An analysis of surface water from an informal settlement, Langrug, Franschhoek: *down a slippery slope*

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DECLARATION

I, Jessica Fell, acknowledge that,

1. I am presenting this dissertation in fulfilment of the requirements for my degree.
2. I know the meaning of plagiarism and declare that all of the work in the dissertation, save for that which is properly acknowledged, is my own.

Signed: Date: 14 August 2017

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ABSTRACT

Contaminated surface water from limited sanitation and drainage systems in informal settlements degrades receiving rivers. However, little is known about the water quality and flow of rivers draining informally settled catchments. This study explores the dynamics of a human water system in an informally settled catchment in the present, and then uses these insights to investigate possible trajectories in the future. The objectives are twofold: (i) to characterise the water quality and flow of a river draining an informally settled catchment in Franschhoek, South Africa, and, (ii) to investigate the hydrologic and water quality effects of future land use and climate changes in the catchment. River water samples were collected during dry days for four months and over five rainfall events. Highly elevated concentrations of NH_3-N (8.4 ± 5.2mg/L), PO_4^{3-} (5.9 ± 7.4mg/L) and TSS (135 ± 124mg/L) were recorded in the informal settlement. Correlation analyses between land use types and water quality showed significant relationships between informal settlement and NH_3-N, PO_4^{3-}, DO, EC and TSS. Multiple regression models investigated six hypothetical land use changes scenarios and indicated that if informal settlement and built-up area doubled in size, there would be an increase in the concentration of NH_3-N by 83%, PO_4^{3-} by 85% and TSS by 86%. During the rainfall events multiple NH_3-N, PO_4^{3-}, TSS concentration peaks were observed, with concentrations peaking at 3.5mg/L, 6.6mg/L and 1868mg/L respectively. Various significant correlations between lagged rainfall and pollutant concentrations revealed that rainfall caused an increase in NH_3-N, PO_4^{3-} and TSS after one hour, while NO_3^--N and DO responded to rainfall after two hours and flow after three hours. Multiple regression models explored two hypothetical climate change scenarios involving an increase in the 10 and 20 year design rainfall depth. The models demonstrated that if the rainfall depth of a 20 year rainfall event increased by 15%, there would be an increase in peak concentration of NH_3-N by 17% and PO_4^{3-} by 15%, a decrease in DO by 21%, and an increase in peak flow by 21%. The results reveal the pervasive impacts of the informal settlement on river water quality, especially as regards nutrient contamination from wastewater. The land use and climate change scenarios serve as a warning of the long term consequences of inevitable land use and climate changes in informal settlements.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 : INTRODUCTION

1.1 Overview

Contaminated surface water plagues informal settlements of the developing world (Jamwal et al. 2011; Monney et al. 2013; Jiusto and Kenney 2015; Capps et al. 2016). The continual flows of surface water pollute the surrounding environment, threaten the health of residents and contaminate receiving waterways (Parkinson and Mark 2005; Nyenje et al. 2010; Alirol et al. 2011; Armitage 2011). Peri-urban catchments in developing countries are becoming increasingly occupied by informal settlements (Paterson et al. 2007). As urbanisation draws more people to cities, the poor are forced to live further out the city, occupying marginal land in the peri-urban area - defined as ' the space around cities that merges into the rural landscape' (Piorr et al. 2011). The land use of these catchments is being converted from agriculture or natural vegetation to urban, and more specifically informal settlements (Tucci 2001). Urbanisation brings with it a range of well-established hydrological challenges (Wong and Eadie 2000; Schoeman et al. 2001; Butler and Davies 2011; Baek et al. 2015). These challenges are primarily associated with the increase of impervious surfaces and the introduction of artificial drainage, which reduces infiltration and increases runoff and pollutant loads (Horner et al. 1994; Mckee et al. 2003). The impacts have multiple adverse effects on urban rivers, a phenomenon termed the "urban stream syndrome", whose notable symptoms include increased flows, flashier hydrographs and elevated concentrations of nutrients and contaminants (Walsh et al. 2005).

Recent work by Braud et al. (2013) suggests that the hydrological impacts caused by urbanisation are also present in peri-urban catchments, although there is a lack of data for these areas (Harremös 2002). Peri-urban areas are characterized by a high degree of heterogeneity, containing a "patchwork of urban, undeveloped (natural) and agricultural lands" (Andrieu and Chocat 2004). Informal settlements in peri-urban catchments are characterised by bare compacted earth with limited sanitation and drainage services, which together produce even more varying and unknown effects on the receiving rivers (Parkinson et al. 2007). According to Parkinson et al. (2007), catchments in these environments have significantly different physical characteristics than those in developed countries, which cause wide variations in the rainfall-runoff response and the resultant volume of peak flow. Furthermore, there are increased pollutants in these environments from urban runoff mixing with wastewater from leaking communal toilets and limited drainage systems (Capps et al. 2016).

Informal settlements are harsh places to live (Kimani-Murage and Ngindu 2007; Ajibade et al. 2013). According to the United Nations Human Settlements Programme, an informal settlement is defined as an area with inadequate access to potable water, sanitation, drainage and other infrastructure, sub-standard housing, a high population density and insecure land tenure (UN-Habitat 2003). The interaction of these factors often results in the serious and extensive contamination of surface water (Olaseha and Sridhar 2003; Borges et al. 2015). Armitage (2011) describes surface water in informal settlements as a toxic cocktail of stormwater mixed with greywater, sewage and urban refuse. Contaminated surface water poses serious health and environmental risks, and often results in the gross pollution of rivers draining informally settled catchments (Masamba and Mazvimavi 2008; Nyenje et al. 2010; Joshi et al. 2014; Monney et al. 2013; Katukiza et al. 2015). For example, Mokaya et al. (2004) found that the Njoro River in Kenya, which flows through informally settled and cultivated land, was contaminated by nutrients caused by the poor sanitation facilities in riparian zones. Jamwal et al. (2008) discovered that point and non-point microbial pollution from sewage effluent and stormwater were responsible for the poor water quality in the river Yamuna, which was caused by the discharge of urban runoff from a slum dominated watershed in India.

In 2001, 924 million people lived in informal settlements, this number is projected to almost double to 2 billion in 2030 (UN-Habitat 2003). According to Niemczynowicz (1999) many of these people will live in peri-urban slums in the vicinity of megacities, resulting in the conversion of these lands to urban, and more specifically informal settlement land use. This will result in the increased consumption of water, however, it is unlikely that it will be matched by the provision of wastewater disposal and treatment services, and other infrastructure (Reed 2013; Capps et al. 2016). Thus, it is probable that the conversion of land in peri-urban catchments to informal settlements will result in the further contamination of receiving rivers. However, it is uncertain how land use changes will manifest in informal settlements in terms of water quality and flow, relative to their well studied urban area counterparts (Tong and Chen 2002; DeFries and Eshleman 2004; Verburg et al. 2004; Praskievicz and Chang 2009).

In addition to land use changes, climate changes will drive hydrologic and water quality changes in informally settled catchments (Savenije et al. 2014). In South Africa, climate change is predicted to cause increased rainfall variability, including more intense rainfall events (Hewitson and Crane 2006; Department of Environmental Affairs 2013). These changes will have varying effects on flow and pollutants in rivers (Kusangaya et al. 2014). The unique characteristics of informally settled catchments may produce differences in rainfall-runoff processes and washoff of pollutants (Parkinson 2002). Furthermore, communities in informal settlements are more vulnerable to climate changes relative to other urban communities (Satterthwaite 2007). Climate and land use changes affect both the quality and quantity of rivers draining informally settled catchments. Managing these changes will require a quantitative understanding of how hydrologic and water quality impacts could manifest in these environments.

Rockstrom et al. (2014) notes that water resource management is entering the turbulent era of the Anthropocene, where humans are controlling the great forces of nature (Savenije et al. 2014). Humans can no longer be considered as external forcings in the hydrological cycle, rather Sivapalan et al. (2012) advocate for a focus on coupled human-water systems that considers interactions, feedbacks and emergent patterns. In the burgeoning informal settlements in peri-urban catchments of the developing world, we remain relatively ignorant of the interactions between humans and the water cycle. Understanding highly contaminated surface water in these environments requires a deeper analysis of catchment dynamics and river water quality and flows. Furthermore, it requires an exploration of the potential ways land use change and climate change could manifest.

In urban catchments of the developed world, there is a firm grasp on hydrology and water quality dynamics of various types of water including stormwater runoff, urban streams and wastewater (Walsh et al*.* 2005; Butler and Davies 2011; Barbosa et al. 2012). Such catchments have been systematically studied and monitored and there are well established relationships between land uses and hydrology, and the expression of rainfall events in these environments (eg. Mulliss et al. 1996; Ahearn et al. 2005; Schoonover and Lockaby

2006; Bach et al. 2010; He et al. 2010; McGrane et al. 2017). Furthermore the impacts of climate and land use changes have been examined, both individually and in tandem, and adaptation strategies have been developed for a broad range of trajectories, based on credible data (Denault et al. 2006; Zhang and Schilling 2006; Viger et al. 2011; Tong et al. 2012; Miller et al. 2014; El-Khoury et al. 2015; Semadeni-Davies et al. 2016).

However, in informal settlements of the developing world, we have a tenuous grasp on the most basic hydrological dynamics (Reed 2013; Jiusto and Kenney 2015; Capps et al. 2016). At best, there is a patchy and incomplete picture of water quality and flows, which have been gained primarily through isolated grab samples and spot measurements (Tucci 2001; Goldenfum et al. 2007). The environment in informal settlements has remained largely unexamined, with a poor understanding of catchment characteristics and behavioural differences which drive the unique hydrology in these areas (Parkinson 2002). There is little consideration of other land uses that exist alongside informal settlements, and the ways these interact and produce varying effects on hydrology (Mokaya et al. 2004; Rodríguez et al. 2013). Schoeman et al. (2001) also recognised the limitations of hydrologic studies in informal settlements of South Africa. These authors noted that very few studies were capable of providing meaningful data with regards to simultaneous water quality and flow measurements that would allow for the derivation of even semi-quantitative relationships. For an assessment of this kind, at least the minimum, maximum and median values for flow and pollutant concentrations, loads and export coefficients of water quality constituents are required for base flow and storm flow. However, for most studies, only mean values were reported, and flow was very seldom measured simultaneously with water quality. Aside from the poor understanding of what happens to water when it moves through an informal settlement in the present, there has been no exploration of how inevitable climate and land use changes could manifest in these environments in the future (Capps et al. 2016).

Sivapalan et al. (2012) assert that the study of human water systems through routine monitoring provides a way to gain more detailed insights into causal relationships. The authors state that through detailed data collection, we can better understand human-water system functions in the present to be able to predict possible trajectories in the future. This study uses this concept to explore the profound hydrologic unknowns in the present and the future in an informally settled catchment in South Africa.

1.2 Aims and Objectives

The aim of this study is to analyse the flow and water quality of a river draining an informally settled catchment, and to investigate these variables under selected climate and land use change scenarios.

Objectives:

- To characterize river water quality and flow during (i) periods with no rainfall (during the wet season) and, (ii) rainfall events
- To determine the relationships between river water quality and land use types in an informally settled catchment
- To establish the relationships between rainfall characteristics and water quality parameter concentrations and flow in a river during rainfall events.
- To model increased rainfall depth due to climate change on river water quality and flow using a range of hypothetical scenarios
- To model land use changes on river water quality using a range of hypothetical scenarios

1.3 Study site

Informal settlements are a ubiquitous part of urban South Africa, with 1.25 million households occupying these areas in 2011 (StatsSA 2012). These settlements, known as slums elsewhere, are often located on marginal land outside of cities, with distinct geographical lines that separate them from higher income areas (Armitage 2011). This is a remnant of the old Apartheid Group Areas Act, which relocated black and coloured South Africans to designated, undeveloped land outside of the City. The forced segregation was designed to repress black South Africans and it's legacy still lives on today, most visibly in the many poverty stricken informal settlements dotted around peri-urban catchments (Bouchard et al. 2007).

Although there is great variability between and within these settlements, they are usually densely populated, inadequately resourced, poorly managed and lacking most basic urban services. Of the basic urban services provided, there are typically a few communal tap stands to supply potable water, a small number of communal toilets, a rudimentary solid waste collection and no formalized drainage system (Armitage 2011). Drainage is not a basic service in South Africa and is usually only a feature in higher income formal urban areas. A formalized drainage system in an unplanned informal settlement is low on the priority list, where emphasis is instead placed on the provision of water and sanitation (Armitage et al. 2010). Surface flows are generated daily from public taps stands, washing facilities, dysfunctional communal sanitation systems, rainfall and the discharge of used household water (Winter 2016). Without adequate drainage, this surface water is a continual menace to residents as it flows past homes and accumulates in foul pools around the settlement. The surface water ultimately discharges into receiving rivers, and results in a range of largely unknown consequences on water quality and flow.

This study is situated in one of the many informally settled peri-urban catchments that are so characteristic of post-Apartheid South Africa. More specifically, the study is located in the Stiebeuel River catchment in the peri-urban area of Franschhoek, 80km out of Cape Town's CBD (Figure 1). The area has a Mediterranean climate with hot and dry summers and cold and wet winters, with an average annual rainfall of 863mm, 80% of which falls within April to September (De Clercq et al. 2006). Franschhoek has a population of 40 000 with three main clusters of development that house the population, namely Franschhoek Town, Groendal and La Motte (Rossouw 2009) (Figure 1). The three areas represent the entire socioeconomic spectrum and are split along geographical lines according to the predominant socio-economic status. The Stiebeuel River catchment is just out of the wealthy town centre, and contains the low income area of Groendal, the informal settlement of Langrug and other land uses. The location of the informal settlement and low income area is a remnant of the old Apartheid Group Areas Act, with residents in the settlements occupying marginal land on the periphery and working in the nearby town and agricultural area.

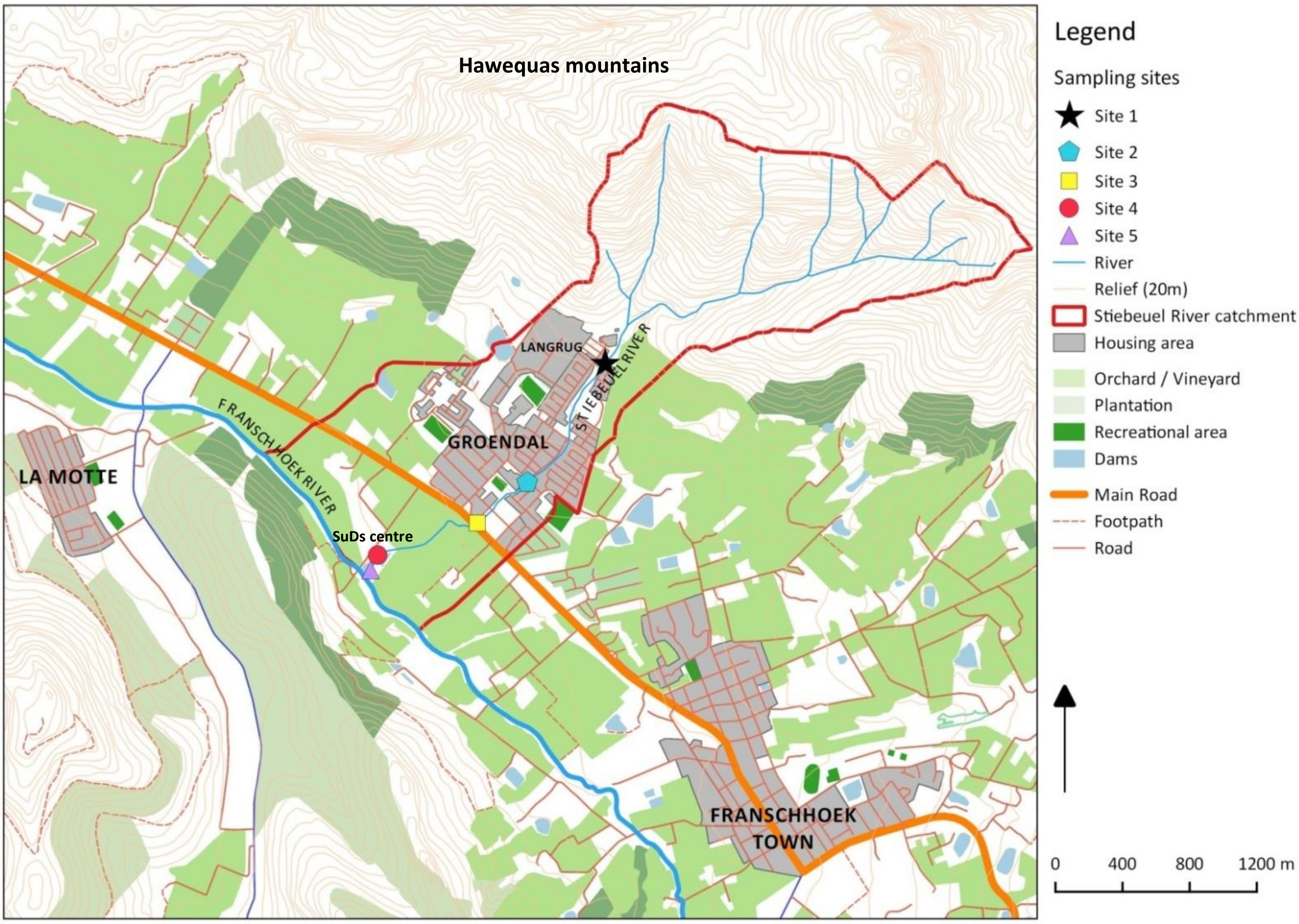

Figure 1. The greater Franschhoek area with the study area (the Stiebeuel River catchment) outlined in red and the informal settlement and low income area indicated.

The Stiebeuel River flows through four main land use types, including the informal settlement and low income area, from its start in the Hawequas mountains to its confluence with the Franschhoek River. The river starts high up in the Hawequas mountains, after which it flows through the informal settlement of Langrug which is encroaching up the mountain slopes. The community in Langrug comprises 6000 residents that live in considerable deprivation in 2500 flimsy densely packed shack homes (Winter 2016). The shacks are characteristic of slums around the world and are constructed with various scrap materials (Figure 2). There are limited basic services in the settlement with one formal paved road, six communal tapstands and 40 flush toilets, most of which are dysfunctional. The ground consists of bare compacted earth that is functionally impervious.

Figure 2. Densely packed shack homes constructed with various materials in the informal settlement of Langrug.

There is a mix of formal and informal drainage channels, with one concrete-lined culvert and various informal earth lined streams and ditches that serve as drainage channels. They often end up conveying a toxic mix of stormwater, blackwater from dysfunctional sanitation systems, discarded greywater and solid waste. The Stiebeuel River, which runs alongside the settlement, receives pollution from the sources described above. The settlement has been the subject of various upgrading projects in the past.

After Langrug, the river meanders through the low income built-up area of Groendal. Groendal consists of small plots of formal housing or government low cost housing with paved roads running between the houses. The majority of the houses have their own plumbing systems and there are conventional stormwater drains in the area.

A main road forms the boundary between Groendal and some vineyards that the river flows through. The wine farms are owned by English and Afrikaans speaking people that live on the farms in upmarket accommodation. Diffuse runoff from the agricultural lands in this zone drain into the Stiebeuel River. Just before its confluence with the Franschhoek River, it flows through the site of the Water Hub, the new site of a Sustainable Urban Drainage (SuDs) centre to treat contaminated water from the upstream areas.

1.4 Study Design and Overview of methods

The focus of this study is to provide insights into the hydrological dynamics of a human-water system in the present and then use these to explore possible trajectories in the future. In the informally settled Stiebeuel River catchment there are varying land uses which each produce unique and unknown effects on the hydrology and water quality in the Stiebeuel River. These unknowns also extend to future trajectories of change, namely land use and climate changes, which present more hydrological uncertainties.

This study addresses these unknowns through two distinct research activities, to explore surface water in the present- through water quality and flow analyses- and the future- through multiple regression modelling. Data collection for both research phases was conducted during the winter rainfall period of 2016. The water quality of the Stiebeuel River was determined by collecting grab samples on dry days in between rainfall events, and by measuring water quality, flow and rainfall during five varying rainfall events. Multiple water quality parameters were analysed to determine water quality, most notably nutrient parameters.

To establish relationships between land uses and water quality in the Stiebeuel river catchment, correlation analyses were performed using remotely sensed data and Geographic Information Systems (GIS). Multiple regression modelling was then used to explore future land use changes on water quality using hypothetical scenarios involving the growth of the informal settlement and built-up area.

Similarly, correlation analyses were used to determine relationships between rainfall and water quality, and rainfall and flow for the rainfall events. Multiple regression modelling was then used to investigate increased rainfall depth due to climate change of a 10 and 20 year design rainfall event on water quality and flow using hypothetical scenarios.

1.5 Limitations

This study was limited by not continuously monitoring surface water quality and flows in the Stiebeuel River. Consequently, the results give no indication of the variability between sample intervals, during which interesting patterns may have emerged. Furthermore, the exclusion of bacteriological water quality parameters, namely *E. coli* and *Faecal coliforms*, limited the study as there was no direct way to measure sewage contamination in the river.

Another key limitation was in not directly analysing surface runoff in the informal settlement before it reached the river. This would have allowed for the effects of the informal settlement on hydrology to be isolated. Issues of security largely prevented equipment to monitor flows and water quality from being placed in the informal settlement. It would have been advantageous to measure the flow at more than one point in the river, and particularly as it flows through the informal settlement.

Lastly, climate and land use changes were not considered in tandem, nor through more complex modelling exercises. The multiple regression models required only a few input parameters; if more parameters were used, such as percentage of impervious coverage, there could have been greater accuracy.

CHAPTER TWO : LITERATURE REVIEW

2.1 Water management in the Anthropocene

In the Anthropocene, the earth is moving away from the stable environmental conditions known to sustain life in the Holocene, to a new era where humans are controlling the forces of nature (Rockstrom et al. 2014). One of the great challenges of this epoch is managing surface water quality and quantity for the earth and humanity (Montanari et al. 2013). In the turbulent Anthropocene, water is required for the resilience of the biosphere to sustain human life, and to cope with the impending shocks from climate change, population growth and land use change (Savenije et al. 2014).

According to Sanderson et al. (2002) less than 17% of the present-day continental surface can be considered without direct human footprint. Humans have changed the response of many hydrological catchments through a multitude of activities; examples include the channelization of rivers, modification of drainage basin characteristics and the alteration of the global climate by the release of greenhouse gases (Walsh et al. 2005; IPCC 2007; Scanlon et al. 2007). Point and non-point source pollution have also heavily impacted the water quality of rivers, runoff and groundwater (Meybeck 2002). Sivapalan et al. (2012) assert that these activities pose increasingly complex water sustainability challenges that cross disciplinary boundaries (Savenije et al. 2014). Examples of such challenges include managing the polluted Njoro river in Kenya that receives contaminated runoff from informal settlements (Mokaya et al. 2004) and the complexities of designing sewer networks with scarce data for mega-cities of the developing world (Rodríguez et al. 2013).

