Youth appeal and entertainment (11, 12)	Inclusion of indigenous knowledge, both local and ancient (8, 12)	Secondary/ opportunity costs***** (5, 7, 11)
Ecosystem services* (7, 8)	Flooding***	Preservation of historical sites (14)	Impacts on number of rate payers****** (7)

* This term is very broad and could possibly be further detailed and included as separate indicators

** In this instance refers specifically to water/ environmental related education and research

*** No stakeholders raised flooding and when asked three stakeholders mentioned that flooding is not currently a concern. Flooding has been included because it a key safety concern for water management, could become an issue if certain solutions are implemented, was raised as being of concern in a pollution committee meeting, and is a concern for high intensity/ high volume rainfall events which may not have occurred in living memory.

**** Resources varied from fishing and aquaculture to medicinal plants, herbs and wood.

***** This term is very broad but is included to encourage alternative thinking about secondary economic impacts and lost or gained opportunity costs.

****** The inclusion of the impacts on a particular economic group is perhaps controversial, however the economic sustainability of Knysna is dependent on retaining sufficient rate payers to support municipal functions.

6.2.3 Proposed solutions

As an illustration of the use of the model, four possible solutions were identified which could help to address water pollution concerns in the catchments surrounding the Knysna Estuary. The solutions were selected from the list of proposed water management solutions identified by stakeholders. All solutions are envisaged for the Bongani Catchment. The selection of very different solutions allows for a demonstration of how the model works, how the solutions performed in each of the dimensions, and how stakeholder world views affect preference of a solution.

- Solution 1 is a ‘do nothing’ solution, which assumes that no additional water pollution interventions are implemented, and the water quality continues on the current trajectory.
- Solution 2 is an intervention proposed by stakeholders in Khayalethu. The solution includes on-going river clean-up campaigns, combined with an awareness campaign. The awareness campaign would focus on residents who live near natural water courses, and the youth, and would seek to raise awareness of pollution issues and the importance of protecting Knysna’s natural environment. The stakeholders proposed that the campaign should be combined with a fashion show where school children would be tasked with making fashion items from recycled or waste material. The fashion show would showcase the children’s work whilst also raising awareness of environmental issues and making these issues ‘fashionable’. The stakeholders have submitted a proposal to the municipality to obtain funding for this proposed solution.
- Solution 3 is the construction of an artificial wetland in the lower reaches of the Bongani River, which would help to treat pollutants before they reach the estuary, but would not affect pollution higher up in the catchment.
- Solution 4 addresses pollution arising from sewage contamination, as well as water quality concerns with regards to effluent from the WWTW. In this scenario all necessary maintenance and upgrades are carried out to minimise contamination of the watercourses with untreated sewage, and to ensure that the WWTW effluent complies with the facility’s licence conditions.

6.2.4 Outcomes

The impacts of the four solutions on the selected environmental, social, cultural and economic indicators was then assessed. For each solution the impact on each indicator was assigned a value of -2 (reducing sustainability, degrading value) to 2 (enhancing sustainability, restoring value) as discussed by Morgan *et al.* (2013). For example, if a solution were to have a very negative impact on tourism a value of -2 would be assigned, but if the impact on tourism was insignificant it would be assigned a score of 0. The mean score of all indicators in each dimension was then calculated, and is presented in Table 6-7 for each of the proposed solutions. The full assessment of each indicator for each proposed solution is presented in Appendix H. Table 6-7 also shows the overall score for each solution if all dimensions are equally weighted.

For this study the assessment of indicators has only been assigned qualitatively. As discussed in Section 0, the assessment and quantification of indicators should be informed by experts within the relevant fields if the tool is to be applied in future. The Mauri Model assessment presented here has been done on a very high level, to give an indication of how the tool could be used. If the tool is to be used to inform solutions then a full assessment would be required to determine which of the solutions is preferred, to understand the full impacts of each solution, and to identify alternative solutions. A mitigation strategy that combines aspects of each proposed solution may well be the most effective strategy. Preference for any particular strategy does not negate the responsibilities of all parties to comply with the law, including compliance with licence conditions at the WWTW.

Based on the high-level assessment, Solution 2 (river clean-up, awareness campaign and fashion show) scores the highest as it has positive social and cultural scores, as well as ranking reasonably for environmental and economic considerations. The ‘do nothing approach’ (Solution 1) yields a negative score as the continued decline of water quality, as well as the build-up of pollutant loads in the estuary, is likely to increase negative health and environmental effects, which in turn may impact tourism, recreation, fishing, and may even cause rate payers to move away from the area. Solutions 3 and 4 (Wetland in the Bongani River, and addressing of sewage and WWTW concerns) score equally. The wetland has a high environmental score of the solutions assessed as it has the potential to treat multiple pollutants before they reach the estuary, although it has no impact on water courses higher up in the catchment. The wetland has no social or cultural benefits and some economic benefits. The wetland would achieve a higher score if the project were modified to incorporate social and cultural concerns, for example including a recreational walkway and bird hide or promoting education or research. The addressing of sewage issues achieves a high environmental score, impacts water bodies within the catchments, and has social benefits associated with improving health and therefore allowing for recreational activities within the entire catchment area.

Table 6-8 shows the effect of overlaying the normalized world view matrices with the model scores. The preferred solution based on each stakeholder's world view is shown in bold. According to the assessment Solution 2 might be preferred by all stakeholders except the Municipal Environmental Department, for whom Solution 3 might be preferred. For the Khayalethu Youth, who strongly value economic considerations, Solution 2 receives a much higher rating than any of the other solutions, as it has the highest economics score (low costs with a positive impact on tourism and income opportunities). The tool does not necessarily give a true representation of which solution a particular stakeholder will favour, but rather a representation of how someone with their world view might perceive the solution. If the tool is to be applied then stakeholders should be re-engaged to determine whether this assessment is representative of their views.