Managing contaminated surface water against the backdrop of a changing climate and strongly modified landscapes requires multi-disciplinary approaches (Liu et al. 2015). These issues cross boundaries and are connected to multiple factors such as socio-economics, landscape dynamics, hydrology and climate (Butler and Davies 2011; Willems et al. 2012). In slums of the developing world, the impacts of contaminated surface water are acute and the lack of knowledge on water quality and flow hampers efforts to control and manage these environments (Parkinson et al. 2007). Guidance for the management of surface water in a changing world is likely to be found in fields such as Integrated Water Resources Management (IWRM), which advocate for "holistic" approaches. Recent shifts that incorporate the management of blue (liquid) and green (rain) water with a broader focus on social-ecological systems and cross-scale interactions are also increasingly relevant (Savenije et al. 2014). There is a pressing need to find solutions to complex hydrologic problems, particularly in slums, which requires an approach that explicitly understands the interactions between human populations and water systems (Pande et al. 2014).

2.2 Evolution of water resource management

People interact with the water cycle in a variety of ways to sustain social and economic and systems (Rosegrant et al. 2009; Butler and Davies 2011). This interaction has long been a part of human history as societies grew and developed technologies to better exploit water resources for agricultural and urban purposes. Excess surface water has always been produced as a result of these activities and drainage has been managed, along with other water resources, under the larger field of water management (Chocat et al. 2007). Savenije et al. (2014) explain that up until the 1970s the field of water management was known by the term "water resources development", after which it changed to "water resources management" in the 1980s and finally to "IWRM" in the 1990s. The evolution of names represents the increasing recognition that water systems cannot be exploited for human use but need to be acknowledged and managed as the lifeblood of the biosphere (Rockstrom et al. 2014). Tracing the evolution of water management approaches provides guidance on managing surface water for an increasingly turbulent era of the Anthropocene (Meybeck 2003).

From the late 18th century, science and technology were used to control and manage water resources for a stable supply (Savenije et al. 2014). During this period, the rational method for calculating storm discharge from a drainage area, and Horton's work regarding the calculation of runoff emerged (Biswas 1970). According to Molle et al. (2009), this pursuit termed "the hydraulic mission", had the primary objective of "taming" nature and exploiting water resources for human use. The mission was marked by large scale water resource development such as dam construction, diversion of rivers, and development of irrigation systems. For example, large dams increased from 5000 globally in 1950 to 45000 in 2000 and irrigated areas doubled from 140 million hectares (ha) to 280 million ha during this same period (Molden et al. 2007). However, the advantages of the hydraulic mission were accompanied by widespread environmental destruction (Molle et al. 2009).

In the urban environment, large technical approaches were also used to address drainage (Poustie et al. 2015). Initially the combined sewer was used to drain stormwater and wastewater together (Butler and Davies 2011). This approach then gave way to the separate sewer in the mid 20th century as it became preferable to separate sanitary sewage and stormwater (Chocat et al. 2007). These types of drainage infrastructure, still in use today, rely on a network of concrete lined pipes which rapidly convey water in the most hydraulically efficient manner (Fletcher et al. 2015). Even though these technical approaches have delivered on the primary drainage objectives of public hygiene and flood protection, they have also been accompanied by adverse environmental impacts (Brown 2005; Wong and Eadie 2000; Wong and Brown 2008; Barbosa et al. 2012). It is widely held that hard engineered drainage infrastructure is responsible for transporting increased volumes of contaminated runoff which degrade rivers and the environment (Van De Meene and Brown 2009).

The multiple adverse ecological impacts caused by technical hard engineered approaches elicited the response: "nature talks back" (Vörösmarty et al. 2013). Examples of these impacts include heavily modified flow regimes from water withdrawals, chronic pollution from point and nonpoint sources, and overexploited groundwater bodies (Meybeck 2003; Gupta et al. 2013). The impacts resulted in an attempt to understand the feedbacks that exist between the water cycle and human systems in an effort to improve water resource management (Savenije et al. 2014). This movement saw the birth of IWRM, which originated in the 1950s but remerged in the early 1990s, emphasising a holistic approach to managing water resources (Parkinson and Mark 2005). IWRM is defined by the Global Water Partnership (2003) as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems". This approach represented a move away from sector specific approaches and offered an integrated perspective with a focus on sustainability (Cohen and Davidson 2011). In the urban environment, the shift to integrated approaches became evident through the adoption of SuDs in many countries (Fletcher et al. 2013). SuDs mimic natural drainage in a landscape by capturing, slowing, and absorbing stormwater, as well as filtering the pollutants that urban development introduces (Horner et al. 1994).

However, the ability of IWRM to integrate social, economic and natural aspects and improve water resource management was, and continues to be, contested (Medema et al. 2008; Bouwer 2000). For nearly two generations, IWRM has been criticised for (i) being an amorphous concept which is vague about what should be integrated (Biswas and Kirpich 2004), (ii) giving little practical guidance and, (iii) having little evidence of success in water programmes, especially in the developing world (Rahaman and Varis 2005). The ability of IWRM to operate successfully in the Anthropocene, where changes are taking place on a planetary scale and over long time periods, is disputed (Gupta et al. 2013). Sivapalan et al. (2014) posit that IWRM does not account for the dynamic interactions between water and people. In addition IWRM focuses solely on blue (liquid) water and fails to account for green water (infiltrated rain), which is a larger resource and drives 80% of global food production (Falkenmark 1997).

New thinking and practice is towards managing blue (liquid) and green (infiltrated rain) water with a broader focus on land–water ecosystem and cross-scale interactions (Gordon et al. 2005; Rockström et al. 2009). It represents a deeper social-ecological resilience-based approach to integrated land and water-resource management (Rockstrom et al. 2014). In this approach, hydrological systems are the interface between environment and society (Montanari et al. 2013). Figure 3 illustrates the evolution in water-resource management during the past 30 years.

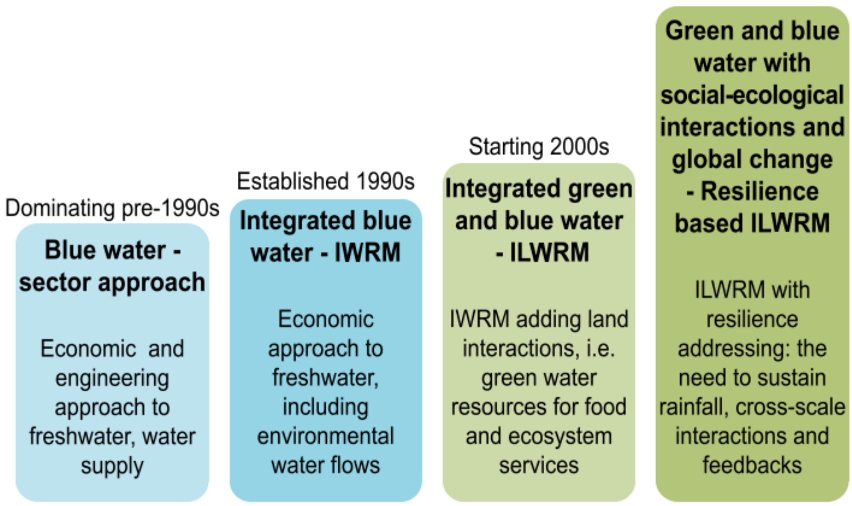

Figure 3. The evolution of water resource management (Rockstrom et al. 2014).

In recent times, a number of concepts have also emerged that conceptualise the interrelations between people and the water system including the "Hydro-social"(Swyngedouw 2009), "Hydrocosmological" cycles (Boelens 2014), "Ecohydrosolidarity" (Falkenmark 2009), the "Waterscapes" concept (Cohen and Davidson 2011) and "Socio-hydrology" (Sivapalan et al. 2012). The emerging science of socio-hydrology offers a promising lens through which to conceptualise and manage the 'wicked problems' of contaminated surface water, climate change and population growth in the Anthropocene (Rittel and Webber 1973; Levy et al. 2016). Elshafei et al. (2014) explain that socio-hydrology considers the co-evolutionary dynamics of coupled human-water systems, focusing on the interactions, feedbacks and emergent patterns of humans and the hydrological cycle. In traditional hydrology, humans are often treated as a boundary or considered as external forcings in the water cycle, under the premise of stationarity (Heine and Pinter 2012; Remo et al. 2012; Di Baldassarre et al. 2013). Furthermore, hydrology often analyses the catchment under idealized conditions, which is increasingly irrelevant in a changing world where the human hand is evident in nearly all aquatic environments (Wagener et al. 2010; Sivapalan et al. 2012). Socio-hydrology considers human actions as part and parcel of the hydrological cycle while considering the multiple interactions between the two (Montanari et al. 2013; Savenije et al. 2014; Ceola et al. 2015). In contrast, IWRM often uses a scenario based approach that does not consider the emergent and spontaneous behaviours of human-water systems (Elshafei et al. 2014; Savenije et al. 2014). IWRM also attempts to control the water system for desired human outcomes while the focus of socio-hydrology is on understanding and predicting future trajectories of co-evolution of coupled human-water systems (Sivapalan et al. 2012).

2.3 Land use and water quantity

The spatial configuration of landscapes, in terms of land use, vegetation and biodiversity, influences the quantity and quality of runoff and receiving waters. In particular, the land use type affects the fate of precipitation among runoff, evapotranspiration, infiltration and groundwater recharge (Sajikumar and Remya 2015). In human-altered landscapes, namely agriculture or urban, there is generally increased runoff and decreased evapotranspiration, infiltration and groundwater recharge (Scanlon et al. 2007).

Agricultural land currently occupies 37% of the global terrestrial land area and poses a big threat to the stability of the biosphere and human systems (Ramankutty et al. 2008; Rosegrant et al. 2009). In comparison to other human activities, agriculture uses the largest amount of freshwater (Shiklomanov 2000), releases the greatest levels of greenhouse gases (Smith et al. 2008) and contributes the most to soil erosion and runoff to receiving rivers (Carpenter et al. 1998). According to Scanlon et al. (2007) agricultural lands impact water by modifying the partitioning of water at the land surface. In cultivated lands there is reduced evapotranspiration, which provides more water for groundwater recharge and baseflow. For example, Scanlon et al. (2005) found that the conversion of natural grasslands to rain-fed agriculture in the Southern High Plains in the USA changed the direction of water flow from upward (through evapotranspiration) beneath natural ecosystems to downward (recharge) beneath cultivated areas. Increased streamflow and recharge in agricultural lands is also due to enhanced overland flow resulting from soil crusting and fallow periods. For example, Leduc et al. (2001) found that intense land use change in Niamey, Niger, modified the hydraulic properties of the top centimetres of the soil and consequently increased surface runoff.

Rockstrom et al. (2014) notes that substantial expansion of agricultural land will be needed to sustain the more water intensive diets of the larger population in the Anthropocene. According to IAASTD (2008) food production may need to increase by between 50 and 70% to meet the growing food demand of an extra two billion people by 2050. This increase in agricultural lands will significantly impact green water through decreased infiltration and evapotranspiration rates (Ringersma et al. 2003). Green water is becoming increasingly important in the literature, especially considering the dependency of nearly all developing countries on green water for their food production (Ringersma et al. 2003; Scanlon et al. 2007; Gordon et al. 2008; Rockström et al. 2009; Rockström et al. 2010). For example 95% of agricultural lands in sub- Saharan Africa are rain fed while in Latin America the figure is almost 90% (FAOSTAT 2005). Rockström et al. (2010) advocate for a paradigm shift in the management of rain fed agriculture in which rainfall is the entry point for surface water management and there is a focus on both green and blue water.

Even though urban areas are much smaller in extent than agricultural areas, they are expanding rapidly. The world’s urban population is projected to reach 6.3 billion people in

2050 and most of this growth will be in developing countries (Alirol et al. 2011). Urbanisation is accompanied by an increase in impervious surfaces, which have a detrimental impact on the natural hydrological cycle (Figure 4) (Horner et al. 1994; Wong and Eadie 2000; Schoeman et al. 2001; Mckee et al. 2003; Butler and Davies 2011; Baek et al. 2015; Semadeni-Davies et al. 2016).

Walsh et al. (2005) state that the effect of increased impervious surfaces and the hydraulic efficiency of conventional drainage infrastructure is producing the flashier hydrographs typical of urban rivers. Weng (2001) identifies some of the typical impacts of urbanisation on hydrology in a study in the Shenzen region in China where there was a high annual surface runoff and increased runoff coefficient values because of the lowered potential maximum storage in the urban area. In another example, Du et al. (2015) found that the rapid expansion of impervious areas from urbanisation in the Longhua Basin, China, had increased peak discharge and flood volume by 140% and 162 % over the past 30 years, respectively.

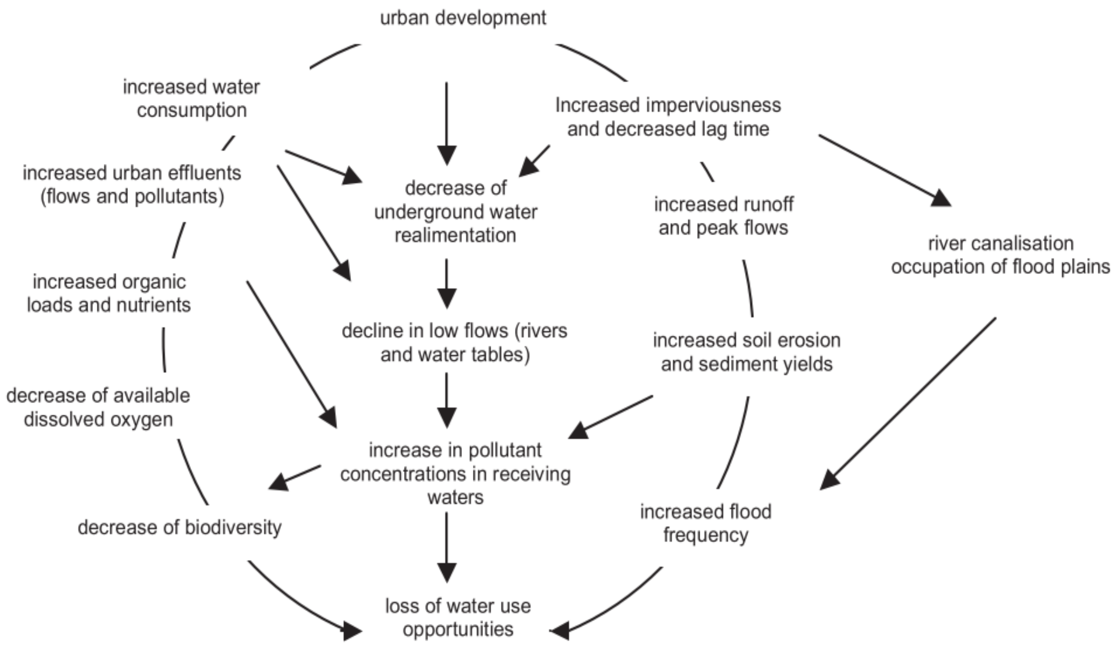

Figure 4. The impact of urbanisation on the hydrological cycle (Chocat et al. 2007).

Catchment imperviousness is often used as a proxy for urbanisation (Tong and Chen 2002; Lee et al. 2002; Baek et al. 2015; Waters et al. 2003). According to Schueler et al. (2009), impervious cover is an ideal watershed metric in that it can be measured, tracked and managed, and is a common currency of understanding by water-sector professionals. Miller et al. (2014) used impervious cover as an indicator of land use change in a peri-urban catchment in Swindon, United Kingdom. The study found that an increase in impervious cover from 11% in the 1960s to 44% in 2010s resulted in an increase of 400% of peak flow (Miller et al. 2014). The authors also highlight the important distinction between Effective Impervious Area (EIA) and Total Impervious Area (TIA) when studying surface water in urban catchments. The EIA is the proportion of the catchment made up of impervious surfaces which are directly connected via constructed drainage to the receiving water while the TIA is the total fraction of a watershed that is covered by impervious surface area (Horner et al. 1994; Walsh et al. 2005). According to Fletcher et al. (2013), not all studies recognise this important distinction, which is unfortunate as EIA provides a much clearer prediction of the hydrology of receiving waters.

Fletcher et al. (2013) note that there are a limited number of studies that have investigated peri-urban catchments, despite the current and potential growth of these areas. In the developing world, peri-urban catchments are increasingly becoming occupied by informal settlements (Niemczynowicz 1999). Miller et al. (2014) point out that it is difficult to isolate land use change impacts on hydrology in peri-urban catchments because of the rapid land use changes and the mix of natural and artificial flow pathways in these areas. Ostrowski (2002) reiterates this, explaining that peri-urban areas and their characteristics are neglected in studies as there is uncertainty around their hydrological behaviour.

Similar to the under-representation of peri-urban areas in the literature, informal settlements in peri-urban areas of the developing world are poorly studied and much of their hydrological behaviour is unknown (Schoeman et al. 2001; Jiusto and Kenney 2015). According to Parkinson et al. (2007), runoff from informal settlements is sometimes difficult to predict and is often lower than would be expected under similar conditions in well planned city areas. This is due to the lack of concrete surfaces which results in higher depression storage and greater infiltration (Parkinson et al. 2007). Furthermore, the limited water supply, sanitation system and drainage infrastructure in informal settlements results in excess water (stormwater and wastewater) ponding in local areas (Armitage 2011). Parkinson and Mark (2005) note that urban catchments in developing countries have different characteristics than those in developed countries, which causes variations in the rainfall–runoff response and the resultant volume of runoff and peak flows. The rapid land use change in developing countries, and slums in particular, also require the continuous update of catchment characteristics, which complicates the design of drainage solutions (Tucci 2001).

Land use change is a primary driver of hydrologic changes in a catchment and there is an urgent need to study the impacts of land use change on surface water, especially in slums of the developing world. According to Scanlon et al. (2007) the impacts of land use change on surface water may rival or exceed those of climate change. Thus, managing the complex interactions between climate change and land use change in the turbulent Anthropocene presents a great challenge (Gordon et al. 2008). Sivapalan et al. (2014)'s call to study the dynamic cross-scale interactions between humans and water systems is critically important, especially in slums of the developing world (Parkinson et al. 2007).

2.4 Water quality

Human activities now affect nearly all water systems and surface water pollution is a major global challenge, marking the entrance of water resource management to the Anthropocene (Meybeck 2003). The link between human land use, namely agriculture and urban, and deteriorating water quality is well established from numerous studies, often using remote sensing and GIS tools (Schoonover and Lockaby 2006; Tu 2011; Bu et al. 2014; Borges et al. 2015). For example, Bu et al. (2014) found that landscape metrics were significantly associated with river water quality in the Taizi River basin, China. Furthermore it was stated that during the rainy season, agricultural and built-up land uses had significant effects on most water quality variables, showing mixed pollution of agricultural, domestic, and industrial sources. Similarly, Tran et al. (2010) demonstrated that land-use and water quality variables were associated with non-point source contaminants (e.g. nutrients and specific conductance) in a study on 29 streams that were located within a variety of land-use categories in the New York State.

Water quality is strongly determined by land use type in a catchment (Li et al. 2008). Land uses such as agriculture, urban and industry are directly reflected in the characteristics of a catchment, and contribute to both point source (e.g. wastewater discharges) and non-point source pollution (e.g. runoff from agricultural and urban areas)(Ahearn et al. 2005; Sajikumar and Remya 2015). Scanlon et al. (2007) asserts that agriculture is a significant contributor to the diffuse pollution of freshwater resources. Agriculture constitutes the world's largest terrestrial biome and uses approximately 70% of all surface water resources (Stehle and Schulz 2015). All agricultural water, barring water lost to evapotranspiration, is recycled back to surface water and groundwater, transporting pollutants to these waters (Ongley 1996). Common contaminants from agriculture include increased concentrations of nutrients such as ammonia, phosphorus and nitrogen (Carpenter et al. 1998; Hofmann et al. 2015), pesticides and insecticides (Capel et al. 2001; Stehle and Schulz 2015), sediments from soil erosion (Brodie and Mitchell 2005) and heavy metals (Nicholson et al. 2003).

Much like agricultural lands, the surface water from urban catchments is polluted by a plethora of contaminants (Horner et al. 1994). The primary sources of pollutants in urban catchments include vehicle emissions, building and road erosion, animal faeces, litter, sewage leakages, atmospheric deposition, spills of household cleaners and motor fluids and direct discharges of wastewater (Butler and Davies 2011). Table 1 lists urban pollutants and their most common sources.

Table 1. The common contaminants from urban areas and their sources (Schoeman et al. 2001)

Pollutants	Sources
Nutrients, faecal bacteria, viruses, organic matter	Domestic wastes, overloaded sanitation systems, night soil dumping, surcharging sewers, absence of sewerage services
Heavy metals, hydrocarbons, oils, toxins, Nitrogen Oxides, Sulphur dioxide	Vehicle emissions, industrial emissions, spills, atmospheric deposition, pavements, roads
Plastics, paper, glass, organic compounds	Litter, inadequate services, solid waste dumping
Suspended solids	Erosion, construction, vegetation removal
Nitrogen compounds	Urban pesticides, herbicides and fertilizers
Phosphorus, Nitrogen and organic	Vegetation, pollen, atmospheric deposition

compounds	
Dust, chlorides, Sulphur compounds, leachates	Wind, rain and groundwater
Dissolved solids, chlorides, phosphates	Laundry water, vehicles
Dissolved solids, sulphates, carbon, particulate matter	Burning of litter, wood and coal (deposition)

The primary reasons for poor water quality in urban areas are widely known as (i) the significant production of pollutants in these areas and (ii) the major loss of infiltration capacity of urban catchments from impervious surfaces (Hatt et al. 2004; Walsh et al. 2005; Schueler et al. 2009). Fletcher et al. (2013) note that at extremely low levels of urbanisation there are significant negative impacts on urban streams. Beach (2003) suggests that urban streams can be degraded when the total catchment imperviousness is greater than 10% while King et al. (2011) suggest that even at 0.5% catchment imperviousness there can a noticeable decline in species richness.

Walsh et al. (2005) identifies conventional stormwater drainage as another driver of urban stream quality degradation. The traditional design of hydraulically efficient concrete lined pipes results in higher flows of contaminated runoff transported to urban streams (Brown 2005; Wong and Eadie 2000). Tucci (2001) confirms this, stating that urban rivers are recipients of both solid and dissolved pollutants, many transported by conventional stormwater drainage. In a study on water quality in an urban stream in North Carolina, USA, Mallin et al. (2009) found that the water was polluted with high levels of faecal bacteria, biochemical oxygen demand (BOD), orthophosphates (PO_4^{3-}), total suspended sediment and low dissolved oxygen levels. Furthermore, the percent watershed development and percent impervious surface coverage were strongly correlated with biochemical oxygen demand, orthophosphate, and surfactant concentrations.

Urban areas are sources of both and diffuse and point source pollution (Jamwal et al. 2011; de Haan et al. 2014). In developing nations, point source pollution has, for the most part, been effectively dealt with through technologies such as the conventional sewer system and wastewater treatment systems (Morales 2016). The current challenge in these areas is diffuse pollution- from agricultural and urban areas- from contaminants such as new pesticides, genetically engineered insecticides, xenobiotics, mercury, drug residues and other endocrine disruptors (Capel et al. 2001; Meybeck 2002; Carpenter et al. 2011). In contrast, developing countries are still dealing with both point source pollution and diffuse pollution (Goldenfum et al. 2007).

The large differences within and between each developing country mean that water quality contaminants differ greatly. Abbaspour (2011) echoes this, noting that the state of water pollution in developing countries is highly variable reflecting socio-economic, physical, institutional and technological factors. Phenomena such as the urban stream syndrome manifest differently in developing countries because of differences in patterns and histories of economic development and urbanization (Capps et al. 2016). Urban streams in developing countries provide multiple uses including ecosystem services, sources of building materials, water for irrigation and household uses and as drainage for natural and anthropogenic (sewage, greywater and solid waste) inputs (Obrist et al. 2006; Armitage 2011). However, Capps et al. (2016) states that we remain relatively ignorant of the effects of urbanization on streams in low income areas.

In no other area do we remain more ignorant of the effects of urbanization on surface water than in slums, also (known as informal settlements) of the developing world (Parkinson and Mark 2005; Reed 2013). The low socio-economic status, high density, weak institutional capacity, lack of basic infrastructure and services and precarious location of slums provide the ideal conditions for highly contaminated surface water (Tucci 2001). For instance, Carden (2013) found that the quality of urban runoff in South Africa is primarily related to the (i) development type (formal versus informal) (ii) development density (expressed as number of people or dwelling units per unit area) (iii) standard or cost of development (low-cost high-density versus high-cost low density), and (iv) level of services provided and degree of service maintenance.

The low investments in urban drainage and lack of sanitary facilities are the main sources of contamination in informal settlements (Tucci 2001). In the absence of formal urban services, surface water is usually a toxic cocktail of stormwater mixed with greywater, blackwater and solid waste (Armitage 2011). Nyenje et al. (2010) note that urban rivers draining informally settled urban catchments in sub-Saharan Africa are deteriorating at an alarming rate. The authors assert that over 80% of wastewater generated in informal settlements remains untreated and is disposed of in the soil or via on-site sanitation systems or directly discharged into rivers.

Surface water pollutants in informal settlements are diverse and include nutrients, sediments, pharmaceuticals, personal care products, viruses, faecal bacteria and organic matter (Palupi et al. 1995; Kimani-Murage and Ngindu 2007; Banadda et al. 2009; Palit et al. 2012; Joshi et al. 2014; Subbaraman et al. 2013; Katukiza et al. 2015). The continual flows of surface water pollute the surrounding environment, threaten the health of residents and contaminate receiving waterways (Parkinson and Mark 2005).

Water quality monitoring studies demonstrate the link between informal settlements and poor water quality. For example, Jagals (1994) found that the stormwater runoff from the Botshabelo informal settlement in South Africa contributed far greater microbial pollution to the Modder River than the effluent from the sewerage outfall works in the same urban area. Wright et al. (1992) reported that stormwater runoff originating from the Khayelitsha informal settlement in South Africa was found to be polluted throughout the year, with the pollution predominantly being of a microbiological nature with correspondingly high concentrations of nutrients and organics. The major source of pollutants was identified as litter and faecal contaminants that were found in abundance in the catchment. Schoeman et al. (2001) found that low cost housing settlements have higher pollutant loads than more expensive formal housing and these settlements of lower socioeconomic status tend to yield the highest loads of faecal bacteria, organic material and nutrients.

However, there are still many unknowns about surface water quality and quantity in informal settlements. Schoeman et al. (2001) in commenting on the limitations of hydrologic studies in informal settlements of South Africa, noted that few studies could provide meaningful data with regards to simultaneous water quality and flow measurements that would allow for the derivation of even semi-quantitative relationships. For an assessment of this kind, at least the minimum, maximum and median values for flow and pollutant concentrations, loads and export coefficients of water quality constituents are required for base flow and storm flow. However, for most studies, only mean values were reported, and flow was very seldom measured simultaneously with water quality. Carden (2013) highlights further gaps noting that the extensive monitoring of urban runoff discharges for the purpose of stormwater quality management is in its early stages of development in South Africa and there are inconsistencies in reported loadings.

A lack of hydrological data in informal settlements is continually cited as a major obstacle in the management of surface water (Tucci 2001; Goldenfum et al. 2007; Capps et al. 2016). Undertaking a monitoring program in informal settlements is complex due both to physical challenges- high density shacks and limited road access- and social challenges such as high crime rates and political instability (Hranova 2014; Jiusto and Kenney 2015). Common features of monitoring programs such as site selection, placement of instrumentation and access to meteorological stations are constrained by security threats and issues of access in these settlements. Aside from the practical aspects, the high costs of instrumentation, maintenance of equipment and laboratory analysis are beyond the resources of most developing countries (Sawunyama 2008). Capps et al. (2016) discuss further difficulties with studying surface water in low income areas including 1) appropriately defining urban areas, 2) accurately predicting urban population growth, and 3) defining globally applicable metrics to measure the effects of urbanization on watersheds. For example, the widely used metric of impervious cover as an indicator of urbanization may not be as relevant in informal settlements as it strongly depends on level of development (Capps et al. 2016).

Despite these difficulties, a high resolution monitoring study is an effective way to characterize surface water quality and quantity in informal settlements (Barbosa et al. 2012). Sivapalan et al. (2012) concur by stating that study of human water systems through routine monitoring is an effective way to gain more detailed insights into causal relationships. Examples from the literature of studies that monitor surface water from informal settlements provide some guidance for this pursuit. Borges et al. (2015) characterised the water quality of the Cunha Canal, Rio de Janeiro, which is surrounded by 133 low income high density slums. The authors monitored pH, dissolved oxygen (DO), salinity, BOD, chemical oxygen demand (COD), total phosphorus (TP) and ammonia nitrogen (NH_3-N) during two time periods (1998 to 2003 and 2004 to 2011) at six points in the catchment. Results revealed that the canal was severely altered and degraded, with characteristics similar to that of sewage effluent. Nyenje et al. (2014) characterised the water quality and quantity of a primary and tertiary channel draining the slum dominated catchment of Lubigi in Kampala, Uganda. The authors used a stream gauge that continuously recorded water levels at 20 minute intervals to measure flow. They obtained long-term daily precipitation data and high resolution rainfall data at 5 min intervals and from a weather station 2km away from the outlet of the catchment. During high runoff events and a period of base flow, hourly grab samples were collected over 24 hours from the primary channel and from the tertiary channel. The samples were analysed for EC, temperature, pH, DO, alkalinity, TP, PO_4^{3-} and total dissolved phosphorus (TDP), NH_3-N, nitrate (NO_3^--N), total solids (TS) and total suspended solids (TSS). In another study, Mokaya et al. (2004) characterized the water quality of the Njoro River, Kenya which flows through informally settled and cultivated land. Samples were taken on six separate occasions at three sites along the stream and measured for pH, temperature, DO, EC, BOD, TP, NH_3-N, NO_3^--N and PO_4^{3-}. Discharge was measured in a cross-sectional transect of the stream channel using a flow meter. It was found that the Njoro River has low water quality, probably as a result of poor farming practices, partially treated effluents, and poor provision of sanitation facilities to the riparian communities. The water quality of the Umtata River in South Africa was assessed at ten sampling sites along the river that had land uses of informal settlement, plantations and a dam (Fatoki et al. 2001). Grab samples were taken between May 1999 and April 2000 to cover the 4 seasons and were analysed for temperature, pH, EC, TDS, NO_3^--N, phosphates, sulphates, cadmium and faecal and total coliforms. The results indicated gross pollution of the river especially as regards microbes and cadmium metal.

The proliferation of low cost, high density informal settlements and the associated increase in contaminated water are a ubiquitous and inevitable part of cities of the future (Parkinson et al. 2007). In the turbulent Anthropocene, the poor will be most affected by surface water quality and quantity issues (Ajibade et al. 2013; Aßheuer et al. 2013). To manage these problems in fast expanding slums and agricultural lands, a monitoring program is vitally important to develop new and innovative ways of dealing with the problems of contaminated surface water (Ashton and Bhagwan 2001; Scanlon et al. 2005).

2.5 Climate change

The hydrologic consequences of land use change and urbanization manifest within the context of a changing climate (Carpenter et al. 2011). In the past century, a rapidly growing and industrializing population has led to increases in greenhouse gas emissions and subsequent changes in climate (Willems et al. 2012). There is consensus among the Intergovernmental Panel on Climate Change (IPCC) that this increase in atmospheric greenhouse gases will cause disruptions to the worlds weather and climate conditions such as frequent or more severe storms, rising sea levels, droughts and increases in average global temperatures (IPCC 2007). There is less consensus on the range of climatic changes that are projected to take place, however it is certain that the availability and distribution of water will be impacted (Kusangaya et al. 2014). In Africa, climate change and variability will impact water availability, water accessibility and water demand (Hendrix and Salehyan 2012). Projections indicate that there will be erratic rainfall, longer dry periods, and more intense rainfall events (Hendrix and Salehyan 2012). In South Africa, climate change impacts could exacerbate existing water-related challenges and create new ones (Mukheibir and Sparks 2003).

South Africa is a water stressed country with a low conversion of rainfall to runoff. The mean annual rainfall is 450mm and there is high inter-annual variability in rainfall with significant differences in water availability in different areas (Turton and Patrick 2005). The arid and semi-arid climate of South Africa means that less than 9% of annual rainfall ends up in rivers, and only about 5% recharges groundwater in aquifers. Moreover, rainfall and river flow are unpredictable in time and unevenly distributed in space, with only 12% of the land area generating 50% of stream flows (Department of Environmental Affairs 2013). Water plays a central role in many sectors, particularly agriculture, mining and power generation. The agricultural sector accounts for 63% of water resource use in the country, whilst mining and bulk industrial water use is 17% (Department of Water Affairs 2013).

2.5.1 Hydrological impacts of climate change in South Africa

There is a high degree of uncertainty in the magnitude of rainfall projections in South Africa. Many studies suggest a decrease in rainfall of up to 50% (Matondo et al. 2004; Tadross et al. 2005; Engelbrecht et al. 2009; Zhu and Ringler 2010) but are not clear on projected changes in mean seasonal rainfall (Schulze et al. 2012). There are different estimates of the percentage reduction in rainfall over southern Africa, with Mazvimavi (2008) predicting a 3-23% reduction and Hulme (1992) projecting a 5-10% reduction. Numerous projections indicate a decrease in rainfall during the growing season over the interior of southern Africa by 2050, with some models predicting a 5 to 15% decrease of growing season rainfall (Kusangaya et al. 2014). To the contrary Tadross et al. (2011) suggest that the north eastern regions of South Africa will receive increased rainfall.

The National Department of Environmental Affairs Long Term Adaptation Scenarios (LTAS) project consolidates much of South Africa's information on climate change impacts and develops adaptation scenarios under a range of plausible future climate conditions (Department of Environmental Affairs 2013). These projections were determined by downscaling two global circulation models (GCMs) from the fourth and fifth assessment reports of the IPCC (AR4 and AR5) and drawing on different scenarios. These scenarios are separated into two main groups, representing unmitigated (Special Report on Emissions Scenarios (SRES) A2 and Representative Concentration Pathway (RCP) 8.5) and mitigated (SRES B1 and RCP4.5) future energy pathways. The projections for runoff range from a 20% reduction to a 60% increase by as early as mid-century, based on an unmitigated global emissions pathway rephrase. Under a constrained emissions scenario, projections of runoff range between a 5% decrease and a 20% increase in annual runoff. On a regional level, there is a projected increase in runoff along the eastern seaboard and central interior and decreases in much of the Western Cape. Overall, a higher frequency of flooding and drought extremes is projected, with the range of extremes exacerbated significantly under the unconstrained global emissions scenario.

With respect to the Western Cape of South Africa, it is projected that there will be late summer increases in precipitation in the interior and to the east of the province and a decrease in early and later winter precipitation for the south-west of the province, with a less clear message during the mid-winter period where the models disagree on the direction of change (Hewitson and Crane 2006). These projections are drawn from downscaled data from 6 GCMs, using a scenario of increases in greenhouse gases that assume that society will continue to use fossil fuels at a moderate growth rate.

Overall, climate change in South Africa will result in increased rainfall variability including more frequent extreme weather events (droughts and floods) (Hulme et al. 2001; Arnell 2003), changing rainfall seasonality and overall warming leading to greater surface water losses to the atmosphere (Department of Environmental Affairs 2013).

Climate changes will not happen in isolation and will occur alongside land use changes and explosive population growth in the Anthropocene (Rockstrom et al. 2014). The interactions and feedbacks between these processes could manifest in a multitude of unknown ways in the future (Liu et al. 2015). Hydrological modelling provides a useful tool to explore a combination of scenarios in the future (Praskievicz and Chang 2009).

2.5.2 Hydrological modelling

According to Legesse et al. (2003), hydrological models provide a framework to conceptualise and investigate the relationships between climate, land use and water resources. They can be broadly classified into empirical, conceptual and physically based distributed models (Legesse et al. 2003). Empirical models are the simplest and represent the relationship between input and output series while conceptual models consider physical laws but in highly simplified form (Silberstein 2006). Physically based distributed models are based on the physics of the hydrological processes and are able to represent the spatial variability of catchment characteristics (Zoppou 2001). There are a range of physically based distributed models that have been used to determine the impacts of climate change and land use change on a catchment; examples include the Personal Computer Storm Water Management Model (PCSWMM) (Shrestha et al. 2014; Akhter and Hewa 2016), the Precipitation Runoff Modelling System (PRMS) (Legesse et al. 2003; Viger et al. 2011) and the Soil Water Assessment Tool (SWAT) (El-Khoury et al. 2015; Sajikumar and Remya 2015; Mango et al. 2011).

Hydrological models can explore climate and development scenarios both separately and together. According to Praskievicz and Chang (2009) there are two general approaches that are used when in climate change studies, the first is by increasing design rainfall by a hypothetical amount (Waters et al. 2003). This approach eliminates the uncertainty associated with GCMs and allows for sensitivity analysis but one disadvantage is that the synthetic increments are not necessarily realistic expressions of increases in GHGs

(Praskievicz and Chang 2009). The second approach is through adjusting rainfall series according to anomalies from the output of a regional GCM (Semadeni-Davies et al. 2016). There are also disadvantages to this approach, namely the inherent uncertainty associated with GCMs, which vary widely in their projections for precipitation, and the choice of downscaling method (Praskievicz and Chang 2009). Shrestha et al. (2014) used both approaches when exploring climate change impacts on surface flooding in Pathumthani, Thailand. The first approach used GCM data and spatially downscaling to create three future precipitation increases in 2021, 2061, 2091 while the second approach used hypothetical increments of current rainfall conditions by 10%, 20%, 30% and 40%. The results indicated that the number of flooded nodes increased as did the surface flooding frequency and the duration of floods. In another example, Waters et al. (2003) investigated the impacts of climate change on the Malvern catchment, Ontario through scenario analysis. The climate change scenario was a 15% increase in the two-year, one-hour design rainfall depth and intensity which resulted in a 19% increase in runoff volume, and a 13% increase in peak discharge, which caused 24% of the pipes in the catchment to surcharge.

Developing land use change scenarios is more challenging as there is a complex range of socio-economic and biophysical factors that influence the rate and spatial pattern of land use change (Verburg et al. 2004). DeFries and Eshleman (2004) expands on this, expressing that identifying and quantifying the hydrological consequences of land use change are not trivial exercises and are complicated by factors such as extrapolating results to other systems. Land use change or development scenarios can be simulated by two methods, the first is by changing catchment characteristics such as the ratio of impervious to pervious surfaces or depression storage, and the second is through using a land use change model (Praskievicz and Chang 2009). There are various land use change models such as the Urban Growth Model (Candau 2000) and the CLUE-s (the Conversion of Land Use and its Effects at Small regional extent) model (Verburg et al. 2002) that project and simulate land use changes using historical trends. Some examples of modelling land use change are from Semadeni-Davies et al. (2016) who explored the impacts of urbanisation on drainage in Helsinborg, Sweden by creating three socio-economic storylines which corresponded to a change in three catchment model parameters of impervious surfaces, drainage area and total storage volume. In another example, Legesse et al. (2003) simulated a land use change scenario in the Ketar River basin, Ethiopia by changing the maximum soil water holding capacity, maximum interception storage, and vegetation cover density. Weng (2001) took a different approach when modelling urban growth effects on surface runoff in the Zhujiang Delta, China and used remote sensing and GIS methods. The author overlaid two Landsat images from 1989 and 1997 to detect urban land cover changes which were then used in the model. Akhter and Hewa (2016) explored the hydrological responses of urbanization scenarios in the Myponga Catchment, South Australia using PCSWMM. The present condition of the catchment was taken as the baseline for the study and seven future urbanization scenarios were hypothetically generated (10%; 20%; 30%, 40%; 50%; 60%; and 70% urbanization). The percentage imperviousness was used as an indicator of urbanization and increased accordingly in each subcatchment from the baseline scenario.

Reliable and accurate hydrological data underpins any modelling exercise (Niemczynowicz 1999). According to Niemczynowicz (1999) high resolution rainfall data is the most important input to hydrological models as it is the driving force of all hydrological processes. In urban areas, the orders of magnitude for assessing runoff include temporal scales from 1 to 10 min, a spatial resolution ranging between 100 and 500 m, and the total surface area covered not exceeding 20x20 km (Fletcher et al. 2013). The generation of surface runoff is another important factor, which requires input data on catchment characteristics such as impervious surface area, topography, land uses and soils (Praskievicz and Chang 2009). Data scarcity is continually cited as a limiting factor in hydrological modelling, especially in developing countries (Legesse et al. 2003; Goldenfum et al. 2007; Rodríguez et al. 2013). According to Kusangaya et al. (2014) Southern Africa is a data scarce region, with most basins being classified as poorly gauged due to the rather low and unevenly distributed hydrometeorological stations. In slums, there is even less data available for hydrological modelling (Tucci 2001; Capps et al. 2016). While hydrological models are useful tools, Sawunyama (2008) warns that they are simple representations of reality that are frequently based on inadequate input data and uncertainties in parameter values. These uncertainties must be acknowledged when interpreting results.

Land use change and climate change are two major drivers of global change and they will continue to exert increasing pressure on surface water in the Anthropocene (Rockstrom et al. 2014). As a result there are a small but growing number of hydrological modelling studies that explore the combined impact of these two changes. Table 2 details a selection of these studies.

Table 2. Selected studies that model the combined impacts of climate and land use changes.

Study area	Study period	Climate change projection	Land use change	Model	Results	Reference
Watersheds of eastern Massachusetts	1995-2024	CGCM3.1 1) SRES A1B 2) SRESB1 3) SRESA2	3 scenarios based on historical change in developed land use 1) Constant - no change 2) Current rate 3) Double rate	ArcView Generalized Watershed Loading Function (AVGWLF)	Increases in monthly streamflows in late fall and winter, while those in the summer months decrease, mainly affected by climate change	(Tu 2009)
Mara River Basin	2002-2099	Adjusting the monthly precipitation and temperature values for the different seasons under SRES A1B	1) Partial deforestation, conversion to agriculture 2) Complete deforestation, conversion to grassland 3) Complete deforestation, conversion to agriculture	Soil Water Assessment Tool (SWAT)	Deforestation is likely to reduce dry-season flows and intensify peak flow. Small decreases in precipitation will lead to increased evapotranspiration and reduced runoff.	(Mango et al. 2011)
Rock Creek basin, USA	2030-2059	ECHAM5 GCM SRES A1B. The mean monthly changes in temperature and precipitation were modelled	3 future scenarios, based on projected population growth patterns and potential development characteristics 1) Conservation 2) Development 3) Planned trend	ArcView Soil Water Assessment Tool Extension (AVSWAT-X)	Modifications in the timing and volume of runoff during the mid 21st Century from urbanisation and climate changes	(Franczyk and Chang 2009)
Vietnamese Mekong River Delta, Vietnam	2005-2050	ECHAM4 GCM 1) Current situation 2) Sea level rise of 50cm 3) Sea level rise of 100 cm 4) Sea level rise of 100 cm and increase of runoff	Historical Landsat images extrapolated to create projections of land cover maps 1) current land use and 2) future land use (2050)	EPA-SWMM 5 and Brezo	Combined influence of climate change and urban growth on the urban flooding situation is significant	(Huong and Pathirana 2013)

Climate change and land use change will have an impact on water quality; however fewer studies have explored these through hydrological modelling (Hrachowitz et al. 2016). Praskievicz and Chang (2009) note that this may be due to the difficulty of obtaining water quality data and because modelling complexity increases with the inclusion of water quality parameters. Modelling water quality is difficult as pollutant loadings depend not only on catchment hydrology but other factors such as channel morphology and vegetation growth (Chang and Franczyk 2008).

Models are an effective way to explore the impacts of future climate and land use change scenarios on surface water quality and quantity (Tu 2009; El-Khoury et al. 2015). Climate and land use changes will disproportionately affect the poor, especially those in informal settlements (Parkinson 2002; Bouchard et al. 2007; Reis et al. 2008; Aßheuer et al. 2013). Thus it is important to investigate climate and land use changes in informal settlements in order to protect the vulnerable communities that reside there. Semadeni-Davies (2016, p125) notes that "a failure to account for such changes implies a society that is unable to respond to global change, whether it be environmental, political or economic, and which is devoid of technical innovation".

2.6 Concluding remarks

Understanding surface water quantity and quality dynamics, against the backdrop of a changing climate and strongly modified land uses are some of the great challenges of the Anthropocene. In the burgeoning informal settlements of the developing world, we have a tenuous grasp on the most basic hydrologic concepts, and insufficient clarity on how to strengthen our understanding of present and future urban river dynamics. The unique characteristics of informal settlements, such as bare compacted earth and inadequate sanitation and drainage services, influence processes such as pollutant production, rainfall runoff responses and river dynamics in unknown ways. Multiple factors that cross disciplinary boundaries, such as hydrology, climate, socio-economics and landscape dynamics, play a role in understanding hydrology in such settlements.

The literature review has provided guidance on the relationship between land use and water quality and flows, and the ways to investigate future land use and climate changes in a catchment. The rest of this thesis investigates these profound unknowns in an informal settlement in a developing country.

CHAPTER 3: RESEARCH METHODS

3.1 Study Design

This study aims to characterise surface water quality and flow, and model surface water quality and flow under selected climate and land use change scenarios in a small informally settled catchment in Franschhoek, South Africa. The study design incorporates two distinct research activities to explore surface water in the present- through water quality and quantity analysis- and the future- through hydrological and water quality modelling.