Table 6-7: Equally weighted Mauri Model Scores

	Score (between -2 and 2)				
Solution	**Enviro.**	**Social**	**Cultural**	**Economic**	**Equal weighting**
1. Do nothing, water quality continues on current trajectory	-0.75	-0.38	0	-0.5	-0.41
2. River clean-up, awareness campaign, fashion show	0.63	0.50	0.38	0.13	0.41
3. Wetland/ reed beds in lower Bongani	1.13	0.00	0.00	-0.13	0.25
4. Municipality addresses sewage and WWTW concerns	0.63	0.50	0.00	-0.13	0.25

Table 6-8: World view assessment of proposed solutions

	Selected stakeholders					
Solution	**SANParks official**	**Knysna Ratepayers Association**	**Environ. Department Municipality**	**Khayalethu Youth**	**Upper Old Place resident**	**Forester**
1. Do nothing, water quality continues on current trajectory	-0.56	-0.56	-0.53	-0.47	-0.43	-0.47
2. River clean-up, awareness campaign, fashion show	**0.46**	**0.40**	0.52	**0.32**	**0.39**	**0.55**
3. Wetland/ reed beds in lower Bongani	0.44	0.39	**0.55**	0.13	0.31	0.37
4. Municipality addresses sewage and WWTW concerns	0.39	0.29	0.46	0.17	0.21	0.47

6.2.5 Critique of the tool

During the stakeholder engagement process and application of the Mauri Model, the following comments were noted regarding use of the tool:

- Some stakeholders struggled with the world view concept.
- The model has value in challenging pre-conceived ideas that decision makers might have about the priorities of different stakeholder groups.
- It is very telling how different stakeholders asserted that their world view to be the most relevant, with compelling arguments. The fact that two groups of stakeholders of very different world views expressed themselves unable to see how anyone could hold a different world view demonstrates how critical this engagement process is. The model adds value in that it could be used as a tool to help different stakeholders understand the opinions and priorities of other stakeholders, and why they favour certain solutions.
- Two stakeholders noted that the analytical hierarchy process prompted them to think differently.
- Various stakeholders found the repetition of questions as part of the analytical process frustrating. Some stakeholders valued the repetition as it allowed them to identify areas where they were conflicted, and to revisit these. Most stakeholders were not completely consistent in their responses.
- One stakeholder found the resolution of the Likert scale too coarse and would have preferred to be able to be able to choose, for example, a value that represents moderately to strongly.
- The model attempts to show which proposed solution would be favoured by different stakeholders, and why. The lumping of indicators under the different dimensions can be deceptive in this regard. For example, a stakeholder may strongly value health and education under the social dimension. These may score poorly for a particular solution, but because recreation, aesthetics and entertainment score well the solution will still be seen to be favoured.
- Allowing stakeholders to help define indicators broadens the thinking of the researcher/ decision maker. Further assessment may lead the decision makers to seek input outside of their field of

expertise, leading to a more trans-disciplinary approach. Whilst those who value a dimension the most should certainly be consulted on relevant indicators, they may have value to add in defining indicators for other dimensions.

- The Mauri Model requires that an equal number of indicators be selected in each field and that all indicators be equally weighted. This approach has limitations in that even within indicator sets some indicators are more important than others. It has the advantage of transparency and less researcher bias in the selection of weightings.
- The outcome of the model is strongly influenced by the selection of indicators. Indicators need to be carefully selected and the process should also be informed by experts in each field, whilst still including the input of stakeholders. The aggregation of indicators needs to be determined with relevant experts, for example water quality could be included as one indicator, or measures of water quality could be included as separate indicators. The interaction between indicators needs to be considered as part of this process.
- Simplification of indicator assessment to only five categories (-2, -1, 0, 1, 2) has advantages and disadvantages. It has advantages in that it is very simple, transparent and there is less room for subjective manipulation of the results. It has disadvantages in that it is possibly overly simplistic and does not allow for range. There is a lot of subjectivity in how complex continuous data is defined into only five categories.
- The complex history of settlement in South Africa means that the inclusion of the cultural dimension is broad, and is not as clearly distinguished as it is in the New Zealand context, where cultural indicators are selected by Māori representatives, and the importance of Māori cultural values are explicitly supported by policy and legislation.
- Several stakeholders challenged the thinking because systems are inter-related, intertwined and cannot easily be separated. The model is reductionist and tries to simplify complex relationships and world views. Nevertheless, it may be a useful tool for bridging the gap between technical thinking and social value systems.

6.2.6 Summary

The Mauri Model was used to understand stakeholder world views, with most of the stakeholders rating environmental concerns as more important than social, cultural or economic concerns. Broader stakeholder engagement is required to determine a wider array of stakeholder world views. The determination of world views showed the divergent world views held by different stakeholders in Knysna, and how stakeholders with entrenched views can fail to understand the world views held by others. The tool adds value in challenging any pre-conceived ideas the researchers or decision makers may have about the world views of stakeholders, and also in providing a basis for further engagement between parties who hold very different world views.

Stakeholder engagement was used to determine relevant indicators in each dimension. This information can assist in applying the Mauri Model or a preferred decision support tool. The information can help decision makers to understand what stakeholders value and how this can be used to inform solutions.

The Mauri Model was applied to four of the identified solutions for addressing water pollution concerns in Knysna. The model was applied at a high level and further engagement with stakeholders and experts would be required to fully apply the model. The analysis showed that a 'do nothing' approaches is not sustainable, as the continued decline of water quality, as well as the build-up of pollutant loads in the estuary, is likely to increase negative impacts across all dimensions. A clean-up and awareness campaign was the preferred solution, as it also scores well for cultural and social dimensions and is inexpensive to fund. The tool demonstrates how the inclusion of other dimensions, such as social considerations, can help to improve proposed solutions. The stakeholder world view matrices were then overlaid over the Mauri Model assessment. This shows how the tool can be used to understand how stakeholder world views may impact the selection of a preferred solution.

The Mauri Model is simple to use but may be considered reductionist. The inclusion of four dimensions ensures that environmental, social, cultural and economic concerns are all incorporated, however it is not representative of the complex interactions and interconnectedness between these dimensions. The equal weighting of the four dimensions allows for transparency, and ensures that cultural practices are considered and indigenous or local knowledge sources are consulted. The complex history of settlement in South Africa means that the inclusion of the cultural dimension is broad, and is not purely representative of indigenous beliefs. The Mauri Model has limitations but it may assist in bridging the gap between technical thinking and social value systems, and help decision makers to determine solutions that are both effective at addressing pollution concerns, and socially acceptable.