The study method broadly follows the stormwater monitoring processes described by Barbosa et al. (2012) which are detailed in Figure 5. The monitoring program consists of three main processes, (i) water quality characterization, (ii) hydrological characterization and (iii) variability of the phenomena. The water quality was characterized at selected sites along the Stiebeuel River through testing for multiple water quality parameters throughout four months of the 2016 rainy season. Water quality analyses were also used to characterise five rainfall events during the same time period. The hydrology was characterized by measuring water flow using a low cost high resolution monitoring instrument at one site on the Stiebeuel River. The flow data were used to understand the daily and weekly patterns in the informal settlement and the relationships between rainfall and flow during five rainfall events.

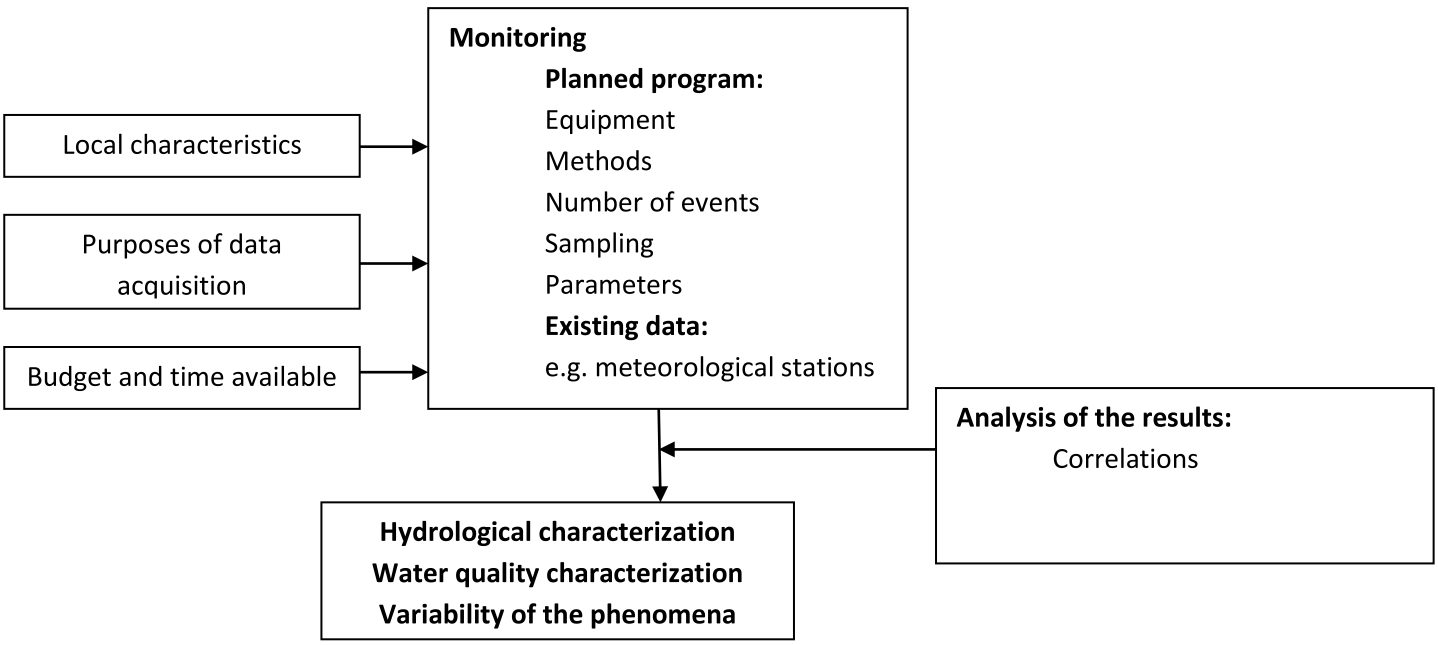

Figure 5. The stormwater monitoring process adapted from Barbosa et al. (2012).

The variability of these phenomena was explored through multiple regression modelling. Hypothetical land use and climate change scenarios were developed to assess the changes on water quality and flow in the catchment.

The combination of data collected from these three processes may provide insights into the dynamics of a human-water system in the present, which can then be used to explore possible trajectories in the future. The exploration of these dynamics in the context of an informal settlement in a developing country adds another layer of complexity and significance to the study design.

3.2 Study Area

The study area is the informally settled Stiebeuel River catchment located in the peri-urban area of Franschhoek, South Africa (Figure 6). Franschhoek is located 80km out of Cape Town's CBD and has a Mediterranean climate with most of its rainfall received in the winter months. The area has an average annual rainfall of 863mm, 80% of which falls within the months of April to September (De Clercq et al. 2006). Agriculture is the predominant land use in the area, with the area being one of six wine regions that comprise the Cape Winelands District. The primary economic activities are agriculture and tourism/hospitality.

Franschhoek has three main rivers, the Berg River, Wemmershoek River and the Franschhoek River, which flows through the bottom of the Franschhoek town. One of the tributaries of the Franschhoek River is the Stiebeuel River, which is the focus of this study.

common to South African peri-urban catchments. Communities with widely varying socio-economic statuses live side by side each other in the catchment and are connected by the river that flows through them.

The area was chosen for study because of the varying land uses and land cover in the catchment that each have their own development densities, infrastructure, social and economic activities, and impervious or pervious surface coverage. These characteristics result in unknown effects on the flow and water quality in the Stiebeuel River, prompting its selection as the study area.

In addition, the area was selected as it contains the Water Hub, a SuDS centre being developed at the bottom of the catchment to treat contaminated water from the informal settlement. This centre is a project lead by the University of Cape Town and this study will contribute baseline data that will be used to inform the design of a SuDS treatment train.

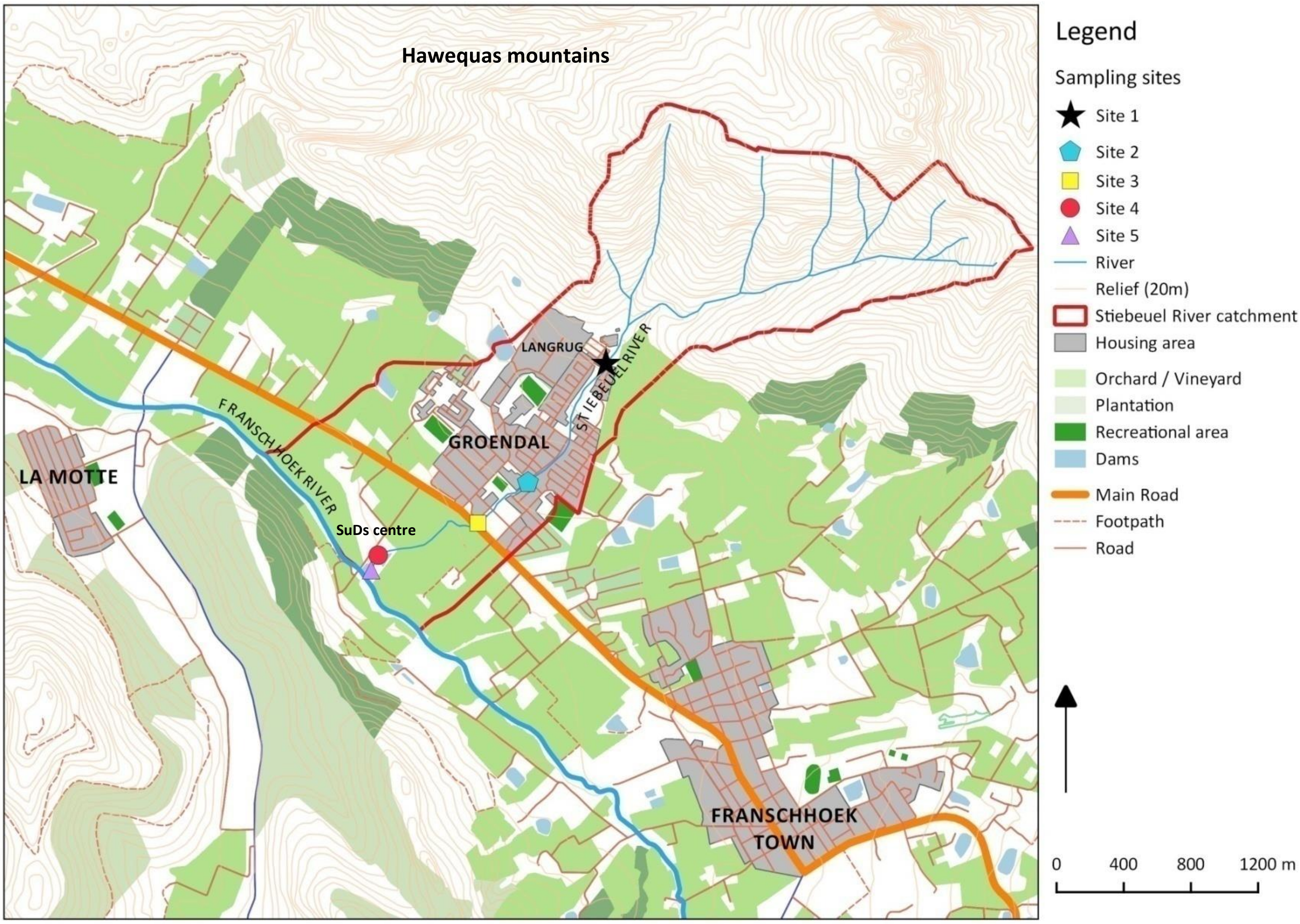

Figure 6. Map of the Franschhoek area showing the three clusters of development and the Stiebeuel River catchment (delineated with a red boundary). The Franschhoek River flows from the southeast to the northwest of the map.

3.2.1 Sample site selection

Four sample sites along the Stiebeuel River were selected for the collection of grab samples (Figure 6). The sites were selected as they were each situated in one of the four land use types in the catchment and could potentially represent the effects of the respective land use types on water quality. In addition, the sites were chosen to be at the top of, in the middle of, and below the informal settlement (Figure 7) to isolate the effect of the settlement on the river. The sites also had to fulfil certain logistical requirements, for example the sites needed to allow for vehicle access for the collection of grab samples, despite there being few formal roads in the informal settlement that will allow for this. Thus the sample sites at the top of and in the middle of the informal settlement were selected as they are adjacent to formal roads.

The sample site at the bottom of the catchment was located in the property of the Water Hub and was primarily selected for security and practical reasons (Figure 6). The sample site was the location for the ultrasonic sensor- which monitored flow- and needed to be placed in a secured location because of the threat of theft in the area. From a practical standpoint, the site was located under a bridge which allowed for the construction of a crump weir which was used, along with the ultrasonic sensor, to measure flow.

Another sample site on the property of the Water Hub was selected for the placement of the ISCO discrete autosampler which collected continuous samples during five rain events. Once again, the site was selected for security reasons as the autosampler was vulnerable to theft. This site was also selected for its proximity to the flow meter, which would allow for the pairing of flow and water quality data during the storm events.

Figure 7. The sample site just below the informal settlement in the Stiebeuel River catchment.

3.2.2 Selection of water quality parameters

The water quality parameters measured in this study include pH, dissolved oxygen (DO), electrical conductivity (EC) and total suspended solids (TSS). These parameters were chosen as they provided background information on the water quality of the Stiebeuel River. Chapman and Kimstach (1996) note that the measurement of DO is a fundamental component of any water quality analysis as oxygen is involved in nearly all chemical and biological processes in water bodies. The measurement of DO can be used to indicate the degree of pollution by organic matter, the destruction of organic substances and the level of self-purification of the water. Conductivity is a useful measurement as it can be used to establish a pollution zone and as a rough indicator of mineral content when other methods are unavailable (Chapman and Kimstach 1996). For example, low EC values are characteristic of high-quality, low nutrient waters while high EC values of indicative of salinity problems and polluted sites (Heald 2009). High levels of TSS indicate the presence of sewage, industrial wastewater and particles from soil erosion. Elevated levels of TSS cause water bodies to lose their ability to support a diversity of aquatic life (Chapman and Kimstach 1996).

Selected nutrients were also tested for and included ammonia nitrogen (NH_3-N), orthophosphates (PO_4^{3-}), nitrate (NO_3^--N) and nitrites (NO_2^--N). These water quality parameters were selected for their importance as surface water contaminants and for their use as indicators of pollution. According to Chapman and Kimstach (1996) ammonia is an indicator source of nitrogen and can indicate pollution from fertilizers, sewage, stormwater runoff and industrial waste. It can be broken down to NO_2^--N and NO_3^--N by nitrifying bacteria if dissolved oxygen is present. NO_2^--N is an intermediate form of nitrogen and rather short-lived as it rapidly oxidises to NO_3^--N. NO_3^--N is an essential plant nutrient but high concentrations can cause eutrophication and other water quality problems. High concentrations of NO_3^--N indicate pollution by human and animal waste or fertilizer runoff (Heald 2009). PO_4^{3-} are a form of phosphorus and originate from detergents, fertilizers, animal faeces, sewage and industrial waste (Heald 2009). Phosphorus is an essential part of the biological cycle in water bodies and high concentrations can indicate pollution and cause eutrophic conditions (Chapman and Kimstach 1996).

These water quality parameters were also selected because of their use in similar studies- especially those assessing water quality in slums- in order to provide a reference point for interpretation and discussion (Koning et al. 2000; Fatoki et al. 2001; Mokaya et al. 2004; Nyenje et al. 2010; Monney et al. 2013; Katukiza et al 2015; Nyenje et al. 2014).

Bacteria, heavy metals and pharmaceuticals are also significant pollutants from agricultural and urban areas but were excluded from this study to narrow the scope and for financial reasons.

3.3 Water quality sampling

Water quality sampling was conducted from August 2016 to November 2016 over a period of rainfall events during the Western Cape rainy season. Sample collection was split into two concurrent phases; one involved taking weekly grab samples on dry days (days that received no rainfall in the wet season) and the other entailed the automatic collection of continuous samples over 5 varying rainfall events.

The one phase involved taking one grab sample at each of the four sampling sites along the Stiebeuel River on a selected day, once every week for 13 weeks. The grab samples were collected around 12pm-3pm on each sampling trip, however this time did vary. The grab samples were collected over 13 nearly consecutive weeks, with the first set collected on the 20 August 2016 and the last set collected on the 24 November 2016. A total of 52 samples were collected from the four sites on the 13 separate sampling trips.

River samples were collected in sterilised 500ml plastic bottles. The sampling procedure entailed rinsing the 500ml plastic bottle with river water from each site twice, and then collecting a sample from just below the surface of the water. The sample was then labelled with the sample site number, and the date and time of sample collection. Once the samples were collected they were transported to a laboratory at the University of Cape Town, where they were either stored in a fridge for later analysis or analysed without delay. The lab analyses for the different water quality parameters are described in section 3.3.1 below.

The other phase of sampling involved the use of an ISCO automatic sampler which collected continuous samples from the Stiebeuel River over five storm events (Figure 8). The autosampler was placed at a site slightly downstream of site 4 and its location can be seen in Figure 6. Depending on the forecasted length of the storm, the autosampler was programmed to collect 500ml samples every hour over the storm. Samples were collected for an hour before the storm, for the duration of the storm and for an hour after the storm. The autosampler was programmed to rinse each bottle twice before taking the sample. The five storm events that were sampled occurred on the 26 September 2016 to 27 September 2016, 6 October 2016, 22 October 2016, 4 November 2016 and 22 November 2016 to 23 November 2016. The storm events had different durations and a total of 91 samples were collected over the 5 events.

After each storm event the samples were transferred to sterilized plastic sample bottles and transported to a laboratory at the University of Cape Town where they were either stored in fridge for analysis or analysed straight away. Figure 6 shows the distribution of the four grab sampling points and the autosampler site in the Stiebeuel River catchment.

Hourly rainfall data was obtained from a weather station in the adjacent catchment.

Figure 8.The ISCO discrete water sampler used in the study.

3.3.1 Laboratory analysis

Eight water quality parameters were tested for and included NO_2^--N, NO_3^--N, NH_3-N, PO_4^{3-}, DO, EC, pH and TSS. Laboratory analyses were conducted at a laboratory in the Environmental and Geographical Science Department at the University of Cape Town.

pH was measured using a hand-held Martini pH 55 meter, which was calibrated to two points, pH 7.01 and pH 4.01, before each use. EC was measured using a hand-held Martini EC59 meter which was calibrated using 1413µs/cm solution before each use. DO was measured using a Milwaukee MW600 smart DO meter which was slope calibrated to 100% (saturation) before each use.

Nutrients were tested for using the Hach DR 2700 Portable Spectrophotometer, according to standard methodology in the HACH Water Analysis Handbook (fifth edition) (Hach Company 1992).

(1) PO_4^{3-} was tested for using the Ascorbic Acid Method (Hach stored program 490 P React. PV)

(2) NO_2^--N was tested for using the Diazotization Method (Hach stored program 371 N)

(3) NO_3^--N was tested for using the Cadmium Reduction Method (Hach stored program 355 N).

(4) NH_3-N was tested for using the Salicylate method (Hach stored program 385 N, Ammonia, Salic).

(5) TSS was tested for using the Photometric method (Hach stored program 630 Suspended Solids)

3.4 Flow

Flow was measured at site 4 in the Stiebeuel River from August 2016 to December 2016 every six minutes using an ultrasonic level sensor and crump weir.

A crump weir was constructed for the purposes of this study and was built under a bridge at site 4. The crump weir consisted of two parallel walls made of concrete slabs with a specially shaped overflow wall on the downstream side of the weir. On the upstream side the wall was sloped at 1:2 and on the downstream side it was sloped 1:5, as per crump weir design standards. The crump weir was selected because of its straightforward structure, high accuracy, relative insensitivity to submerged conditions and ability to handle litter and debris.

An ultrasonic level sensor powered by solar power was attached to the side of a bridge and used to measure distance to the water which was then calculated into flow. The level sensor was placed upstream of the weir where streamlined flow was achieved, approximately 1m upstream of the weir crest. The ultrasonic level sensor recorded measurements every 6 minutes and uploaded them onto an open source website, from which high resolution data records were downloaded. The ultrasonic level sensor works on the time of flight principle and measures the distance from the sensor to the water level by sending an ultrasonic sound wave to the water. The sound wave is reflected off the water surface and the sensor reads the echo, and then calculates the distance to the water using the speed of sound. The depth of water over the weir was then calculated by subtracting the distance to the water from the sensor from the distance from the sensor to the weir crest (distance from sensor to the weir crest - distance from sensor to water).

Figure 9. The crump weir and ultrasonic level sensor used to measure flow in the study.

Once the depth of water over the weir had been calculated, the crump weir discharge equation was used to calculate the flow (Equation 1)(Chadwick et al. 2013). This was repeated for each measurement recorded by the ultrasonic level sensor over the five month period.

$$Q = C_d C_v b g^{\frac{1}{2}} h^{\frac{1}{2}} \quad (1)$$

where

Q = flow (m^3/s)

C_d = Discharge coefficient

C_v = Velocity coefficient

b = width of weir

g= gravitational acceleration

h = depth of water above weir

In some instances during the data collection period, the flow was measured less frequently than every 6 minutes as a result of battery related issues, particularly on days where there was not enough sunlight to charge the solar panel. The flow was calibrated manually throughout the course of the data collection period.

3.5 Data analysis

The water quality data from the grab samples, which occurred on dry days (days that received no rainfall in the wet season) and rainfall events were analysed separately.

The analyses for the dry days comprised the following three subsections:

(i) Descriptive statistics including graphs, tables and box and whisker plots to examine water quality.

(ii) Correlation analyses between the concentrations of water quality parameters and percentage of land use types in the Stiebeuel River catchment, using remote sensing and GIS tools.

(iii) Multiple regression models to explore the potential consequences of hypothetical land use changes on water quality in the catchment, using the statistical relationships estimated from the correlations

The analyses for the five rainfall events included the following three subsections:

(i) Descriptive statistics including hydrographs, pollutographs and tables to examine water quality, flow and rainfall over the events

(ii) Correlation analyses between rainfall and water quality parameters, and rainfall and flow, including various lagged rainfall correlations.

(iii) Multiple regression models to explore the potential consequences of hypothetical climate changes, related to increased rainfall volumes, on water quality and flow in the Stiebeuel River, using the statistical relationships estimated from the correlations.

CHAPTER FOUR : RESULTS AND DISCUSSION

The results and discussion section is separated into two main parts that analyse the hydrology and water quality of the Stiebeuel River catchment during (1) dry days (days that received no rainfall within the wet season), and (2) rainfall events within the wet season, all of which were recorded over a four month period. The two sections are each divided further into three subsections.

4.1 Land use and water quality

Quantitative relationships between urban areas and poor water quality have been established in numerous studies using GIS and remote sensing tools (eg. Griffith 2001; Schoonover and Lockaby 2006; Li et al. 2009; Tu 2011; Bu et al. 2014). Informal settlement land use is rarely distinguished from urban in such studies, despite the ubiquity of informal settlements and the contaminated surface water within them (Olaseha and Sridhar 2003; Aßheuer et al. 2013; Monney et al. 2013). Informal settlement can be considered as analogous to urban, sharing similar characteristics including, artificially hardened surfaces, high population density and significant pollutant production (Armitage 2011; Jiusto and Kenney 2015). However, it is different in other respects as dwellings are constructed of scrap materials, surfaces are compacted but not 'technically' impervious, and there is increased pollution from the limited formal urban services (Mokaya et al. 2004; Parkinson et al. 2007; Monney et al. 2013; Nyenje et al. 2014). These distinct characteristics have unique effects on river water quality and flow, which are explored below.

4.1.1 Land use classification

Ortho-rectified true colour digital aerial imagery at 0.5m Ground Sample Distance from 2014 and digital elevation model (DEM) data (5m resolution) was obtained from the The Chief Directorate: National Geo-spatial Information. The South African National Geo-spatial Information uses airborne platforms to acquire digital aerial imagery using an Intergraph DMC, or a similar contracted camera (National Geo-spatial Information n.d.). Using the DEM, the catchment of the Stiebeuel River was delineated by the watershed delineation tool (WDT) in PCSWMM. The WDT generates a dendritic SWMM network of sub-catchments and uses the concept of a target sub-catchment size, rather than a minimum area for channelization (CHI n.d.). Once the catchment area and boundaries were defined, the catchment was divided into four zones based on the catchment topography and the location of the four sampling points using Quantum Geographic Information System (QGIS).

After the four zones were delineated, land use types were identified and manually digitized in QGIS using the aerial imagery and land use ESRI shapefiles. Before manually digitizing the catchment, an attempt was made to use the South African 2013-2014 national land cover dataset to provide the land use types (Figure 10) (© GEOTERRAIMAGE - 2014). The dataset is derived from Landsat 8 imagery and is based on 30x30m raster cells, ideally suited for ± 1:75,000 - 1:250,000 scale. The Stiebeuel River catchment is a small catchment with a scale around 1:17 000, and the 30x30m resolution was too coarse for the detail required, especially in the informal settlement. The land-cover dataset does recognise and classify informal areas under the built-up category and describes them as "areas containing high density buildings and other built-up structures typically associated with informal, often non-regulated, residential housing" (Geoterraimage 2014, pp.48). However, the true extent of the informal settlement is not captured in the national land-cover dataset, nor is the distinction between the informal settlement and the low income community strong enough (Figure 10). Thus, the catchment was manually digitized as it allowed for the requisite level of detail.

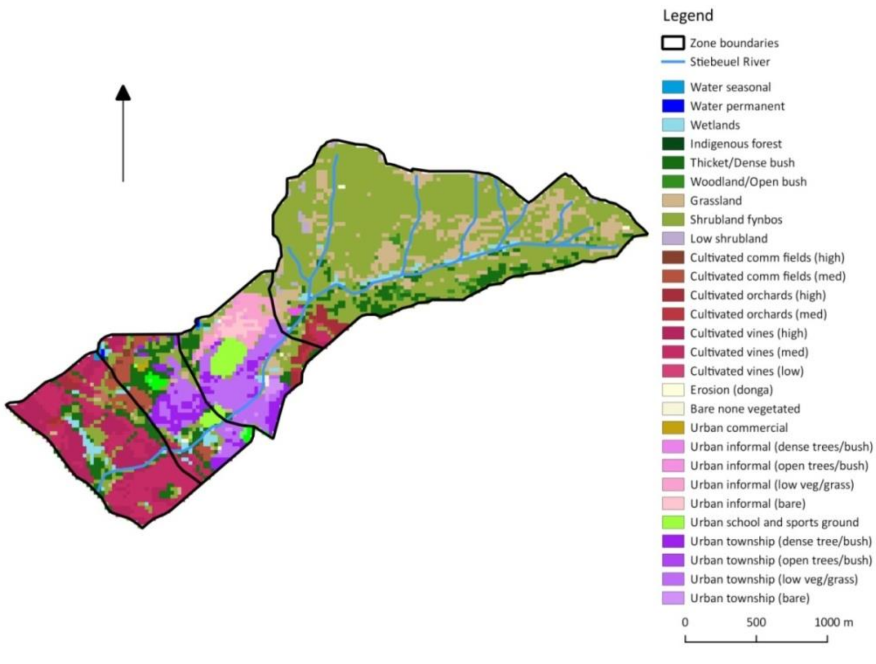

Figure 10. The land use types in the Stiebeuel River catchment according to the South African 2013-2014 national landcover dataset.

Figure 11 shows the delineated land use types in the catchment. Four dominant land use types were identified and include (1) agriculture, dominated by viticulture (2) vegetated land, dominated by fynbos with some recreational land, (3) built-up land (formal urban area), (4) informal settlement (shack dwellings and hardened gravel roads and pathways). The percentage of each land use type in each of the four zones was calculated in QGIS by overlaying land use layers to the four zones, and dividing the area of a land use type in a zone by the total area of that zone.

Each water quality measurement was taken in each zone, and can therefore be associated with a percentage of any given land use type (as each zone is constituted by different proportions of each land use type, as described above). Correlations between each water quality parameter (WQP) and each land use type (LUT) were thus calculated. For selected WQP and LUT pairs, a simple linear regression was estimated. As the interest is the effect of the LUT on the WQP measurements, the land use percentages are taken as the independent variable and the water pollutant concentrations as the response variable.

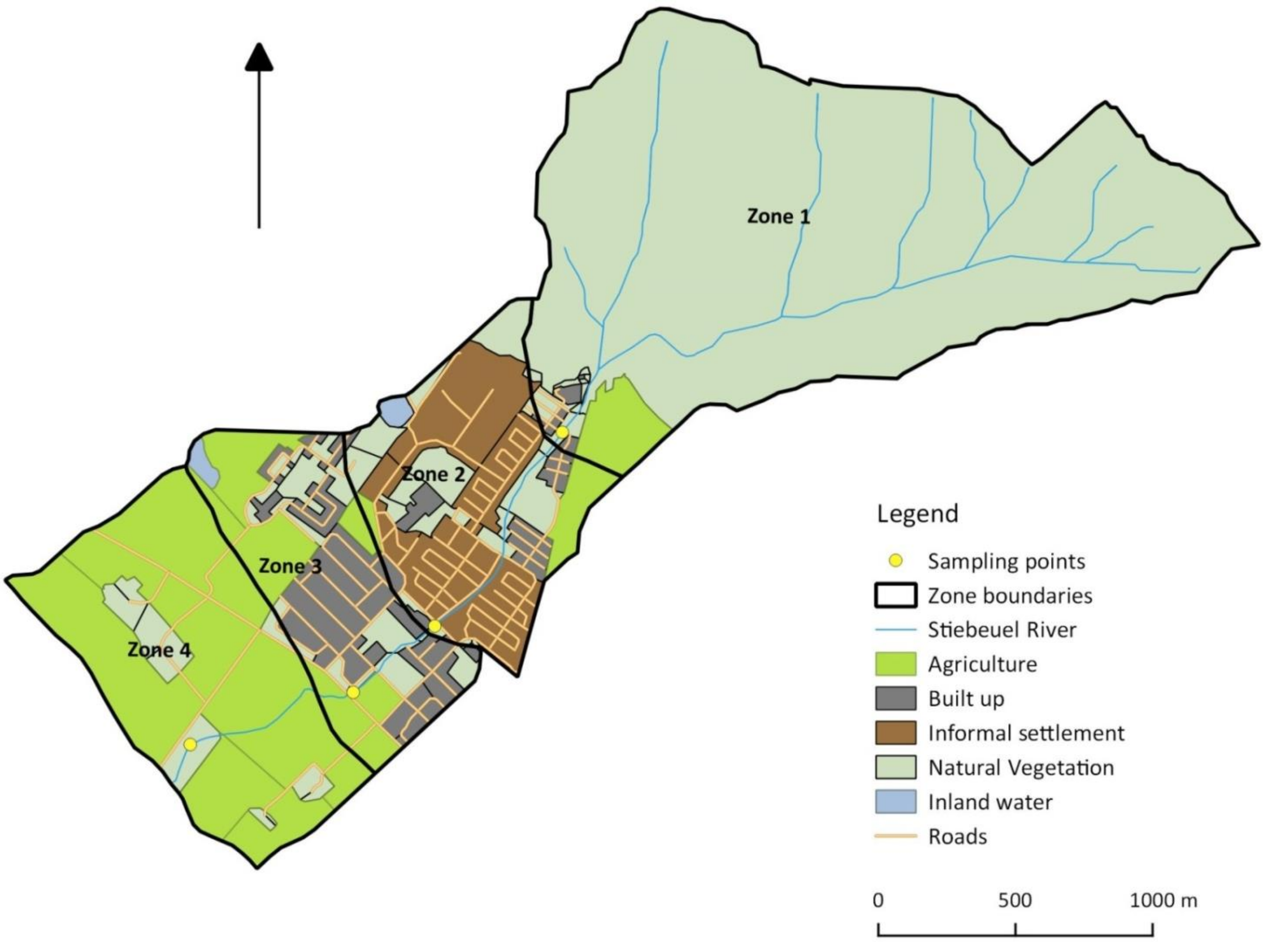

Figure 11. The delineated land use types of the four zones in the Stiebeuel River catchment.

4.1.2 Land use distribution

Natural vegetation dominated zone 1, covering 89.5% of its total land area (Figure 11 and 12). The Stiebeuel River begins in the mountainous area in this zone and is fed by various smaller streams that drain into the main river channel, thus accounting for the dominant LUT. The informal settlement covered more than half of zone 2 at 55.9%, with the rest of the zone 2 being covered by natural vegetation (25.8%), built-up (10.6%), agriculture (7.7%). Zone 3 had the most varied composition of LUTs, with agriculture and built-up dominating the total land area at 32% and 36.6% respectively. Agriculture dominated zone 4 in the lower reaches of the Stiebeuel River, comprising 88.1% of the total area. Agriculture and natural vegetation dominated the catchment as a whole, covering 32.6% and 36.9% respectively, with informal settlement covering the next largest proportion at 18.9% and built-up covering 11.6% of the total area.

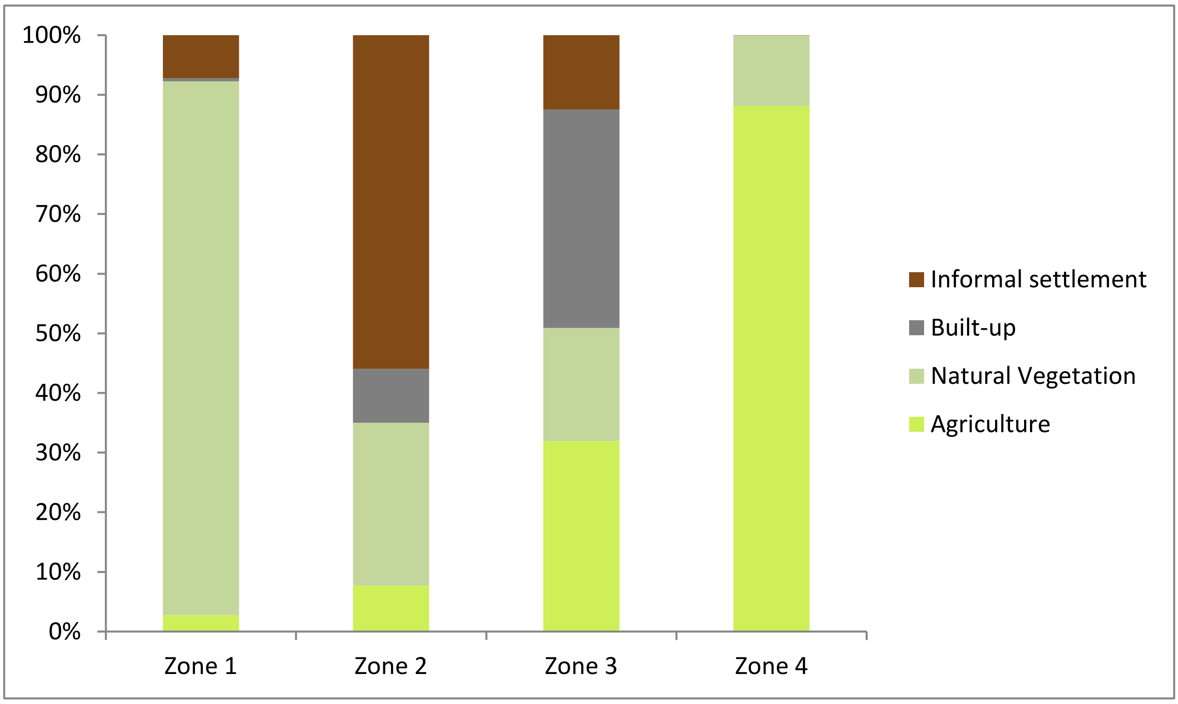

Figure 12. The land use composition (%) of the four zones in the Stiebeuel River catchment.

4.1.3 Water quality

The water quality parameters at each site along the Stiebeuel River catchment are displayed in Table 3 and Figure 13. The site numbers correspond with each zone so that site 1 represents the water quality of zone 1 and so forth. All of the water quality parameters show significant spatial differences among the four zones. Site 1 had the best water quality over the catchment, with the lowest nutrient concentrations (NO_2^--N, NO_3^--N, NH_3-N and PO_4^{3-}) and EC and TSS values. This condition of the water quality is expected as there is negligible human influence in zone 1 and the water flows exclusively through a natural area.

Table 3. The average and standard deviation of the eight water quality parameters from the four sampling sites in the Stiebeuel River catchment.

		NO_2^--N (mg/L)	NO_3^--N (mg/L)	NH_3-N (mg/L)	PO_4^{3-} (mg/L)	pH	DO (mg/L)	EC (µs/cm)	TSS (mg/L)
Site 1	Average	0.005	0.30	0.01	0.34	6.62	6.49	36.38	9.46
	Standard deviation	0.004	0.11	0.02	0.52	0.77	2.08	4.98	8.34
Site 2	Average	0.050	1.05	8.40	5.94	6.69	3.49	362.92	135.15
	Standard deviation	0.059	1.13	5.18	7.36	0.71	2.36	312.68	124.28
Site 3	Average	0.072	1.78	3.74	1.80	6.33	4.72	194.08	26.77
	Standard deviation	0.097	1.38	3.11	1.24	0.82	2.34	68.64	14.68
Site 4	Average	0.058	2.52	2.16	0.85	6.63	5.76	185.54	26.08
	Standard deviation	0.088	1.41	2.88	0.48	0.60	1.84	57.34	26.89

In contrast, site 2 had the poorest water quality of the whole catchment, with the highest NH_3-N, PO_4^{3-}, EC and TSS values and the lowest DO concentrations (Table 3 and Figure 13). The river flows through the informal settlement of Langrug in zone 2 and is polluted by the diffuse and point source contaminants it receives from the settlement (Figure 11 and 12). Rivers with similar trends that flow through slums have been reported in other locations (Table 4) where water quality parameter concentrations are the same or even higher. For example, the average NH_3-N concentration at site 2 (8.4mg/L) is comparable to the Yemetu Stream in Nigeria (9.3mg/L) and the Nsooba Channel in Uganda (10.4mg/L) while the average PO_4^{3-} concentration of 5.94mg/L was higher than the average reported in the Njoro River (0.3mg/L) and the New Calabar River (0.01-0.057), but lower than the figure reported in the Old Fadama slum.

Table 4. Selected water quality data from rivers and drainage channels in other locations *NO_3^{2-} (values are reported either as ranges with the average in brackets or as averages with the standard deviation.)

River or drinage channel	Location	NO_3^--N (mg/L)	NH_3-N (mg/L)	PO_4^{3-} (mg/L)	EC (µs/cm)	DO (mg/L)	Reference
3 Major drainage channels	Old Fadama slum, Ghana	43.87 ± 30.07	16.39 ± 5.02	12.59 ± 2.22	2480 ± 880	0.21±0.15	(Monney et al. 2013)
Njoro River	Kenya	0.38 ± 0.13	1.54 ± 0.47	0.30 ± 0.12	-	6.1 ± 1.6	(Mokaya et al. 2004)
Nsooba channel	Uganda	0.5–3.6 (1.61)	6.8–12.1 (10.4)	0.11–0.78 (0.36)	471–612 (554)	0.03–1.87 (0.7)	(Nyenje et al. 2014)
Yemetu Stream	Ibadan, Nigeria	-	9.3	-	-	2.8	(Olaseha and Sridhar 2003)
Mukuvisi River	Zimbabwe	0.19-1.75*	0.09-2.47	-	86.7-783.3	4.48-5.97	(Phiri 2000)
Gwebi River	Zimbabwe	0.06-0.99*	0.07-0.2	-	137.5 -331.7	4.01-7.07	(Phiri 2000)
New Calabar River	Niger Delta, Nigeria	0.012-0.17	0.012-0.17	0.01-0.057	46-950.7	-	(Chindah 1998)
Stiebeuel River	Franschhoek, South Africa	0.3-2.52	0.01-8.4	0.34-7.36	36.38-362.92	3.49-6.49	This study

Elevated concentrations of NH_3-N (8.4mg/L) and PO_4^{3-} (5.94mg/L) at site 2 in the Stiebeuel River could be attributed to wastewater (greywater and sewage) runoff from the informal settlement. Limited sanitation and drainage systems in the settlement mean that most wastewater generated from households was discharged outside people's homes or into informal drainage channels, and ultimately drained into the river. The relatively high average TSS of 135.15mg/L at site 2 probably assisted in the transport of these nutrients via sediments to the river. The informal settlement has few paved roads and mainly consists of hard gravel and stone surfaces, which are easily eroded by rainfall and by runoff from excess wastewater.

The lowest average DO level of 3.49mg/L was found at site 2 in the catchment. Chapman and Kimstach (1996) assert that DO levels below the value of 5mg/L adversely affect the functioning and survival of aquatic communities.

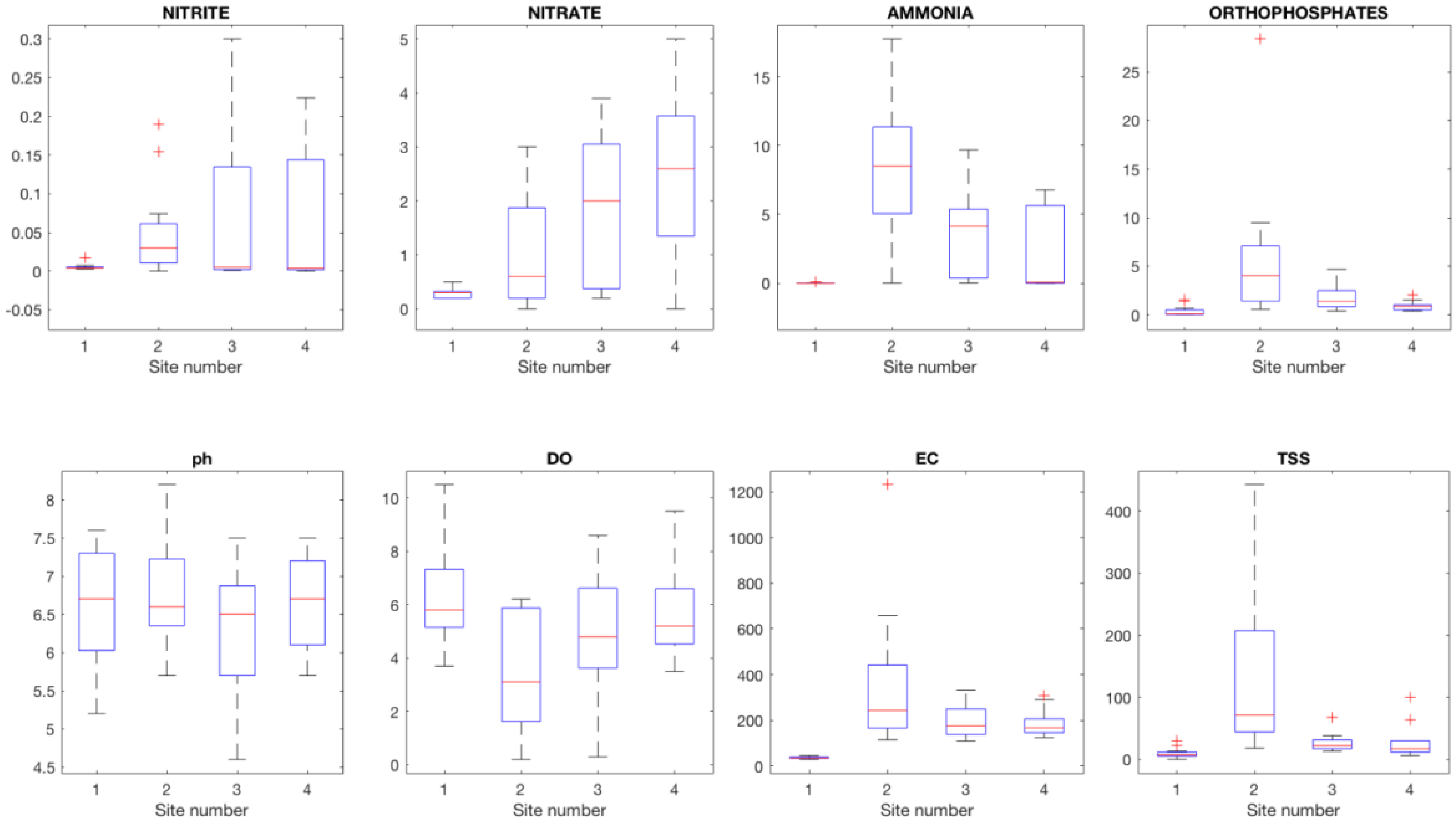

Figure 13. Box and whisker plots of the eight water quality parameters with the four sample sites indicated along the x-axis (+ signs denote outliers).

The low average DO levels at site 2 may be linked to the elevated NH_3-N concentrations at the site through the process of nitrification (Figure 13). Jianlong and Ning (2004) explain that in the process of nitrification, ammonia is first oxidized to nitrite by ammonia-oxidizing bacteria and then further oxidised to nitrate by nitrite-oxidising bacteria. DO is a co-substrate in the nitrification process and its concentration influences the reaction rate of both ammonia and nitrite oxidation (Stendahl 1990). Thus, the low DO levels could be attributed to the wastewater that the river receives from the settlement, which contain high levels of NH_3-N that are likely to deplete DO. Furthermore, the high concentration of suspended solids at site 2 most likely promotes the nitrification process and, in turn, the removal of ammonium from the river. The existence of suspended solids increases the contact chances between bacteria and nitrogen, accelerating the nitrification process (Xia et al. 2004).

The highest concentrations of NO_3^--N (2.52mg/L) were found at site 4 and could be attributed to (i) nitrogen from fertilizers in the adjacent agricultural lands, this concurs with the assertion by Edwards and Withers (2008) that NO_3^--N generally dominates runoff from agricultural land, and (ii) nitrate emanating from the nitrification of NH_3-N enriched wastewater, received as runoff from the informal settlement in zone 2 (Figure 11).

The river's assimilative capacity was demonstrated by various water quality parameter concentrations improving from site 2 to site 4. NH_3-N concentrations decreased by 74%, PO_4^{3-} decreased by 86%, TSS decreased by 81% and EC decreased by 49% while DO increased by 65% from site 2 to site 4.

4.1.4 Average daily flow

Table 5. The average, maximum and minimum daily flow for weekdays, weekends and both.

	Average flow (m^3/s)	Maximum flow (m^3/s)	Minimum flow (m^3/s)
Weekdays	0.207	0.668	0.023
Weekend	0.085	0.504	0.016
All (dry week sample)	0.173	0.579	0.023

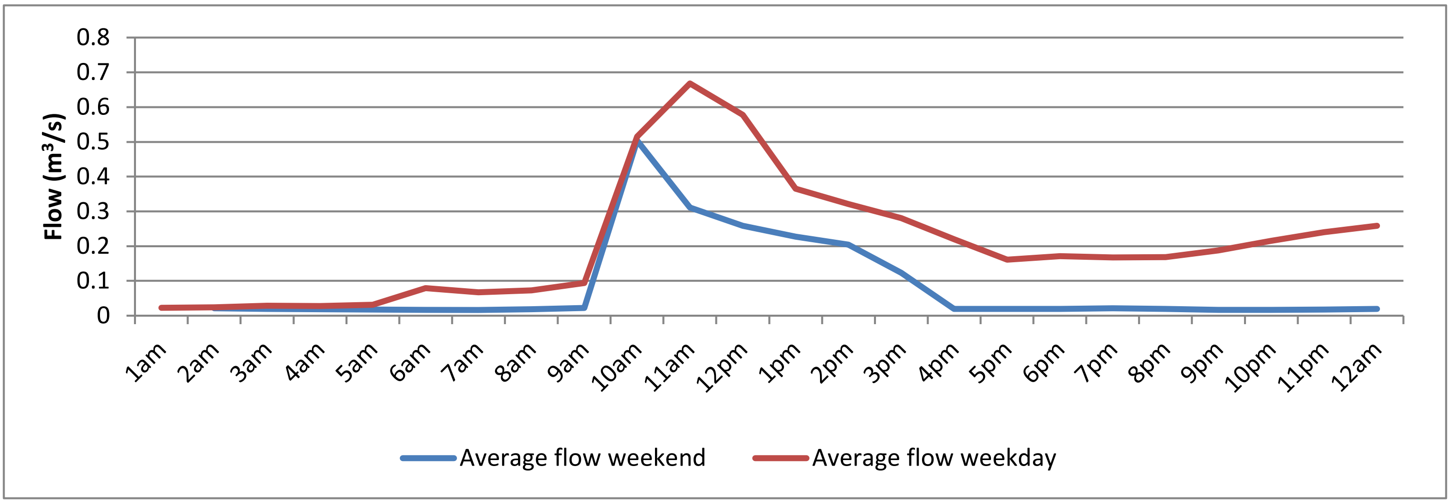

Figure 14. The average daily flow during the weekend (indicated by a blue line) and weekday (indicated by a red line) in the Stiebeuel River.