6.3 Assumptions and limitations

The following assumptions and limitations apply to the findings of the stakeholder engagement and Mauri Model assessment:

- A limited number of stakeholders were interviewed, and the world view within the interview group has a bias favouring environmental concerns. Broader stakeholder engagement is recommended for further research.
- Stakeholder engagement is an iterative, on-going process. Only one interview was undertaken with each stakeholder as part of this study.
- All data presented in the stakeholder section is the result of interpretation of the interview material by the researcher. In some cases, answers have been grouped with other similar answers, thereby losing any detail or nuance to the answers, and possibly making the responses overly generic.
- Some stakeholders have attempted to represent the views of their organisation but these are naturally influenced by the personal views of the individual, and have not been approved by the organisations.
- The function of indicators should perhaps have been further clarified with stakeholders. Some stakeholders interpreted indicators to mean indicator species. Some stakeholders did not rate certain indicators of importance because they did not perceive these indicators to be currently of value, or because they did not believe that this indicator would be affected. Examples are the issue of flooding and the issue of impact on tourism. Three stakeholders noted that flooding is not currently an issue. To not include flooding as an indicator would be an oversight, because flooding might be a very important issue to these stakeholders if it were to occur. Similarly, one stakeholder commented that

impact on tourism is important but should not be included because the stakeholder did not feel that water management concerns would impact tourism. If the impact on tourism was excluded as an indicator then it would not be possible to assess whether, in fact, this indicator would be impacted. The perceived impact on an indicator should not be used to determine whether that indicator is of value, particularly given that solutions might have secondary effects that are not perceived at an early stage of the project.

- The selection of indicators based on the number of stakeholders who selected these indicators may exclude some important indicators proposed by only one stakeholder. It is recommended that if this tool is used a second round of stakeholder engagement be undertaken. During the follow-up interview all stakeholders should be provided with the full list of identified indicators to comment on or prioritize. Experts in each field should also be consulted in the selection of indicators.
- Only a high-level, qualitative assessment of the proposed solutions using the Mauri Model was undertaken for this study. Further research, and consultation with relevant experts, would be required to fully apply the model.
- The preference that certain stakeholders might feel for a solution is used as an indication of how stakeholder world views can be applied to selected solutions. The solutions were not further workshopped with stakeholders, to receive input on whether this is an accurate representation of their preferences.

7. Conclusions and recommendations

7.1 Conclusions

The Knysna Estuary is of vital conservation importance to South Africa, provides important ecosystem services, and is key to the economic well-being of Knysna. Literature shows that the Knysna Estuary, and in particular the Ashmead Channel, is experiencing negative environmental impacts due to elevated nutrient concentrations, which can lead to eutrophic or hypertrophic conditions, with associated toxic algal blooms and loss of biodiversity. Elevated TSS concentrations could impact water clarity and have detrimental effects on benthic communities. Published historical data on pollution concentrations in the water courses and storm drains that flow to the estuary are limited in duration and spatial extent, and are dated, making it difficult to get a clear picture of the contribution of the catchments to pollution concerns. Water quality sampling and hydrological modelling was undertaken to address this knowledge gap in order to inform solutions and management strategies to address pollution in the Knysna Estuary.

The water quality sampling and analysis identified the Bongani River, in particular, as a significant source of nitrogen and phosphorus concentrations to the Ashmead Channel. This confirms the findings of earlier researchers. Both Total Inorganic Nitrogen (TIN) and Soluble Reactive Phosphorus (SRP) concentrations were significantly higher than historical values (2010 to 2013). TIN concentrations were found to be significantly higher than those in the Salt River Catchments, and not significantly different from concentrations at the WWTW outflow. TIN concentrations in the Upper Bigai (Site 1c) were not significantly different to concentrations in the lower Bongani. Based on the output of the hydrological modelling, TIN and SRP loads of 990 and 140 kg/day respectively were estimated for the Bongani River outfall for a 1:20 year 1-day storm. There is considerable uncertainty associated with these loads but they are useful in illustrating the magnitude of the nutrient loading emanating from the Bongani River.

Nutrient concentrations in the lower Bongani River were significantly higher than those measured in the semi-formal settlements in the upper headwaters. The decline in water quality downstream is unexpected as the middle reaches of the river are a natural water course, with some intact riparian vegetation, which flows through undeveloped catchment in the middle reaches. A combined dilution effect and natural treatment in the water course, should improve water quality in the lower reaches. It is concluded that a significant nutrient source is located between the monitoring points in the upper and lower reaches. Further monitoring is recommended to identify this source of the nutrient enrichment. A similar approach is recommended to identify the source of nutrient enrichment in the Bongani tributary.

At most sample sites in the Bongani, Bigai, Salt and CBD catchments, nitrogen and phosphorus concentrations were high enough to be conducive to eutrophic or hypertrophic conditions. The estimated concentrations of toxic un-ionized ammonia were elevated at many of the sampling sites, and could have detrimental effects on aquatic ecosystems. It is recommended that TAN concentrations be managed to limit the ecological damage of un-ionized ammonia.

The Knysna WWTW discharges effluent into the Ashmead Channel. Data from 2013-2017 shows that the effluent had a very low compliance rate with the licence conditions, particularly for nitrogen, phosphorus and TSS. Elevated concentrations, combined with sustained high flows, leads to high nutrient and TSS loads to the estuary. The estimated concentrations of un-ionized ammonia were very high, and could lead to acute impacts on aquatic organisms. Measurements as part of this study identified the WWTW effluent as one of the most significant sources of TIN, as compared to other sampling sites. TIN and SRP concentrations were found to be conducive to hypertrophic conditions, and were not significantly different from measurements in 2010-2011. It can be concluded that the WWTW has been a source of unacceptably high nutrients for at least nine years. Elevated *E. coli* counts measured at the effluent outflow site could indicate inadequate sewage treatment at the facility. Water Quality concerns at the WWTW need to be urgently addressed.

Elevated TSS data was recorded for discharge points from the Knysna Golf Course, sites below the hospital, the Salt River and the stream outflow at Point. Elevated turbidity data was also recorded for the sites below the hospital and for the Long Street Drain. Increased turbidity and TSS measurements were observed during or immediately after storms. TSS concentrations were significantly lower than historical data for the Salt and Bongani Rivers, and the Long Street Drain.

E. coli concentrations, as measured by the Knysna Municipality, are unacceptably high in the lower Bongani River and the Ashmead Channel. *E. coli* concentrations measured over three years show that compliance with the required standard for recreational use was only achieved 27% of the time in the lower Bongani River, and 37% of the time in the Ashmead Channel. This low compliance is indicative of a chronic, rather than intermittent, pollution issue. *E. coli* spikes were experienced in the Bongani River, the Knysna CBD, the upper Bigai River, and the Salt River. Additional, limited testing undertaken by the KBP highlighted unacceptably high *E. coli* concentrations in many locations within the Bongani Catchment, and in the Upper Bigai River. The most likely source of elevated *E. coli* is human faecal pollution. Sewage leaks and manhole overflows were identified as problematic by most of the stakeholders interviewed. Sewage leaks could also contribute to elevated nutrient concentrations. Water contaminated with human faecal pollution can cause water-borne diseases in those exposed to the water, for example through recreational use. Typical diseases that are associated with human faecal pollution are '*gastroenteritis, giardiasis, hepatitis, typhoid fever, cholera, salmonellosis, dysentery, and eye, ear, nose and skin infections*' (DWAF, 1996a, p. 33). Some of these diseases can be particularly dangerous for young children and people with compromised immune systems. Stakeholder interviews have indicated that children play and swim in the Bongani River in at least two locations. Oysters are no longer commercially cultivated in the estuary, but poor water quality could have adverse impacts on subsistence fisher people, those consuming the fish, and people undertaking recreational activities in the estuary and the Ashmead Channel.

Insufficient data was available for this study to substantiate the claim that '*the Bigai River valley, which retains over 2 km of reedbeds, filters much of the pollution and traps solid waste, emphasizing the importance of reedbeds for the sustainability*' (Marker, 2003, p. 40). TIN, SRP and *E. coli* were all unacceptably high in the Bigai River above the reeds, and the limited data collected does seem to indicate a substantial improvement in *E. coli* and nutrient concentrations in the lower Bigai River, possibly as a result of dilution or treatment through the reed beds. Further monitoring is recommended to establish whether the impact of the reedbeds is significant, as this could inform a potential solution for water quality issues in the Bongani Catchment.

Stakeholders were consulted to provide insight into possible pollution sources, water management challenges, and proposed solutions. Sewage leaks and overflows, as well as the quality of effluent discharge from the WWTW, were consistently identified by most stakeholders as pollutant sources. Litter and sediments were additional pollutants identified as a source for concern for multiple stakeholders. Anecdotal evidence indicates that water pollution has negatively impacted the health of some residents, and that some residents no longer partake in recreational activities that could expose them to contaminated water. The existing environmental impacts of pollution on the Knysna Estuary have been well documented in the literature, and these and potential future impacts are concerning to many of the stakeholders. Environmental impacts higher up in the catchments are also a concern to stakeholders, and can have cultural, social and economic costs. Through the engagement process stakeholders were able to suggest indicators which should serve as performance measures for any proposed solution. Stakeholders also proposed multiple changes in water management approaches, or solutions to address pollution issues. This information can be used to inform possible solutions. The Mauri Model was used to show how the equal valuation of environmental, economic, social and cultural dimensions can impact the selection of a preferred solution. When the stakeholder world views are applied to the selection process, the tool can be used to help decision makers to understand how different stakeholders might perceive solutions, and to inform the design of a solution that is socially acceptable, as well as technically feasible.

7.2 Recommendations for improving surface water management

The results of water quality sampling have been assessed, a hydrological model has been built, and stakeholders have been consulted on current water management challenges in Knysna. These three processes have provided insight into how catchments are contributing to pollution in the Knysna Estuary. On-going research and monitoring are recommended, however based on the findings of this study, the following are proposed to improve catchment surface water management, and limit pollution impacts to the estuary and other natural water courses:

- Effluent from the WWTW needs to achieve compliance with the licence conditions (DWS, 2014). Detailed recommendations to achieve this compliance fall outside the scope of this study.
- It is strongly recommended that the Knysna Municipality investigate the source and cause of sewage leaks and overflows, particularly in the Bongani Catchment and the Upper Bigai Catchment. Proactive management and rapid responses to reported issues would help to minimise the negative impacts of sewage spills. Locations where long-term, on-going problems are reported should be the immediate focus of interventions measures. Intervention measures need to be urgently put in place to protect the health of the Knysna Estuary, and that of the people exposed to contaminated water through recreational or other activities.
- It is recommended that on-going and adaptive water quality monitoring be used to determine pollutant sources and to inform solutions.
- The possibility of using Sustainable Drainage Systems (SuDS) to reduce pollutant loads to the estuary should be further investigated.
- The stakeholder engagement has shown that measures to manage litter, river clean-ups and awareness campaigns are likely to be supported by Knysna residents and stakeholders.
- Other recommendations proposed by stakeholders are discussed more extensively in Section 6.1.4.

7.3 Recommendations for further research

The following areas are recommended for further research:

- Continued water quality monitoring, to build a database of water quality data that can be analysed for spatial and temporal patterns. The continued monitoring of *E. coli* is strongly recommended. Resumption of TSS monitoring could be useful in determining areas of high mobilisation of sediments, particularly at Sites 8, 9, 12 and 18. It is recommended that nutrient testing as Sites 8 and 9 be resumed, and the source of elevated nutrients investigated.
- Further water quality testing at the site below the hospital is recommended. This could be linked with a survey of the occurrence and distribution of antibiotic resistant bacteria.
- Testing for Total Inorganic Phosphorus, rather than Soluble Reactive Phosphorus, will enable better comparison with the water quality guidelines criteria.
- Extending the water quality monitoring to include a site downstream of all Khayalethu runoff, but upstream of the major sewage line. Similarly, on-going monitoring of Site 4g is recommended, and should TIN elevations remain high, add additional monitoring points downstream of semi-formal housing in the Upper Old Place catchment, but upstream of the major sewage line. Add a monitoring point immediately downstream of the organic waste dump.
- Monitor a site downstream of the reed beds on the Bigai to test the hypothesised improvement in water quality as a result of the reed beds.
- Extended monitoring in the Knysna CBD could allow for a comparison between the water quality originating from the Pledge Nature Reserve, and that originating in other parts of the CBD. The results of this dissertation indicate that the quality of water originating in the Pledge Nature Reserve may significantly better than that in the nearby Rawson Street Drain.
- Monitoring of heavy metal and hydrocarbon water quality data, particularly around the industrial area and the N2 highway.
- Continued flow monitoring, and in particular the capture of larger storm data.
- Alternative measures of low flow storm events and base flows.
- Water level data has been captured for the Bigai River as part of this project. Due to time constraints this data was not analysed. Modelling and calibration of this catchment could serve as a useful cross-check against the calibration parameters for the Bongani River.
- Investigation of groundwater flow, and the impact thereof on flows.
- Extension of the hydrological model to include other catchments that drain to the estuary.
- Continuation of hydrological modelling to determine pollutant loads to the estuary and to model possible intervention strategies, including SuDS.
- Determination of pollutant loads to the estuary, and possibly the relative contribution of loads from different catchments or sub-catchments. Accuracy of the loading predictions is very dependent on the accuracy of both flow and pollutant concentration data.
- Broader stakeholder engagement, as discussed in Section 6.1.