The flow of the Stiebeuel River was recorded every six minutes for the four month data collection period. The flow gauge was placed at site 5, downstream of the informal settlement, and in the agricultural area. Average hourly and daily flows were calculated from five weeks worth of dry day data for weekdays (Monday-Friday), weekends (Saturday-Sunday) and for both.

Table 5 presents the average, maximum and minimum daily flow for weekdays, weekends and both. Figure 14 illustrates the average hourly flow over a 24 hour period, on an average weekday (red line graph) and an average weekend day (blue line graph). The average hourly weekday flow is higher than the average hourly weekend flow, peaking at 0.668 m^3/s on weekdays compared to 0.504 m^3/s on weekends, suggesting more inputs to the river on weekdays than weekends. On weekdays the flow is relatively low from 1am to 5:30am, after which there is an increase, perhaps as residents from the informal settlement use water as they begin their day. At 9:30am, the sharpest observed increase in flow occurs, with an increase of approximately 0.4 m^3/s over a one hour period. There is another smaller increase in flow from 10:30am to 11:30am, with flow increasing by approximately 0.2 m^3/s over the hour. Thereafter, a decrease in flow is observed. On weekends, a similar pattern is observed, however the initial increase occurs later than it does on weekdays, only at 9:30am.

There is a relatively large input to the river every day, around 9:30am, suggesting there is a release of water. The sharp increase is observed at exactly the same time each day and suggests a mechanical input of water to the system. Wastewater and greywater runoff from the informal settlement will affect the flow, but is unlikely to occur in such a mechanical and consistent manner.

4.2 Relationships between land use types and river water quality parameters

To further explore the relationships between pollutants and land use in the Stiebeuel River catchment, pairwise correlations were estimated between each WQP and LUT percentage. Table 6 shows the estimated correlation coefficients with estimates found to be significantly different from zero indicated in the footnote.

Table 6. Correlation coefficients between the eight water quality parameters and the five land use types with significance at $p<0.05$ and <0.01.

	Agriculture	Natural vegetation	Built-up	Informal settlement
NO_2^--N	0.175	-0.324[a]	0.220	0.036
NO_3^--N	0.557[b]	-0.529[b]	0.117	-0.197
NH_3-N	-0.153	-0.366[b]	0.179	0.632[b]
PO_4^{3-}	-0.196	-0.178	0.066	0.510[b]
pH	-0.011	0.050	-0.177	0.069
DO	0.110	0.270[a]	-0.201	-0.416[b]
EC	0.001	-0.404[b]	0.122	0.487[b]
TSS	-0.207	-0.197	-0.016	0.610[b]

[a] Significance at 0.05 probability level

[b] Significance at 0.01 probability level

A number of the correlations were found to be significantly different from zero; for instance, the estimate for the correlation between natural vegetation and DO is a considerably positive. This means that when the percentage of natural vegetation increases, the DO value tends to increase, and vice versa. Figure 15 illustrates this - the larger natural vegetation percentages correspond to the higher DO measurements. In the case of natural vegetation and DO, the estimated regression coefficient is 0.02, meaning that when natural vegetation increases by one, the DO value increases by 0.02.

The estimates do not indicate whether increased informal settlement land use will cause higher NH_3-N concentrations, or whether there is a direct causal link at all. In this case, a causal link seems plausible as it is known that human activities in the informal settlement produce large amounts of NH_3-N (Parkinson and Mark 2005; Obrist et al. 2006; Armitage et al. 2010). Land use itself does not cause pollution, rather human activities on the land determine the type and extent of pollution (Lee et al 2009). Thus, the correlations presented in Table 6, will be taken as tentative generalizations of the relationships between land use and water quality.

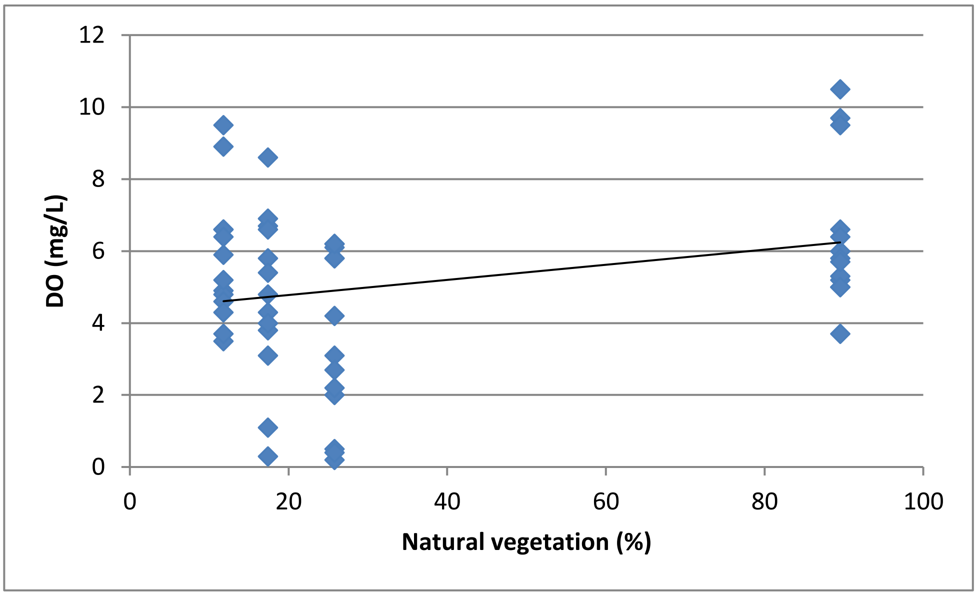

Figure 15. Scatterplot showing natural vegetation (%) and DO and the estimated regression relationship.

In contrast, for some of the pairwise correlations the null hypothesis cannot be rejected; for example, the built-up area variable cannot be concluded to have significant correlations with any of the water quality parameters.

The correlation coefficients estimated in Table 6 differ in size but are not near to 1, or -1. Land use, therefore, does not fully explain variation in water quality parameters across the Stiebeuel River catchment. Evidently, other factors contribute to concentration changes. The significant correlation estimates range from -0.325 to -0.523, and from 0.277 to 0.632, and indicate the proportion of water quality parameter variation that is explained by land use.

4.2.1 Discussion

Numerous studies have found that natural or vegetated areas are associated with good water quality while built-up and agricultural land uses are linked to poor water quality (Li et al. 2008; Lee et al. 2009; Bu et al. 2014). The results of this study are consistent with the findings of such previous studies. Natural vegetation is significantly negatively correlated with four WQPs, and significantly positively correlated with DO, indicating a relationship between natural vegetation and good water quality. The zone dominated by natural vegetation receives no diffuse or point source pollution and accounts for this relationship.

Agriculture land use is significantly and positively correlated with NO_3^--N. The relationship could be attributed to (i) nutrient enriched runoff from fertilizers in the agricultural area (zone 4) contributing to riverine NO_3^--N, which concurs with various other similar studies (Sliva and Williams 2001; Mehaffey et al. 2005; Stutter et al. 2007), or (ii) NO_3^--N from wastewater transported from the zones above, which contain the informal settlement and built-up area. However, there is limited use of fertilizers in the vineyards in the study area. Hence, it is likely that NO_3^--N in the most downstream zone emanated from the nitrification of NH_3-N enriched wastewater transported from the informal settlement.

In contrast, agriculture has weak negative correlations with most other WQPs. This is similar to a study by Tu (2011), where the percentage of agricultural land had significant negative relationships with most water quality indicators. The author posits that developed land is a more significant source of pollution than agriculture. The same may be true for this study, as informal settlement land use has a significant positive correlation with all but two WQPs, suggesting that developed land is the primary contributor to poor water quality. The positive correlations between informal settlement and NH_3-N, PO_4^{3-}, EC and TSS, and the negative correlation with DO, points to wastewater discharges from the settlement as significant contributors to the pollution of the river. This was expected as contaminated wastewater from limited sanitation, drainage and waste collection services in the settlement results in the pollution of the river. Further evidence is provided by the highest concentrations of WQPs over the Stiebeuel River catchment occurring in zone 2, which is dominated by informal settlement land use at 55.9% (Figure 11).

The built up LUT is not significantly correlated with any WQPs, which is unexpected considering the strong correlations between built-up lands and poor water quality in other studies (Lenat and Crawford 1994; Schoonover and Lockaby 2006). The weak correlations between built-up land use and WQPs in this study do not eliminate built-up areas as sources of surface water pollutants, but rather indicate that other factors control pollutant concentrations. Once again, it is most likely that the informal settlement land use is the most significant contributor of pollutants over the catchment.

The results from this section contribute to a small, but growing, body of knowledge which proves that surface water is from informal settlements is highly contaminated, and more so than from other urban areas. By monitoring water quality and assessing catchment characteristics, a quantitative relation between an informal settlement and poor river water quality was established. This relationship strengthens our understanding of the role of these settlements in the widely reported degradation of urban rivers in the developing world.

As the world rapidly urbanises, with 6.3 billion projected to live in cities by 2050, much of the urban poor will be forced to live in slums of the developing world (Parkinson and Mark 2005; Alirol et al. 2011). The land use coverage of catchments will change, as more areas are converted into urban land use, whether in the form of conventional impervious surfaces, or as slums, with hardened surfaces but fewer concrete lined areas. Considering this, the section below models theoretical land use change scenarios and their potential effects on water quality parameters in the Stiebeuel River catchment.

4.3 Land use change scenarios in the Stiebeuel River catchment

Surface water from slums is some of the most highly contaminated water in urban areas (Mokaya et al. 2004; Monney et al. 2013; Katukiza et al. 2014; Nyenje et al. 2014). As catchments in the developing world progressively become dominated by urban and informal settlement land uses, it is probable that pollutant production will increase and river quality will decrease. This section explores the effects of hypothetical land use changes on river water quality.

DeFries and Eshleman (2004) warn that identifying and quantifying the hydrological consequences of land use change are not trivial exercises and are complicated by factors such as (i) the relatively short length of hydrological records, (ii) the relatively high natural variability of most hydrological systems and, (iii) the complex range of socio-economic and biophysical factors that influence land use change (Verburg et al. 2004). One of two common methods to simulate land use change is by developing hypothetical scenarios and then adjusting catchment characteristics, such as the ratio of impervious to pervious surfaces (eg. Legesse et al. 2003; Akhter and Hewa 2016; Semadeni-Davies et al. 2016). In this study, land use changes are simulated by changing the percentage of land use proportions in the Stiebeuel River catchment by hypothetical amounts. This approach was primarily chosen for the sake of simplicity as it eliminates the need to consider the multitude of complex interacting factors that drive land use changes (Lambin et al. 2001).

Praskievicz and Chang (2009) note that modelling is an inherently probabilistic exercise, with uncertainty amplified at each stage of the process, from scenario generation to issues of scale, to simulation of hydrological processes. Scenario creation involves a degree of crystal ball gazing as a scenario is a picture of a conceivable future, as opposed to a prediction (Semadeni-Davies et al. 2016). Water quality modelling is also a complex exercise. Praskievicz and Chang (2009) note that loading of water quality constituents depends not only on basin hydrology but other factors such as channel morphology and vegetation dynamics; topics complex enough to require models of their own. The regression modelling below is a simplistic exercise that has only assessed the relationship between proportion of land use and water quality concentrations. The regression models ignore other important catchment characteristics that influence water quality, such as impervious surface coverage, soils and topography, and the results must be approached with caution.

4.3.1 Multiple regressions

Multiple regression equations were developed for land use proportions and various water quality parameters, using the significant correlations estimated in Table 6. The predictive regression equations for NO_2^--N, NO_3^--N, NH_3-N and PO_4^{3-}, DO, EC and TSS are displayed in Table 7. The pairwise correlations estimated in Table 6 are reflected in these regressions. For instance, in the predictive equation for NO_2^--N, there is a negative sign before the regression coefficient for natural vegetation, reflecting the negative (pairwise) correlation estimated between NO_2^--N and natural vegetation (Table 7). In the case of the NO_3^--N predictive equation, the signs of the correlations are similarly reflected by the regression coefficient signs: agriculture is positively correlated with NO_3^--N, indicated by the positive regression coefficient sign for agriculture, while natural vegetation is negatively correlated with NO_3^--N, reflected in the negative regression coefficient sign for natural vegetation. These remarks extend to the other predictive equations in Table 7, where the signs of the regression coefficients are consistent with the pairwise correlations estimated earlier.

Table 7. Multiple regression equations for seven water quality parameters with the r^2 value indicated.

Parameter	Prediction equation	r^2
NO_2^--N	Y = 0.07 - 0.0007 (NV)	0.105
NO_3^--N	Y = 1.398 + 0.015(A) - 0.013(NV)	0.359
NH_3-N	Y = 2.798 + 0.121(IS) - 0.04(NV)	0.478
PO_4^{3-}	Y = 0.367 + 0.099(IS)	0.26
DO	Y = 5.297 - 0.043(IS) + 0.0165(NV)	0.218
EC	Y = 200.5 + 3.9(IS) - 2.15(NV)	0.35
TSS	Y = 7.436 + 2.217(IS)	0.372

Six hypothetical land use scenarios were modelled using the predictive equations in order to explore the effects of land use change on water quality parameters in the Stiebeuel River catchment. The regression equations provide estimates for the dependent variables (water quality parameter concentrations) based on these hypothetical land use scenarios. Six hypothetical land use scenarios were developed, which focused on growth in the informal settlement and built-up land use, as it is most plausible that these areas will expand further. For instance, there has been significant growth in the informal settlement from less than 500 informal dwellings in 2007 up to approximately 1700 in 2011 and to 2500 in 2015 (Winter, 2016). The scenarios include no growth scenarios for agriculture and natural vegetation, as there is little space for these land use types to expand into. Varying land use compositions were assumed in each scenario to create informal settlement, built-up and informal settlement/built-up dominated catchments. It was assumed that natural vegetation and agricultural lands were converted to informal settlement and/or built-up land use types. Fractions of natural vegetation and agriculture were reduced accordingly at proportional rates. The six scenarios are presented in Table 8 and as part of Table 9.

Table 8. The six hypothetical land use change scenarios.

Scenario	Growth
1	Informal Settlement proportion increased by half of original size
2	Informal Settlement proportion doubled in size
3	Built-up proportion increased by half of original size
4	Built-up proportion doubled in size
5	Informal Settlement proportion and Built-up proportion each increased by half of original sizes
6	Informal Settlement proportion and Built-up proportion each doubled in size

Table 9 presents the predicted water quality of the six hypothetical land use scenarios. These predicted concentrations merely give an estimation of pollutant concentrations in different scenarios, and are based on regression models that are dependent on limited input data, as restricted by the scope of this study. Thus, the predicted concentrations are tentative extrapolations, intended to give a rough indication of the potential impacts of land use composition changes on water quality in the Stiebeuel River catchment.

Table 9. The predicted water quality concentrations of the six hypothetical land cover scenarios with the measured Stiebeuel River catchment averages indicated at the bottom.

Land use scenarios					**Water quality parameters**						
Scenario	**Agriculture**	**Natural Vegetation**	**Built-up**	**Informal settlement**	**NO_2^--N (mg/L)**	**NO_3^--N (mg/L)**	**NH_3-N (mg/L)**	**PO_4^{3-} (mg/L)**	**DO (mg/L)**	**EC (µs/cm)**	**TSS (mg/L)**
1	28	31.5	12.0	**28.5**	0.050	1.41	4.96	3.18	4.63	243	70.63
2	23	27	12.0	**38.0**	0.054	1.40	6.29	4.12	4.16	290	91.70
3	30	33	**18.0**	19.0	0.049	1.42	3.75	2.24	5.05	203	49.57
4	26	31	**24.0**	19.0	0.051	1.39	3.83	2.24	5.02	207	49.57
5	27	26.5	**18.0**	**28.5**	0.054	1.46	5.16	3.18	4.55	254	70.63
6	17.5	20.5	**24.0**	**38.0**	0.059	1.40	6.55	4.12	4.05	304	91.70
Measured Stiebeuel River catchment averages					0.046	1.41	3.58	2.23	5.12	194	49.37

4.3.2 Discussion

NH_3-N, NO_2^--N, NO_3^--N, PO_4^{3-}, EC and TSS concentrations are predicted to increase, while DO concentrations are predicted to decrease under all scenarios (Table 9). NH_3-N, PO_4^{3-} and TSS concentrations are predicted to peak in scenario 2 and 6, suggesting that a future expansion of informal settlement and/or built-up area could result in increased NH_3-N, PO_4^{3-} and TSS concentrations. TSS and PO_4^{3-} both peaked at the same concentrations in scenarios 2 and 6, indicating that an increase in built-up land has no predicted effect on the water quality parameters, and suggesting informal settlement has the largest influence. NH_3-N concentrations were predicted to be their highest in scenario 6, and were thus influenced by the increase in built-up land use. The peak concentrations of these three parameters are markedly higher than the current catchment averages, with land use changes inducing an increase in peak concentration of NH_3-N by 83%, PO_4^{3-} by 85% and TSS by 86% relative to their current averages. An increase in informal settlement area will likely result in increased wastewater and sediment being transported to river which will elevate pollutant concentrations (Olaseha and Sridhar 2003; Monney et al. 2013).

NO_2^--N and NO_3^--N concentrations are predicted to increase, in most cases, from the current catchment averages, in scenarios 2, 5 and 6, as informal settlement land use increases in proportion (Table 9). According to Chapman and Kimstach (1996), NO_3^--N concentrations that exceed 1mg/L indicate human impacted waters and have a negative impact on aquatic life. The NO_3^--N, concentrations found under all scenarios would exceed this limit, indicating the potential pollution of the river by NO_3^--N in the future.

There is little variation in the predicted NO_2^--N concentrations. This is linked to the low r^2 value presented in Table 7, which shows that the regression model did not explain a lot of variation in NO_2^--N concentrations. The r^2 value indicates the amount of variation explained in the predicted concentrations by the regression equations, with a value of 1 indicating that all the variation has been explained, and a value of 0 indicating that the explanatory variables account for none of the variation. For instance, the NH_3-N prediction equation has the highest r^2 value of 0.478, and this is reflected in the larger NH_3-N variation, with concentrations ranging from 3.83mg/L to 6.55mg/L. The r^2 values, in Table 7, are in the range of 0.1 to 0.5, indicating the proportion of the predicted concentration variation that is explained by the changes in land use compositions in the Stiebeuel River catchment. It is expected that the r^2 values would be low, as water quality concentrations are influenced by multiple factors that are hard to isolate and predict (Chapman and Kimstach 1996; Praskievicz and Chang 2009).

DO concentrations exhibited similar trends to NH_3-N, PO_4^{3-} and TSS, reaching their lowest concentrations in scenarios 2 and 6. At the lowest predicted concentration in Scenario 6, of 4.05mg/L, DO was 20% lower than the current catchment average. According to Chapman and Kimstach (1996) DO levels below the value of 5mg/L adversely affect the functioning and survival of aquatic communities. The DO concentrations found under scenarios 1,2,5 and 6, that is, the scenarios involving increases in informal settlement land use, are projected to be below this limit.

Thus, the future expansion of the informal settlement could increase NH_3-N, NO_2^--N, NO_3^--N, PO_4^{3-}, EC and TSS concentrations, and decrease DO concentrations. This would likely lead to the deterioration of the Stiebeuel River, primarily by means of nutrients from wastewater in the informal settlement. Land use does not cause pollution, instead, human activities on the land determine the types and extent of pollution. Thus, the increase in informal settlement land use will most likely result in a higher population density producing increased amounts of wastewater and litter, which will not be met with more urban services or infrastructure development, resulting in increased pollution. Reed (2013) comments on this well-known phenomenon in the present day, noting that the increasing urban population is forcing more people to live in marginal areas, where more water is being consumed, yet the provision of water supplies is not matched by the provision of waste water disposal systems. Capps et al. (2016) echo this sentiment, noting that slums are of special concern in cities undergoing rapid urbanization in developing countries, as the rates of infrastructure development typically lag behind rates of urban expansion. In the turbulent Anthropocene, the poor will be most affected by surface water quality issues (Ajibade et al. 2013; Aßheuer et al. 2013).

The scenario results from this section depicted a possible range of future water quality conditions, painting a bleak picture of a future marked with the expansion of the informal settlement. Without interventions, these scenarios are grave warnings of the long term implications of inevitable land use changes on rivers in urban and peri-urban catchments.

However, the scenarios could be of value in developing adaptation strategies to protect the poor from the consequences of future land use changes. Using this information, more comprehensive and sustainable catchment management programs could be developed. The results also demonstrated the value of simple regression modelling in assessing a range of scenarios.

4.4 Rainfall events in the Stiebeuel River catchment

Grab samples in the section above provided insights into the dynamics of the Stiebeuel River during days between rainfall events, indicating the poor water quality over the catchment. This section investigates how rainfall runs off the surface of the informally settled Stiebeuel River catchment, and the effects this may have on flow and pollutant concentrations in the receiving Stiebeuel River.