- Full application of the assessed decision support tool would require much more detailed identification and assessment of indicators, as well as investigation of alternative solutions.

The following measures would assist in reducing areas of significant uncertainty:

- Establishment of an additional rainfall gauge / gauges higher up in the catchment, ideally with sub-hourly data collection.
- Consider construction of weirs at monitoring stations, to reduce the uncertainty associated with use of the Manning's equation for calculating flow from measured water levels. Alternatively, the Bongani River both upstream and downstream of the gauging site could be cleared of deposited sand, rocks and vegetation.
- Use of alternative flow measurement techniques to confirm the flow data.
- If appropriate locations can be found, then additional flow monitoring higher up in the catchment would greatly assist in isolating areas of uncertainty. Construction of weirs might be required.
- Continuous sampling would add considerable value to data collection efforts.
- On-going and adaptive water quality monitoring will help to reduce uncertainty in the current water quality sampling database.

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Appendix A: Water Quality Monitoring Points

Table A1: Phase 1 water quality monitoring points

Site	DWS/ SSI/ Mun. name*	Description
Site 1		George Rex, East of Leisure Island
Site 2**		George Rex, near Armstrong Rd
Site 3		George Rex, Knysna Golf course
Site 4	DWS KL-05/ Mun. AR5b	Bongani River outflow
Site 5	DWS KL-04/ SSI & Mun. AR5a	George Rex - Knysna WWTW discharge
Site 6		George Rex, drains from old place
Site 7		Below N2 – George Rex junction
Site 8		Below Costa Sarda & Knysna Hospital
Site 9		Western culvert below Knysna Hospital
Site 10		At end of Union Street
Site 11	DWS KL-06/ SSI & Mun. AS9	CBD: Queen Street Drain
Site 12	DWS KL-07/ SSI & Mun. MS3	CBD: Long Street Drain
Site 13	DWS KL-08/ SSI & Mun. MS4	CBD: Station Drain
Site 14	DWS KL-09/ SSI & Mun. MS5	CBD: KADA Drain
Site 15		Drain below Paradise
Site 16	DWS KL-10/ SSI & Mun. US2	Salt River mouth
Site 17		East Point
Site 18		West Point at stream mouth

* Name assigned by the DWS, SSI or the Knysna Municipality

** Only one sample was taken at Site 2. Sampling at this location was abandoned as it was dry at high tides.

Table A2: Phase 2 water quality monitoring points

Revised sites	DWS/ SSI/ Mun. name*	Description
Site 1a		Bigai at Howard Street Culvert
Site 1b		Bigai tributary near Hope Street
Site 1c	SSI LR2.2	Bigai, Hornlee lower
Site 1d		Bigai, Hornlee upper
Site 4	DWS KL-05/ SSI & Mun. AR5b	Bongani River outflow
Site 4a		Vigilance Drive lower
Site 4b		Bongani adjacent to industrial area
Site 4c		Khayalethu Stream, Khayalethu Clinic
Site 4d	SSI AR5b1.4**	Bongani River, Judah Square
Site 4e	SSI AR5b1.4**	Bongani River, Bongani
Site 4g		Bongani Tributary – Upper Old Place
Site 4h		Vigilance Drive north pipe
Site 4i		Vigilance Drive east pipe
Site 5	DWS KL-04/ SSI & Mun. AR5a	George Rex - Knysna WWTW discharge
Site 8a		At N2 below Knysna Hospital - east
Site 9a		At N2 below Knysna Hospital - west
Site 11	DWS KL-06/ SSI & Mun. AS9	CBD: Queen Street Drain
Site 14b	SSI MR5.2	Channel at Stepping Stones – Rawson St.
Site 14c	SSI MR5.1	Channel at Stepping Stones – Trotter St.
Site 16a		Salt at Old Cape Road Culvert
Site 16b		Salt tributary from Simola - Old Cape Rd
Site 16c		Salt 200 m upstream of mouth
Site 18		West Point at stream mouth

* Name assigned by the DWS, SSI or the Knysna Municipality

** Unclear which of these sites Arb1.4 represents, or if it is the combination of the two flows

Appendix B: Hydrological model calibrated parameters

Table B1: Calibrated storage and roughness values

	Surface Manning's (n)		Storage (D)	
	Starting	Calibrated	Starting	Calibrated
Forest	0.6	0.8	7.5	5
Roofs	0.011	0.01	1.5	1
Paved/ tar roads	0.012	0.01	1.5	1
Bare earth/ dirt roads	0.05	0.02	3	1.5
Grass	0.3	0.4	5	2.5

Table B2: Calibrated land use fractions

	Dense semiformal	Industrial	Semiformal	Formal
Roofs	32%	36%	30%	17%
Paved/ tar roads	27%	41%	20%	16%
Bare earth/ dirt roads	21%	0%	30%	0%
Grass	21%	23%	20%	67%

Table B3: Calibrated factors of input parameters

Factors:	Starting	Calibrated
Width (m)	100%	50%
Slope (%)	100%	90%
Imperviousness (%)	100%	100 - 115%*
Irregular channel roughness	100%	200%**

* Catchment dependent

** Starting input parameters for irregular channels (transects) resulted in fast response time.

Appendix C: Interview questions

As part of my Masters' studies I would like to understand what is most important to you. Once you have read and signed the consent form please can you help me by answering the following questions?

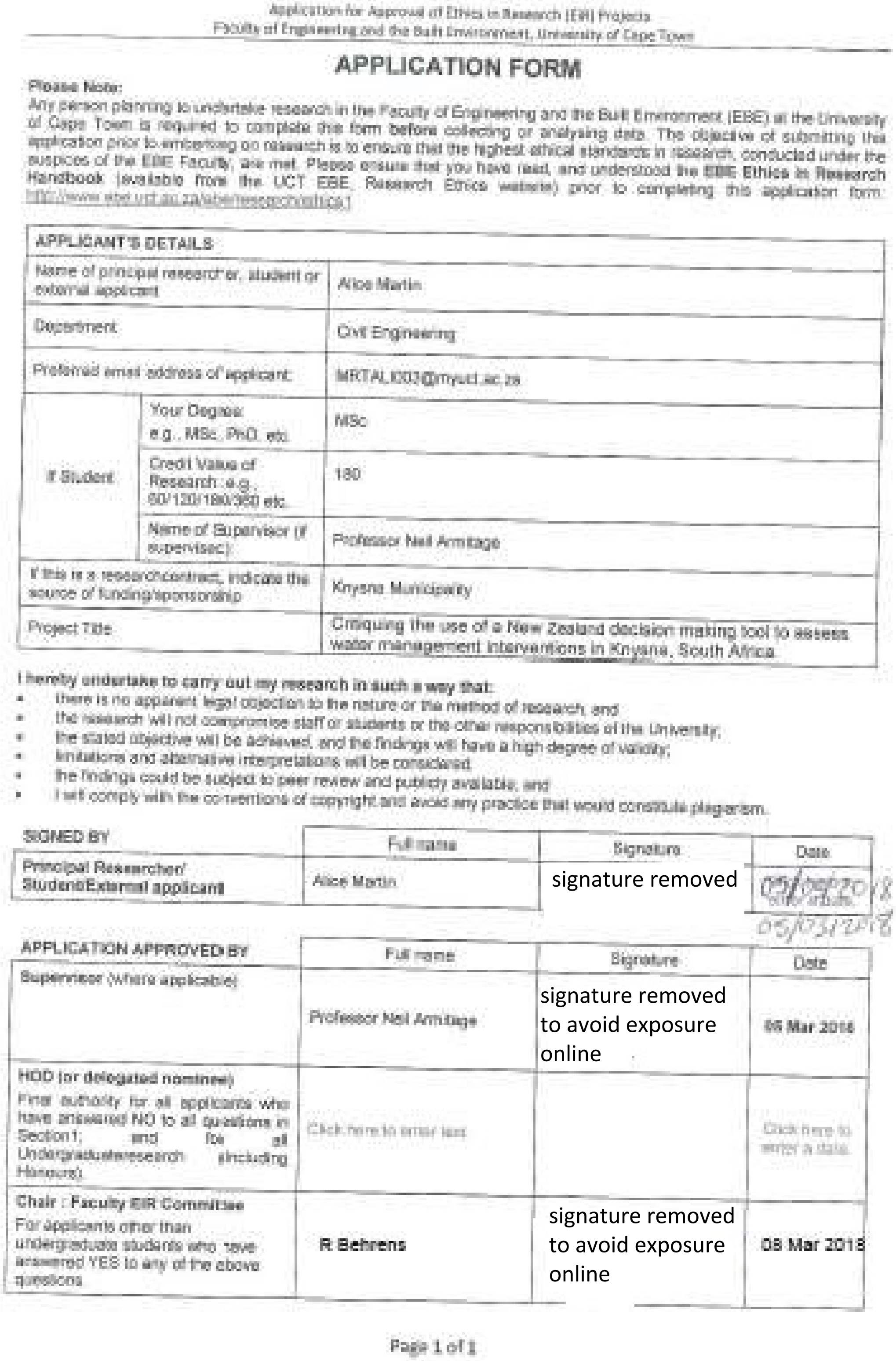
(Researcher explained the four dimensions of environmental, cultural, social and economic and particularly the distinction between cultural and social in this context. Note that the tone of the questions below was adapted to make them more relatable for people from different socio-economic backgrounds.)

1. Which is more important to you, environmental or social concerns, or are they equally important to you? Is the (environmental/social concerns) strongly, moderately or only slightly more important than (environmental/social concerns).
2. Which is more important to you, environmental or economic concerns, or are they equally important to you? Is the (environmental/ economic concerns) strongly, moderately or only slightly more important than (environmental/ economic concerns).
3. Which is more important to you, environmental or cultural concerns, or are they equally important to you? Is the (environmental/cultural concerns) strongly, moderately or only slightly more important than (environmental/cultural concerns).

4 – 12 *Questions follow the same process for all of the other well-beings being compared to each of the others in turn. Requiring that questions are repeated in reverse (comparing social to environmental when environmental has already been compared to social) allows for checking of the consistency of answers.*

13. Do you have any concerns with current water management in Knysna?
14. Is there anything you would like to see changed about water management in Knysna?
15. Are there good management practices you would like to see continuing?
16. For new water projects what would be the most important things you would want the municipality to consider?
17. Do you know of any industries or individuals who are polluting the rivers or estuary?

Appendix D: Ethics approval



Application for Approval of Ethics in Research (EiR) Projects
Faculty of Engineering and the Built Environment, University of Cape Town

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		Alice Martin
Department		Civil Engineering
Preferred email address of applicant		MRTALI002@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 researchcontract, indicate the source of funding/sponsorship		Knysna Municipality
Project Title		Critiquing the use of a New Zealand decision making tool to assess water management interventions in Knysna, South Africa

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.

SIGNED BY	Full name	Signature	Date
Principal Researcher/ Student/External applicant	Alice Martin	signature removed	05/03/2018

05/03/2018

APPLICATION APPROVED BY	Full name	Signature	Date
Supervisor (where applicable)	Professor Neil Armitage	signature removed to avoid exposure online	05 Mar 2018
HOD (or delegated nominee) Final authority for all applicants who have answered NO to all questions in Section1; and for all Undergraduateresearch (Including Honours)	Click here to enter text.		Click here to enter a date.
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions	**R Behrens**	signature removed to avoid exposure online	**08 Mar 2018**

Page 1 of 1

Appendix E: Stakeholder water management challenges

Table E1: Full list of water management challenges raised by stakeholders

Category	Water management challenge	Stakeholders
Management	Problems are not being addressed, there is a lack of response/ slow response to reported issues	1, 3, 6, 9, 10, 14
	Development, without sufficient supporting infrastructure, has and will negatively affect the receiving environment	4, 5, 7, 12, 13
	There are too many players and a lack of co-ordination between players in the water and environmental management sectors, there is no over-arching vision	6, 8, 9, 12
	There is a lack of implementation and enforcement of regulations	9, 11, 12
	There are too many surveys, stakeholder engagements, strategy documents and meetings but insufficient action is being taken to address issues	2, 8, 9
	There is a lack of buy-in from the municipality on proposed environmental projects	10, 11
	Water security/ quality hasn’t been well managed historically	7, 11
	Youth don't find environmental issues interesting, and these need to be presented in a way that is relevant to the youth	10, 11
	Incompetence is an issue, one stakeholder raised this issue for the municipality and one for outside contractors employed by the municipality	2, 7
	Water is treated as waste rather than as a resource	8, 12
	There is a general lack of respect for the natural environment and water within Knysna communities	5, 8
	Tasks need to be completed correctly the first time (‘Do right first time’)	9
	The municipality appears to have few/ no performance measures and performance is not assessed according to performance measures	2
	Decision makers do not always involve communities in projects and decision making that affects them	12
	Decision makers are not present at meeting of the relevant committees	5
	There are illegal connections of stormwater into the sewage system	8
	Red tape is hindering appropriate response to environmental issues	9
	Agriculture is less environmentally regulated than forestry	5
	CWP staff don't clean satisfactorily and some of the appointed staff are from outside of the community	11
	Measurement is not always adequate, for example water consumption is based on measurements at the WWTW not on municipal water supply	8
	Solid waste is not always collected	12