4.4.1 Event Hydrographs

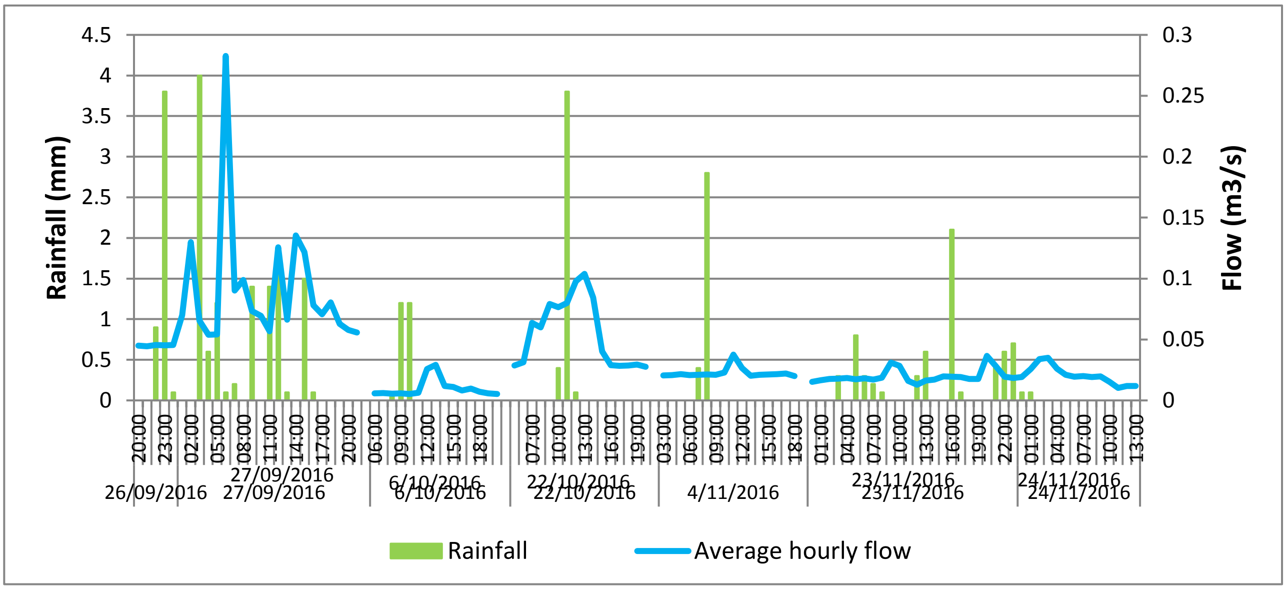

Figure 16. Hydrographs from the five rainfall events with the hourly rainfall displayed by the green bar graph and the average hourly flow displayed by the blue line graph.

Table 10. Various hydrological metrics from the five rainfall events.

	Date	Total Rainfall (mm)	Duration (hr)	Rainfall intensity (mm/hr)	Peak rainfall (mm)	Peak flow (m^3/s)	Average flow (m^3/s)	Lag time (hrs)	Antecedent dry days
1	26-27/09/2016	17	19	0.9	4	0.2827	0.0894	3h	18
2	6/10/2016	2.5	3	0.8	1.2	0.0293	0.0056	4h	12
3	22/10/2016	4.3	3	1.4	3.8	0.1038	0.0847	2h	5
4	4/11/2016	3.2	2	1.6	2.8	0.0376	0.0212	3h	7
5	22-23/11/2016	6.7	23	0.3	2.1	0.0365	0.0203	4h	3

Differences in the event-driven hydrographs and hydrological metrics in Figure 16 and Table 10 demonstrate the variable rainfall-runoff response of the Stiebeuel River catchment. Event 1 exhibited the flashiest hydrograph with four observed flow peaks. The high total and peak rainfall and flow resulted in much sharper rises to flow peaks here than is visible during the other events. The highest flows occurred during event 1, despite the 18 antecedent dry days, and the low antecedent soil moisture content. A soil crust probably developed due to the high intensity rainfall which decreased infiltration and increased overland flow (Valentin and Bresson 1992; Römkens et al. 2002; Chamizo et al. 2012). By contrast, the hydrograph of event 5 had gentle rising and falling limbs with three small flow peaks. The low intensity and long duration rainfall likely resulted in slower infiltration rates and lower amounts of overland flow (McGrane et al. 2017).

Rainfall peaks followed flow peaks two to three hours later, with the exception of event 5, where a four hour response time is observed (Figure 16). The second peak flow is the largest in event 1 and 5, whereas the third flow peak is the largest during event 3, highlighting the role of infiltration and saturation excess runoff in a predominantly pervious catchment.

Part of the catchment is occupied by an informal settlement (18.9%), where the land cover is not 'conventionally' impervious as it is not covered by concrete. However, it is functionally impervious as the soil is hard and compacted. Horner et al. (1994) note that even when surfaces remain pervious, development often removes, erodes or compacts topsoil, which retards infiltration and offers much less storage capacity.

4.4.2 Event Pollutographs

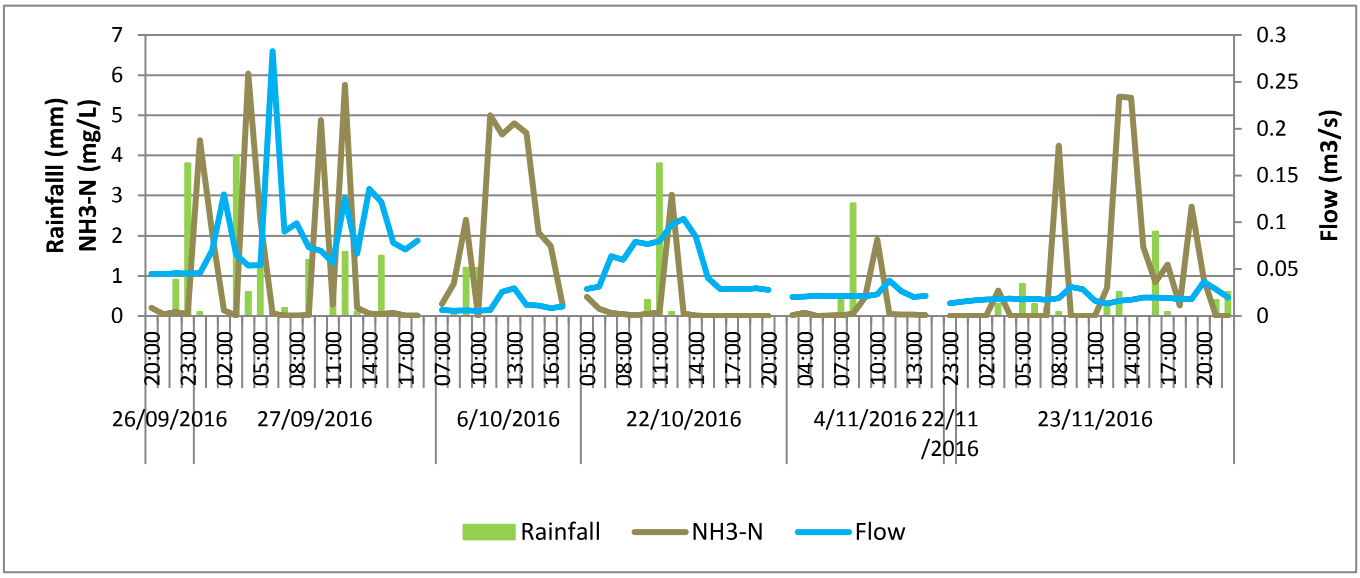

Figure 17. NH_3-N pollutographs from the five rainfall events with the average hourly rainfall displayed by the green bar graph, the average hourly flow displayed by the blue line graph and the average hourly NH_3-N concentrations displayed by the brown line graph.

For all the events, NH_3-N responds to rainfall peaks approximately one to two hours later, increasing rapidly (Figure 17). The multiple NH_3-N concentration peaks during events 1, 2 and 5 are characterised by sharp increases in NH_3-N followed by rapid decreases to zero, occurring over a period of approximately three to four hours. This indicates contaminated nutrient enriched wastewater being washed off the surface of the informal settlement by the rainfall. The drastic spikes in NH_3-N over the event provide rare insights into the detrimental effect of an informal settlement on a river after a dry period. The peak concentration of 6.04mg/L is highly elevated and markedly larger than the average concentration of 2.16mg/L recorded during dry weather flow (Table 11).

PO_4^{3-} and TSS concentrations peak approximately an hour after a rainfall peak, suggesting the pollutants are more mobile than NH_3-N, which took longer to reach the river (Figure 18). Once again, the multiple sharp concentration peaks indicate the rapid flushing of the pollutants off the catchment into the river by rainfall, demonstrating the adverse effect of the informal settlement. The peak concentrations during event 1 and 3 were highly elevated, with PO_4^{3-} peaking at 6.6mg/L and TSS peaking at 1868mg/L during event 1 (Table 11).

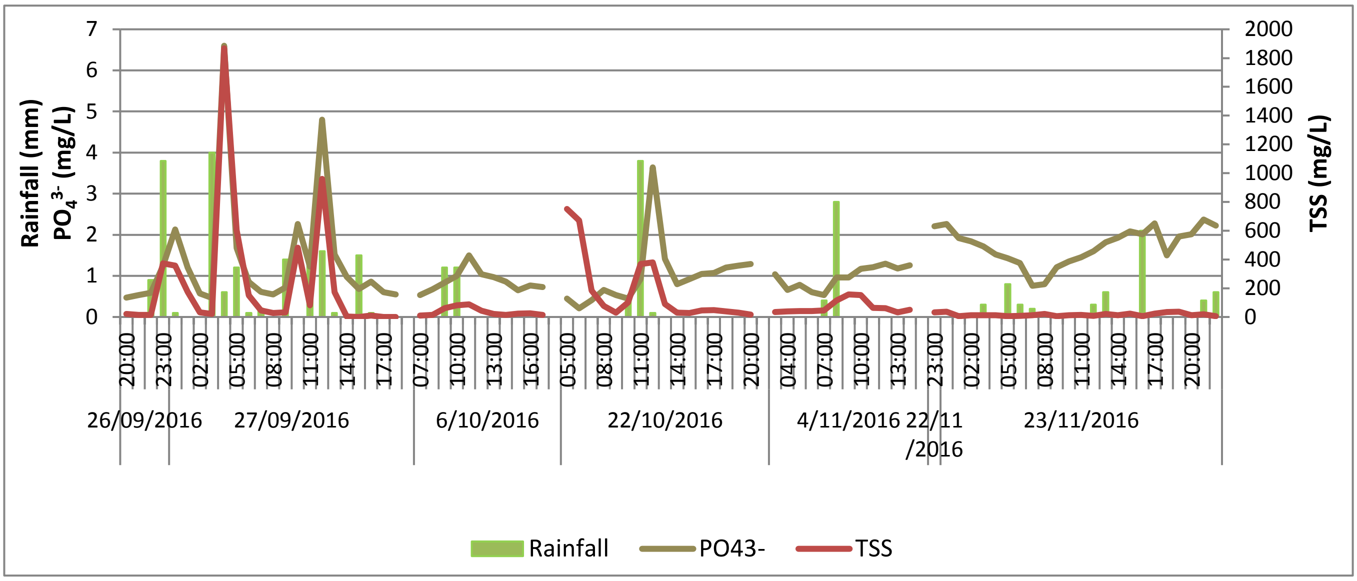

Figure 18. PO_4^{3-} and TSS pollutographs from the five rainfall events with the average hourly rainfall displayed by the green bar graph, the average hourly PO_4^{3-} concentrations displayed by the brown line graph and the average hourly TSS concentrations displayed by the red line graph .

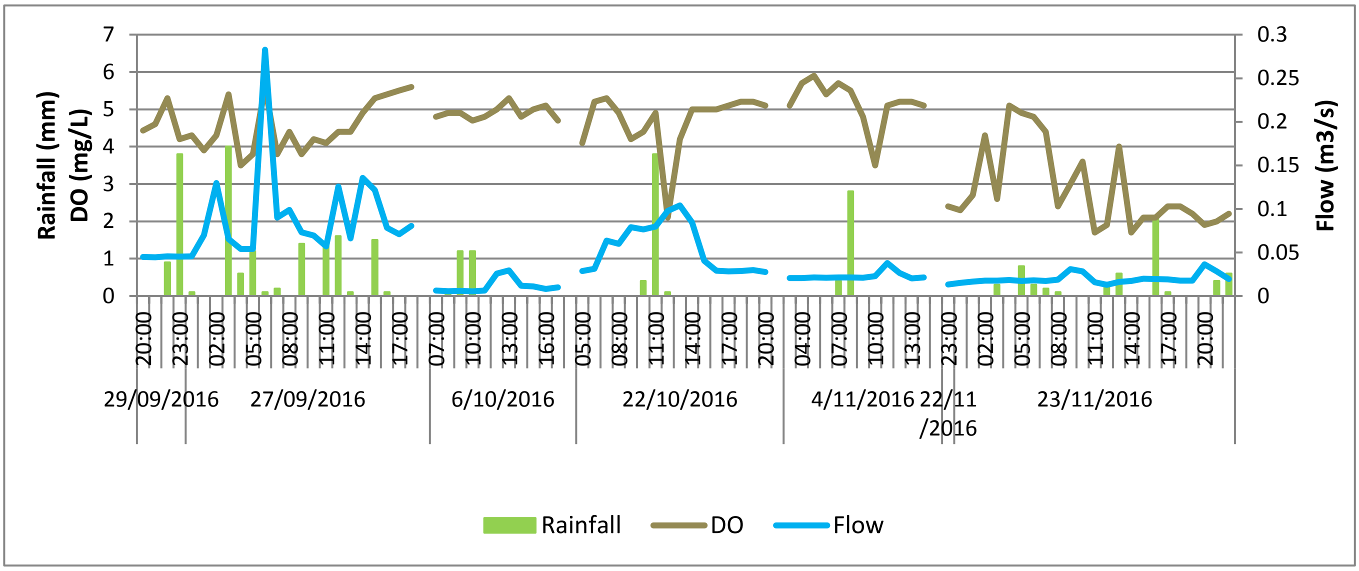

Figure 19. DO pollutographs from the five rainfall events with the average hourly rainfall displayed by the green bar graph, the average hourly flow displayed by the blue line graph and the average hourly DO concentrations displayed by the brown line graph.

The flushing of wastewater into the river during the first two hours of the events also affects DO concentration, with a reduction in DO during this time (Figure 19). DO reaches a low of 2.1mg/L during event 1 after one hour of rainfall, as a result of turbid and organic laden runoff being mobilized from the areas in the catchment (Table 11) (McGrane et al. 2017). The average DO concentrations over the events were lower than 5mg/L, with the exception of event 4, compromising the functioning and survival of aquatic communities and indicating the gross pollution of the river during the events (Chapman and Kimstach 1996).

The 18 dry days preceding event 1 likely account for the highly elevated pollutant concentrations and indicate the detrimental effect of these settlements on river water quality after dry periods. The pollutographs provides rare insights into the effects of event-driven removal of nutrients stored at the surface of an informal settlement after a dry period, which will become increasingly common in the future. NH_3-N, PO_4^{3-} and TSS do not exhibit a first flush effect over the events, suggesting that other mechanisms such as precipitation/dissolution or dilution are more dominant (Nyenje et al. 2014). The Stiebeuel River catchment is predominantly pervious and the first flush of polluted runoff most likely infiltrated the soil.

Table 11. Water quality parameter concentrations over the five rainfall events and during dry weather flow at site 4.

Pollutant		Event 1	Event 2	Event 3	Event 4	Event 5	Site 4 dry weather
NH_3-N (mg/L)	Average (st dev)	1.2 (±2.0)	2.4 (±2.0)	0.3 (±0.7)	0.2 (±0.5)	1.0 (±1.7)	2.16 (±2.88)
	Peak concentration	6.04	5	3.02	1.9	5.46	-
NO_3^--N (mg/L)	Average	2.2 (±1.2)	2.8 (±0.3)	3.1 (±1.9)	4.7 (±1.5)	5.1 (±1.1)	2.52 (±1.41)
	Peak concentration	3.5	3.1	5.8	6.9	7.2	-
PO_4^{3-} (mg/L)	Average	1.4 (±1.5)	0.9 (±0.3)	1.0 (±0.8)	1.0 (±0.3)	1.7 (±0.4)	0.85 (±0.48)
	Peak concentration	6.6	1.5	3.64	1.3	2.37	-
DO (mg/L)	Average	4.6 (±0.7)	4.9 (±0.2)	4.7 (±0.8)	5.2 (±0.6)	2.9 (±1.1)	5.76 (±1.84)
	Minimum concentration	3.5	4.7	2.1	3.5	1.7	-
TSS (mg/L)	Average	236 (±430)	35 (±28)	180 (±236)	69 (±45)	16 (±10)	26 (±26)
	Peak concentration	1868	87	750	157	37	-

4.5 Relationships between rainfall and water quality parameters

Pairwise correlations were estimated between the *hourly differences in the various WQPs* and *rainfall measurements with various lags* to further explore the five monitored rainfall events in the Stiebeuel River catchment. Hourly differences in a certain WQP are denoted with a delta symbol (e.g. ΔNH_3-N denotes the hourly changes in NH_3-N measurements). The hourly differences in WQPs were chosen as the response variable, as opposed to the hourly concentrations, as the interest is whether, and to what extent, rainfall appears to *affect* WQP measurements. The interest is in the short-term change of the measurements, and whether these changes are correlated with rainfall. A positive correlation indicates that rainfall is associated with a positive difference (i.e. an increase) in a certain WQP.

The rainfall without lags is simply the measured rainfall in millimetres (mm) during the relevant hour in which the WQP difference was measured. Lagged rainfall measurements are also introduced to allow for the possibility of a *delayed effect*; for instance, the rainfall during a particular hour might correlate with WQP changes in the next hour. The inclusion of various lags allows for the examination of how long it appears to take for rainfall to affect each WQP.

Table 12 shows the correlation coefficients between the *hourly differences in the various WQPs* and *rainfall measurements with various lags*. Estimates found to be statistically significantly different from zero are indicated in the footnote.

Table 12. Correlation coefficients between the hourly differences in the various water quality parameters and rainfall measurements with various lags.

	Rainfall	Rainfall lag 1h	Rainfall lag 2h	Rainfall lag 3h
Δ NH_3-N	0.01	0.41[b]	-0.28[a]	-0.07
Δ NO_3^--N	0.01	-0.26[a]	0.34[a]	-0.06
Δ PO_4^{3-}	0.08	0.46[b]	-0.49[b]	-0.07
ΔEC	0.09	0.40[b]	0.06	-0.21
ΔDO	0.01	-0.28[a]	0.02	0.25[a]
ΔTSS	0.15	0.35[a]	-0.42[b]	-0.08
ΔpH	-0.18	0.01	-0.13	0.22[a]
Average hourly discharge	0.16	0.22[a]	0.24[a]	0.63[b]
[a] Significance at 0.05 probability level [b] Significance at 0.001 probability level				

4.5.1 Discussion

Hourly differences in NH_3-N are found to be positively correlated to rainfall in the previous hour. This result suggests that rainfall causes an increase in NH_3-N concentrations within the following hour. Strictly speaking, this correlation merely implies an association between lagged rainfall and NH_3-N increases and not necessarily a causal relationship; however, a causal interpretation in this case seems plausible because (i) the time lag allows any causal effect to be captured and, (ii) it is widely held that rainfall is a primary driver of pollutant concentrations over a rainfall event (Mulliss et al. 1996; Bertrand-Krajewski et al. 1998; Lee et al. 2002; He et al. 2010; McGrane et al. 2017). Therefore, for the remainder of this section, the correlations between lagged rainfall and water quality parameter changes will tentatively be taken to be causal.

Not only does rainfall appear to cause an increase in NH_3-N after one hour, it also appears to be associated with a decrease in NH_3-N in the hour following that, as indicated by the significant negative correlation between the hourly differences in NH_3-N and rainfall lagged by two hours. Two hours after rainfall, it is most likely that NH_3-N is being flushed through the river, and, runoff from the far areas of the catchment is reaching the river and diluting concentrations (Crabtree 1988; Harremoës 1988).

PO_4^{3-}, TSS and EC follow this same trend: one hour after rainfall, a concentration increase tends to be observed, followed by a concentration decrease in the subsequent hour. The similar response times of TSS and PO_4^{3-} is expected as TSS is often reported as the transport mechanism of PO_4^{3-} (Buck et al. 2004; Chua et al. 2009; Nyenje et al. 2014).

The correlation coefficients mentioned above vary in size but are not near to 1 (or -1 in the case of the two hour lag). Rainfall, therefore, does not fully explain variation in water quality parameters across the Stiebeuel River catchment. Clearly, other factors contribute to concentration changes. There are a range of other factors that are widely known to affect concentration changes over rainfall events, which could have been included in the correlations (Zabaleta and Antigüedad 2013). Notable variables included in other studies are antecedent dry days (He et al. 2010), first flush strength (Han et al. 2006), rainfall intensity (Lee et al. 2002), land use (Hathaway et al. 2012), impervious area (Kang et al. 2008), catchment area (Soller et al. 2005) and rainfall duration (Gupta and Saul 1996).

NO_3^--N exhibit the reverse of the trends described above; hourly differences are negatively correlated with rainfall in the previous hour (suggesting that rainfall causes a decrease in NO_3^--N), and positively correlated by rainfall lagged by an additional hour (indicating a subsequent NO_3^--N increase). The increase after two hours of rainfall, appears slightly larger than the initial decrease (comparing the estimated coefficients), which may be explained by subsurface runoff, which takes longer to be transported to the river as infiltration first has to occur (Edwards and Withers 2008).

Variation in DO concentration follows a similar pattern to NO_3^--N: after one hour of rainfall, there is a decrease in concentrations. However, a subsequent increase is not observed in the following hour, but only the hour after that; indicated by the positive correlation with rainfall lagged by three hours. The initial decrease is perhaps explained, at least in part, by the increased NH_3-N, PO_4^{3-} and TSS observed after one hour of rainfall: the increase in these nutrients indicate the flushing of wastewater from the informal settlement and agricultural area into the river. DO is likely to be depleted during this time as bacteria decompose the wastewater and organic matter in the process of nitrification (Stratton and Mccarty 1967; Koning et al. 2000; Jianlong and Ning 2004).

Finally, rainfall appears to cause larger flow measurements in the subsequent few hours, most significantly after three hours. These results suggest that rainfall-runoff process takes three hours to have an effect on flow in the Stiebeuel River. The lag times displayed in Table 10 range from two to four hours, which lend support to the one, two and three hour rainfall lag found in the correlations. The large pervious coverage of the Stiebeuel catchment was most likely a modulating factor on the rainfall-runoff response. Subsurface flow and catchment wetness were probably important hydrological processes which influenced the relatively longer response time of three hours (McGrane et al. 2017).

The correlations strengthened our understanding of flows and pollutants washed off the surface of an informal settlement during a rainfall event. Through continuously monitoring the series of rainfall events, previously unknown insights were provided into the dynamics of various pollutants and flow in a river draining an informally settled catchment. The results showed that NH_3-N, PO_4^{3-}, EC, TSS and flow had the fastest responses to rainfall, increasing after an hour of rainfall, and indicating the sudden flushing of wastewater into the river. NO_3^--N and DO were slower to respond, taking two hours and pointing to the transport of NO_3^--N by subsurface runoff. NH_3-N, PO_4^{3-}, EC, TSS decreased after two hours and revealed the dilution of these pollutants. Flow responded to rainfall after three hours and was modulated by the large pervious coverage in the catchment.