Category	Water management challenge	Stakeholders
Pollution	Sewage leaks and manhole overflows are reporting to the environment	1, 2, 3, 4, 5, 6, 7, 9, 11, 13, 14, *
	Litter is a pollutant of concern	5, 6, 9, 11, 12, 13, *
	The capacity and/or quality of effluent at the WWTW is a concern	1, 4, 6, 7, 9, 13
	Siltation and sedimentation of streams and the estuary is concerning	2, 9, 13, 14, *
	Nutrient enrichment and eutrophication of streams, the estuary and in particular the Ashmead Channel is concerning	2, 7, 9, 13
	Stormwater runoff from informal areas and streams flowing through these areas is of poor quality	11, 12, 13
	Unpleasant smells indicate poor water quality	1, Hornlee Resident, *
	Waste is being disposed of in rivers	10, 11, *
	There is a risk of contamination of dams that supply drinking water due to sabotage or pollution issues at the water source	10, 11
	Chemical pollutants like oil, diesel, petrols, paints are problematic	4
	Discharge of brine from the Reverse Osmosis plant may start to have detrimental environmental impacts	13
	The impact of the use of herbicides and fertilizers at the three golf courses is not known	13
	A large sewage pipe crossing the river above Upper Old Place is poorly secured to the supporting pylons and at one point fell off	14
	Sewage blockages result from the flushing of incorrect material down toilets	11
	Inappropriate use of dustbins (for example as means to transport goods) leads to littering	11
	Smoke from fires at the garden waste dump negatively affects residents	12
General environmental and social concerns	Health concerns relating to exposure to contaminated water through direct contact or consumption of agricultural produce irrigated with river water, or consumption of fish	1, 3, 10, 11, 14
	There has been a decline in river water quality over time	1, 10
	There has been a decline in the health of the estuary over time but incremental changes are not always visible, particularly given the flushing effect	7, 9
	Flushing of the estuary carries pollutants out to sea	6, 7
	Lack of flushing of the Ashmead Channel has led to a pollutant build-up	6, 13
	Concerned about the impact of abstraction on the ecological reserve, particularly during extreme dry weather conditions	13
	Natural systems are extremely compromised - especially around George Rex Drive	4
	Wetlands are being very poorly managed	4

*Witnessed on site

Appendix F: Stakeholder world views

Environmental Organisation 1, employee 1:

Mauri Wellbeing	Ecosystem	Community Social	Hapu Cultural	Whanau Economic	Total
Ecosystem	0	1	3	2	**42%**
Community Social	-1	0	2	1	**31%**
Hapu Cultural	-3	-2	0	-3	**3%**
Whanau Economic	-2	-1	3	0	**25%**
					100%

Environmental Organisation 1, employee 2:

Mauri Wellbeing	Ecosystem	Community Social	Hapu Cultural	Whanau Economic	Total
Ecosystem	0	3	3	3	**50%**
Community Social	-3	0	-2	2	**17%**
Hapu Cultural	-3	2	0	2	**28%**
Whanau Economic	-3	-2	-2	0	**6%**
					100%

Environmental Organisation 2:

Mauri Wellbeing	Ecosystem	Community Social	Hapu Cultural	Whanau Economic	Total
Ecosystem	0	2	2	3	**44%**
Community Social	-2	0	1	1	**25%**
Hapu Cultural	-2	-1	0	1	**19%**
Whanau Economic	-3	-1	-1	0	**11%**
					100%

Environmental Organisation 3:

Mauri Wellbeing	Ecosystem	Community Social	Hapu Cultural	Whanau Economic	Total
Ecosystem	0	2	3	2	**44%**
Community Social	-2	0	2	0	**25%**
Hapu Cultural	-3	-2	0	-2	**6%**
Whanau Economic	-2	0	2	0	**25%**
					100%

Environmental Organisation 4:

Mauri Wellbeing	Ecosystem	Community Social	Hapu Cultural	Whanau Economic	Total
Ecosystem	0	3	3	3	**50%**
Community Social	-3	0	2	0	**22%**
Hapu Cultural	-3	-2	0	-3	**3%**
Whanau Economic	-3	0	3	0	**25%**
					100%

Judah Square Rastafarian community:

Mauri Wellbeing	Ecosystem	Community Social	Hapu Cultural	Whanau Economic	Total
Ecosystem	0	1	1	1	**33%**
Community Social	-1	0	0	2	**28%**
Hapu Cultural	-1	0	0	2	**28%**
Whanau Economic	-1	-2	-2	0	**11%**
					100%

Knysna Municipality environmental section:

Mauri Wellbeing	Ecosystem	Community Social	Hapu Cultural	Whanau Economic	Total
Ecosystem	0	3	3	3	50%
Community Social	-3	0	3	2	31%
Hapu Cultural	-3	-3	0	1	11%
Whanau Economic	-3	-2	-1	0	8%
					100%

Knysna Ratepayers' Association:

Mauri Wellbeing	Ecosystem	Community Social	Hapu Cultural	Whanau Economic	Total
Ecosystem	0	2	3	0	**39%**
Community Social	-2	0	2	-2	**19%**
Hapu Cultural	-3	-2	0	-3	**3%**
Whanau Economic	0	2	3	0	**39%**
					100%

Knysna Resident 1:

Mauri Wellbeing	Ecosystem	Community Social	Hapu Cultural	Whanau Economic	Total
Ecosystem	0	3	3	3	**50%**
Community Social	-3	0	1	2	**25%**
Hapu Cultural	-3	-1	0	2	**19%**
Whanau Economic	-3	-2	-2	0	**6%**
					100%

Knysna Resident 2:

Mauri Wellbeing	Ecosystem	Community Social	Hapu Cultural	Whanau Economic	Total
Ecosystem	0	3	3	3	**50%**
Community Social	-3	0	3	1	**28%**
Hapu Cultural	-3	-3	0	2	**14%**
Whanau Economic	-3	-1	-2	0	**8%**
					100%

Knysna Resident 3:

Mauri Wellbeing	Ecosystem	Community Social	Hapu Cultural	Whanau Economic	Total
Ecosystem	0	-1	2	3	**36%**
Community Social	1	0	3	2	**42%**
Hapu Cultural	-2	-3	0	1	**14%**
Whanau Economic	-3	-2	-1	0	**8%**
					100%

Knysna Resident 4:

Mauri Wellbeing	Ecosystem	Community Social	Hapu Cultural	Whanau Economic	Total
Ecosystem	0	0	0	-3	**17%**
Community Social	0	0	3	-3	**25%**
Hapu Cultural	0	-3	0	-3	**8%**
Whanau Economic	3	3	3	0	**50%**
					100%

Stakeholder in the commercial forestry industry:

Mauri Wellbeing	Ecosystem	Community Social	Hapu Cultural	Whanau Economic	Total
Ecosystem	0	2	0	0	**31%**
Community Social	-2	0	-2	-1	**11%**
Hapu Cultural	0	2	0	-1	**28%**
Whanau Economic	0	1	1	0	**31%**
					100%

Xhosa Initiation school:

Mauri Wellbeing	Ecosystem	Community Social	Hapu Cultural	Whanau Economic	Total
Ecosystem	0	-3	3	-3	**17%**
Community Social	3	0	-2	-2	**22%**
Hapu Cultural	-3	2	0	-2	**17%**
Whanau Economic	3	2	2	0	**44%**
					100%

Appendix G: Mauri Model full list of identified indicators

Environmental	Social	Cultural	Economic
Water quality including siltation and nutrients (1, 2, 3, 4, 5, 6, 7, 8, 9, 13, 14)	Health when exposed to water (1, 2, 3, 9, 10, 11, 12, 14)	Spiritual/Cultural/Religious practices (10, 11, 12, 13)	Resources for personal use or for sale (1, 3, 4, 5, 10, 11, 12)
Aquatic fauna health, especially endemic species and fish (1, 2, 3, 4, 5, 6, 7, 9, 11, 12, 13)	Education/ research (2, 3, 9, 11, 12)	Resource gathering for cultural practices (10, 11, 12)	Impact on tourism (5, 7, 8, 9, 11, 12)
Litter (5, 6, 9, 11, 12, 13)	Access to public space/ recreation (1, 5, 7, 9, 11)	Recognition, tolerance, awareness of different cultures (11, 12)	Abstraction/ use of river water, and the economic impacts of poor-quality water (1, 10, 11, 12, 14)
Biodiversity (2, 5, 6, 8, 9, 13)	Clean water and sanitation (7, 10, 11, 12)	Passing down of cultural knowledge (11, 12)	Capital cost (5, 7, 11)
Bird health (1, 2, 7, 9, 13)	Empowerment, co-creation and community involvement (2, 8, 12)	Pride/ show-casing of some cultural practices (11, 12)	Maintenance/ operational costs (5, 7, 11)
Aquatic plant health (2, 4, 5, 9, 13)	Smell (1, 9, Bichai resident)	Safe drinking/ washing water for initiates (10, 12)	Employment/ income opportunities (5, 11, 12)
Terrestrial plant health (4, 6, 11, 12)	Youth appeal and entertainment (11, 12)	Inclusion of indigenous knowledge, both local and ancient (8, 12)	Secondary/ opportunity costs (5, 7, 11)
Ecosystem services (7, 8)	Flooding	Preservation of historical sites (14)	Impacts on number of rate payers (7)
Tidal exchange (4, 6)	Aesthetics (9, 12)	Protection of spiritual/ cultural/ religious places (10, 12)	Raising youth awareness of alternative careers e.g. conservation, engineers (11)
Ecological reserve (5, 13)		Sense of identity (11, 12)	Cost-benefit ratio (7)
Impact on salinity (13)		Historical association with place (14)	Supply of services such as water and sanitation (7)
Blue-green corridors (5)			Business education (11)
Terrestrial fauna health (11)			Prioritization of spending (7)
Functioning of the estuary (4)			Cost incurred (10)
Algal blooms (2)			
Functions similarly to the surrounding environment/ designed in context (8)			
Promotion of infiltration and evapotranspiration (8)			
Limitation of erosion (8)			

Appendix H: Mauri Model indicator assessment

Table H1: Assessment of environmental indicators

Environmental	**Solution 1**	**Solution 2**	**Solution 3**	**Solution 4**
Water quality	-1	1	2	1
Aquatic fauna health, especially endemic species	-1	0	1	1
Litter	0	2	0	0
Terrestrial plant health	0	1	1	0
Bird health	-1	1	1	1
Siltation/ water turbidity	-1	0	2	0
Biodiversity	-1	0	1	1
Aquatic plant health	-1	0	1	1
Total	**-0.75**	**0.63**	**1.13**	**0.63**

Table H2: Assessment of social indicators

Social	**Solution 1**	**Solution 2**	**Solution 3**	**Solution 4**
Health when exposed to water	-1	0	1	2
Environmental awareness/ education/ research	-1	1	0	0
Access to public space/ recreation	-1	0	0	1
Clean water and sanitation	0	0	0	0
Youth appeal and entertainment	0	1	0	0
Smell	0	1	0	1
Empowerment	0	1	0	0
Flooding	0	0	-1	0
Total	**-0.38**	**0.50**	**0.00**	**0.50**

Table H3: Assessment of cultural indicators

Cultural	Solution 1	Solution 2	Solution 3	Solution 4
Spiritual/Cultural/Religious practices	0	0	0	0
Resource gathering for cultural practices	0	0	0	0
Recognition, tolerance, awareness of different cultures	0	1	0	0
Passing down of cultural knowledge	0	0	0	0
Pride/ show-casing of some cultural practices	0	1	0	0
Safe drinking/ washing water for initiates	0	0	0	0
Preservation of historical sites	0	0	0	0
Sense of identity	0	1	0	0
Total	**0.00**	**0.38**	**0.00**	**0.00**

Table H4: Assessment of economic indicators

Economic	Solution 1	Solution 2	Solution 3	Solution 4
Capital cost	0	-1	-2	-2
Maintenance costs	0	-1	-1	-1
Impact on tourism	-1	1	0	0
Resources for personal use or for sale	0	0	0	0
Employment/ income opportunities	0	1	1	1
Impact on aquaculture/ fishing/ shellfish (3)	-1	1	1	1
Impact on businesses (1)	-1	0	0	0
Impacts on number of rate payers (1)	-1	0	0	0
Total	**-0.50**	**0.13**	**-0.13**	**-0.13**