Concluding remarks

The results from this section contribute to understanding how rainfall events are observed in informally settlement catchments. Rainfall events disproportionately affect the urban poor that reside in informal settlements, as these areas are often found on marginal land that is poorly drained and prone to flooding (Parkinson 2002). Intense rainfall causes many detrimental effects in informal settlements, which range from physical damage to property from flooding, to the spreading of disease from contaminated stormwater, to the "social amplification" of disasters, which disproportionately affect women, the elderly and physically disabled people (Parkinson 2003). As future climate changes cause increasing rainfall variability and more intense storm events, the vulnerable communities that live in these settlements will be affected the most.

4.6 Climate change scenarios in the Stiebeuel River catchment

Climate change is projected to cause higher intensity storm events over South Africa (Department Enviromental Affairs 2013). It is probable that these events will result in increased runoff and river flow, and an increase in pollutants transported to rivers. The section below explores the potential effects of future climate changes in the informally settled Stiebeuel River catchment, through regression modelling.

Hypothetical scenarios are used to investigate increased rainfall volumes on Stiebeuel River water quality and flow. Multiple other studies have used this approach when modelling climate change, with different authors applying various climate change factors to rainfall (Niemczynowicz 1989; Mccabe and Hay 1995; Xu 2000; Pyke et al. 2011; Shrestha et al. 2014; Waters et al. 2003). Increasing design rainfall by synthetic amounts was the chosen approach in this study considering the high degree of uncertainty in rainfall projections in South Africa. Only one hypothetical increment is explored as the interest is not in the projected increases themselves, but rather the potential magnitude and direction of climate change over a range of scenarios.

There is inherent uncertainty associated with both modelling and scenario creation. Semadeni-Davies et al. (2016) warn that futurology is a dangerous game, in that a scenario is a picture of a possible future rather than a prediction. The authors also note that common methodologies used in hydrology and decision making, such as the design rainfall concept, demand certainty yet scenarios are inherently uncertain and require some degree of crystal ball gazing. The regression modelling used in this section is a simplistic exercise, that only considers the statistical relationship between the independent variable (rainfall) and dependent variable (flow or the selected water quality parameter) when assessing climate change scenarios. There is no consideration of catchment conditions such as impervious surface coverage, soils and topography, which are known to have important impacts on the generation of surface runoff and, in turn, river flow and pollutant concentrations (Miller et al. 2014; McGrane et al. 2017). The lack of catchment data entered into the regression models means the results must be interpreted with caution, beyond the healthy scepticism that should already be attached to models and the use of scenarios (Silberstein 2006)

4.6.1 Multiple regressions

Multiple regression equations were developed for rainfall at various lags (rainfall lagged by one hour is denoted by R_{t-1}, and so on) and average hourly flow, and hourly changes in pollutant concentrations, using the significant correlations estimated in Table 12. Note that the various lagged rainfalls have low pairwise correlations (<0.1 and >-0.1), making them suitable as independent variables. The predictive equations for hourly changes in DO, NH_3-N, PO_4^{3-} and average hourly flow are displayed in Table 13. The pairwise correlations estimated in Table 12 are reflected in these regressions. For instance, hourly changes in NH_3-N were positively correlated with rainfall lagged by one hour, which is reflected in the positive sign before the regression coefficient of 1.002 of rainfall lagged by one hour, in the ΔNH_3-N regression equation. The r^2 values in the table indicate the proportion of the variation that is explained by the regression equation. For instance, a low proportion of the variation in NH_3-N is explained by the explanatory variables, while PO_4^{3-} variation is explained more thoroughly, indicated by the high r^2.

Table 13. Multiple regression equations for flow and changes in DO, NH_3-N and PO_4^{3-}.

Parameter	Predictive equation	r^2
Average hourly flow	$y = 0.023 + 0.0108(R_{t-1}) + 0.008262(R_{t-2}) + 0.031(R_{t-3})$	0.472939
ΔDO	$y = 0.0334 - 0.2633(R_{t-1}) + 0.243(R_{t-3})$	0.127559
ΔNH_3-N	$y = -0.137 + 1.002 (R_{t-1}) - 0.693 (R_{t-2})$	0.254787
ΔPO_4^{3-}	$y = 0.0249 + 0.6474(R_{t-1}) - 0.679(R_{t-2})$	0.471766

Four hypothetical rainfall events were modelled using the predictive equations to explore the effects of future climate change on water quality parameters and flow. The regression equations provide estimates for the dependent variables (flow and changes in NH_3-N, PO_4^{3-} and DO) based on these hypothetical rainfall events. The hypothetical rainfall events were based on the rainfall volumes of a 1 in 10 and 1 in 20 year design rainfall event, and the same design rainfall events with a climate change factor applied. The design rainfall depths for the 1 in 10 and 1 in 20 year rainfall event were for a duration of 24 hours and were obtained using the "Design Rainfall Estimation" software (version 3) (Smithers and Schulze 2003). The software estimates design rainfall depths for any location in South Africa; the location specified in this study was the latitude and longitude (degrees and minutes) of site 4 in the Stiebeuel River catchment, where the flow gauge was located. Once the rainfall depths for the two return periods were generated by the software, a climate change factor of 15% was applied, that is, 15% of the rainfall depths were added to the current rainfall depths. The four rainfall volumes were then distributed over a 24 hour period to create a hypothetical storm, with each hour being assigned a rainfall depth. The four scenarios are presented in Table 14, with the first scenario involving the current 1 in 10 year design rainfall depth (1 in 10 year present), and the second scenario including a climate change factor applied to the present 1 in 10 year design rainfall depth, making it a 1 in 10 year future event. Scenario 1 and 3 thus represent the present (baseline) rainfall while scenario 2 and 4 indicates the events with the climate change factor applied.

Table 14. The four hypothetical rainfall scenarios used in the multiple regression equations.

Scenario	Return period	Duration	Rainfall depth (mm)
1	10 year present	24 hours	94.2
2	10 year future	24 hours	108.3
3	20 year present	24 hours	111.3
4	20 year future	24 hours	128.0

Figure 19 shows the predicted concentrations of PO_4^{3-}, NH_3-N, DO while Figure 20 shows the flow over the hypothetical events. These estimates are taken tentatively as the hypothetical rainfall events involve larger volumes of rainfall than in our dataset and such an extrapolation should be treated with great caution. Note that in the case of PO_4^{3-}, NH_3-N and DO, the regression equations involve hourly changes to concentration levels, therefore, an initial value needs to be assumed, to which the changes that the regression predicts can be applied to. The initial NH_3-N and PO_4^{3-} values were taken as the average of the first concentration recorded at the beginning of each event.

4.6.2 Discussion

NH_3-N and PO_4^{3-} concentrations are predicted to be higher, while DO is predicted to be lower over the duration of a future 10 and 20 year rainfall event (scenarios 2 and 4) compared to a present 10 and 20 year rainfall event (scenarios 1 and 3) (Figure 20). In the case of NH_3-N and PO_4^{3-}, this is indicated by the red line graph (NH_3-N or PO_4^{3-} future) having higher concentrations, in general, than the green line graph (NH_3-N or PO_4^{3-} present). The predicted concentrations suggest that increased rainfall volumes, due to future climate changes, could lead to poorer river water quality.

For a 1 in 10 year event, future climate changes would induce an increase in peak concentration of NH_3-N by 10% and PO_4^{3-} by 50%, while DO would decrease by 90% from scenario 1 to scenario 2. In the case of a 20 year event, future climate changes would induce an increase in peak concentration of NH_3-N by 17% and PO_4^{3-} by 15%, while DO would decrease by 21% from scenario 3 to scenario 4. The greatest increase in NH_3-N and PO_4^{3-} concentrations, and the greatest decrease in DO, was found under scenario 4 (Table 15).

In the case of NH_3-N, at the end of the events the concentrations do not decrease to the concentrations at the beginning of the storm; in all four scenarios the concentrations plateau even when rainfall decreases. This data is different to the measured data in section 6.4, which the regression models were developed from. In the four scenarios, the hourly rainfall depths are much larger and the rainfall is more consistent overall than in the measured data. The estimated regression relationships are being extrapolated to these new scenarios, and this is not always very robust, thus the predicted concentrations are taken tentatively. The NH_3-N concentrations in the measured data exhibit large and sudden changes, which the regression is largely unable to explain, thus the output data is artificially smooth.

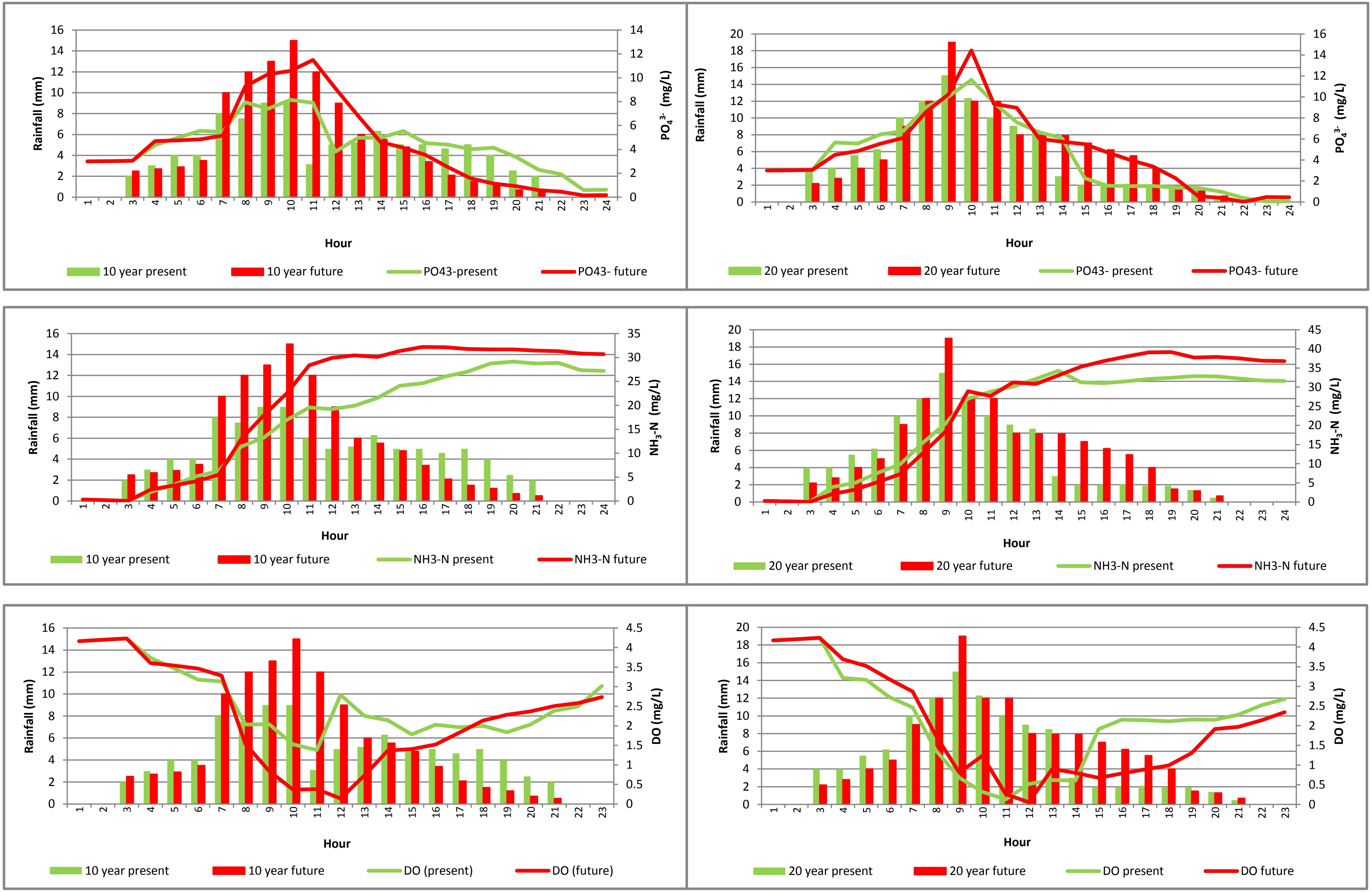

Figure 20. The predicted PO_4^{3-}, NH_3-N and DO concentrations over the duration of four hypothetical rainfall events. Present events are indicated in green while future events are in red.

DO concentrations decrease to nearly 0mg/L in the four scenarios, with the lowest predicted concentration reaching 0.05mg/L in the 20 year future event (Table 15). All the predicted concentrations are below 5mg/L, and would indicate poor water quality during future rainfall events in the Stiebeuel River (Chapman and Kimstach 1996).

The elevated measured concentrations of NH_3-N and PO_4^{3-} in this study were attributed to the sewage effluent and greywater runoff from the informal settlement of Langrug. DO concentrations were also linked to wastewater, as it was postulated that DO levels were depleted by the wastewater through the process of nitrification (Stratton and Mccarty 1967; Bansal 1976; Stendahl 1990; Koning et al. 2000). If rainfall volumes increase, it is possible that more wastewater could be transported to the river, which could adversely affect the water quality. Moreover, it is possible that the informal settlement in the Stiebeuel River catchment will increase in size in the future, which could have a combined impact, with future rainfall increases, on NH_3-N, PO_4^{3-} and DO concentrations.

Table 15. The peak concentrations and peak flow over the hypothetical events with the measured rainfall events indicated in the bottom row.

Scenario		PO_4^{3-} (mg/L)	NH_3-N (mg/L)	DO (mg/L)	Flow (m^3/s)
1	10 year present	8	29	1.38	0.40
2	10 year future	12	32	0.14	0.66
3	20 year present	12	34	0.13	0.67
4	20 year future	14	39	0.05	0.81
	Measured rainfall events	6.6	6	1.7	0.28

Flow is predicted to be higher during the 10 and 20 year future event relative to the 10 and 20 year present event (Figure 21). For a 10 year event, future climate changes would cause an increase in peak flow of 65% from scenario 1 to 2, while for a 20 year event peak flow would increase by 21% from scenario 3 to 4. Under all the scenarios peak flow is higher than the measured peak flow of 0.28 m^3/s.

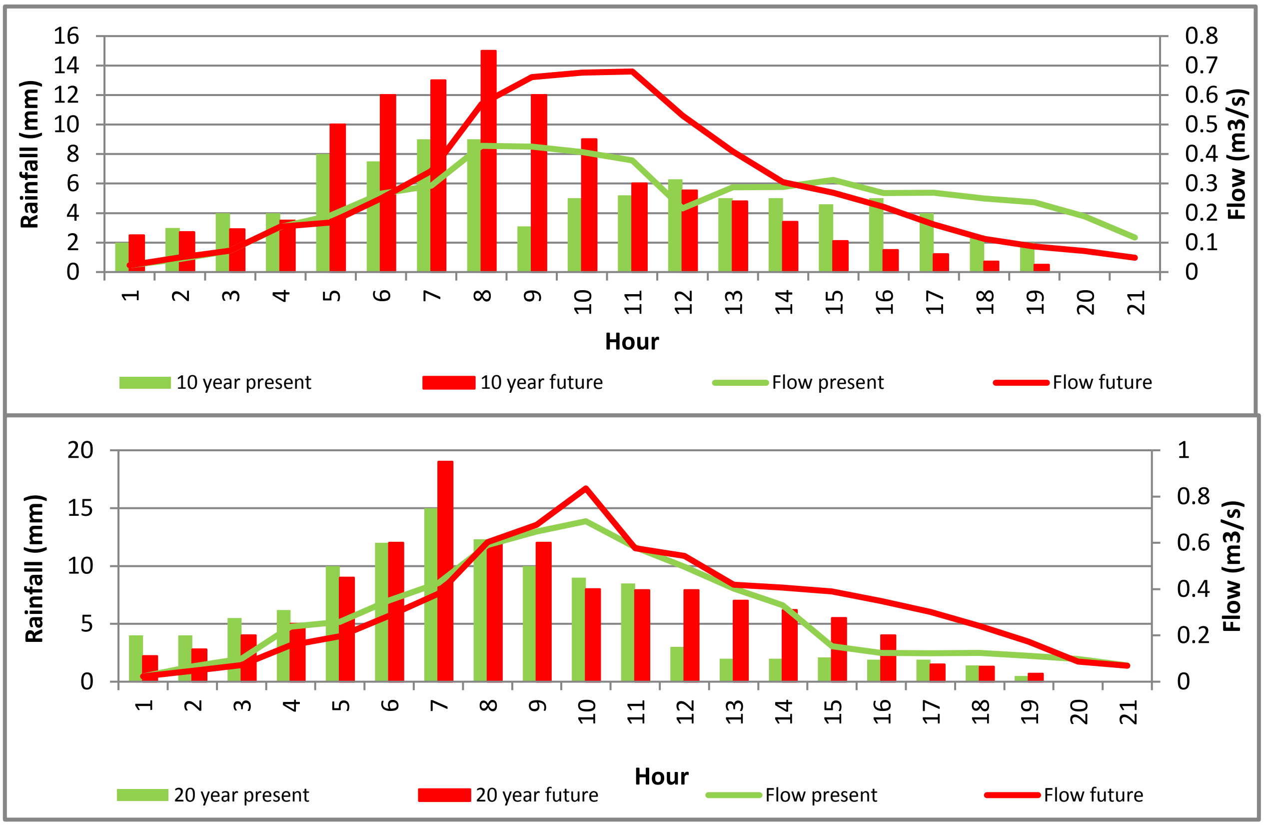

Figure 21. The predicted flow over the duration of two hypothetical rainfall events. Present events are indicated in green while future events are in red.

It is plausible that increased flows could result in the flooding of the Stiebeuel River during higher intensity rainfall events caused by climate change. This could have detrimental impacts on the vulnerable community of Langrug, in zone 2 of the Stiebeuel River catchment. The literature details the multiple adverse impacts of flooding in informal settlements (Olaseha and Sridhar 2003; Parkinson 2003; Armitage et al. 2010; Jamwal et al. 2011; Ajibade et al. 2013; Monney et al. 2013). The increased runoff will also influence the transportation of pollutants to the river, possibly washing higher concentrations of pollutants off the catchment. Higher flows will also influence dilution of pollutants, with longer and more intense rainfall events resulting in increased dilution.

The results from the scenarios provide a warning of the long term consequences of future climate changes in an informal settlement. Rainfall events of increasing intensity will have dire effects on flow and water quality, with pollutant concentrations and peak flows reaching dangerously high levels in a future marked with climate change. Little consideration has been given to how climate changes could manifest in informal settlements, and the results from this section have contributed to filling this gap.

Land use change and climate change are two major drivers of global change and they will continue to exert increasing pressure on surface water in the Anthropocene (Rockstrom et al. 2014). This study did not consider climate and land use changes in tandem, assessing them separately in sections 6.1 and 6.2. It is probable that these two types of changes will impact one another, with Praskievicz and Chang (2009) noting that they may either ameliorate or amplify one another's effects at different spatial and temporal scales. In both instances, humans are the causes of such change, rather than an external forcing in the water cycle, as traditional hydrology assumes (Heine and Pinter 2012; Remo et al. 2012; Di Baldassarre et al. 2013). New fields, such as socio-hydrology, offer a promising lens through which to conceptualise and manage these problems, as it considers the co-evolutionary dynamics of coupled human-water systems and focuses on the interactions, feedbacks and emergent patterns of humans and the hydrological cycle (Sivapalan et al. 2012; Savenije et al. 2014; Elshafei et al. 2015). As Rockstrom et al. (2014) puts it, there needs to be a broader focus on social-ecological systems and cross-scale interactions.

CHAPTER FIVE : CONCLUSION

Informal settlements have unique characteristics, such as bare compacted earth and inadequate sanitation and drainage services, which influence pollutant production, rainfall runoff responses, infiltration rates and river dynamics in a catchment. Relatively little is known about the flow and water quality within informal settlements, in comparison to their well studied urban counterparts. Furthermore, it is uncertain how future climate and land use changes could manifest in these catchments.

This study aimed to characterise the surface water quality and flow in the informally settled Stiebeuel River catchment. The results concur with what is already well known to anyone that lives or works in an informal settlement, that surface water found in these environments is highly contaminated, and results in the gross pollution of receiving rivers.

5.1 Key findings

This study addressed the primary objectives of (i) determining the drivers of water quality and flow, both on dry days and during rainfall events, and (ii) quantitatively ascertaining the effects of future climate and land use changes on hydrology and water quality. The monitoring program during dry days revealed the pervasive impacts of the informal settlement on Stiebeuel River water quality, and the relationships between land use patterns and water quality in the catchment. Catchment-wide analysis showed that natural vegetation, built-up, agriculture and informal settlement, each dominated one of the four zones in the Stiebeuel River catchment. Surface water quality was the poorest in the zone dominated by the informal settlement, with highly elevated concentrations of NH_3-N, PO_4^{3-} and TSS, and low levels of DO. Informal settlement land use, rather than built-up land use, was significantly correlated with the most water quality parameters (NH_3-N, PO_4^{3-}, DO, EC and TSS), demonstrating the statistical relationship between the informal settlement and poor water quality. The limited sanitation, drainage and waste collection services in the settlement likely contributed to the diffuse and point source pollution of the river by wastewater. NO_3^--N concentrations were linked to agriculture, with the highest concentrations found in the zone dominated by agriculture. The significant correlation pointed to either (i) diffuse agricultural sources being an important contributor to riverine NO_3^--N or (ii) wastewater from the informal settlement being transported down the river.

Despite the highly elevated pollutant concentrations around the informal settlement, the assimilative capacity of the river was demonstrated by the improvement of water quality downstream of the informal settlement. For example, NH_3-N concentrations decreased by 74%, while TSS concentrations decreased by about 81%, from the site in the informal settlement to the furthest downstream site in the catchment.

Multiple regression models indicated that if the coverage of informal settlement and built up land use type expanded in the catchment, NO_2^--N, NH_3-N, PO_4^{3-}, EC and TSS concentrations would increase. Of the six hypothetical land use change scenarios considered, the most deleterious impacts on water quality were predicted to occur if the proportion of informal settlement and built-up area doubled in size. In this scenario, NH_3-N increased by 83%, PO_4^{3-} increased by 85%, TSS increased by 86% and DO decreased by 21% from the current catchment averages. If such a land use change occurred, it is likely that a higher population density would produce increased amounts of waste and litter, which would pollute the river.

In addition to exploring land use and water quality in the catchment during periods with no rainfall, five varying rainfall events were monitored. Event-driven pollutographs and hydrographs demonstrated the variable expression of the rainfall events, with a high intensity and long duration event producing the flashiest hydrograph. The event had the highest peak flow, yet the longest period of antecedent dry days, indicating the possible development of a soil crust. By contrast, a long duration low intensity rainfall event produced a hydrograph with gentle rising and falling limbs, indicating slower infiltration rates and lower amounts of overland flow. The pollutograph of the event with 18 antecedent dry days produced multiple NH_3-N, PO_4^{3-}, TSS concentration peaks, indicating the wash off of nutrient enriched wastewater from the informal settlement surface into the river. The highly elevated NH_3-N, PO_4^{3-}, TSS concentration spikes over the event provided rare insights into the detrimental effect of an informal settlement on a river after a dry period. There were no first flush effects, which highlighted the likely role of infiltration in a predominantly pervious catchment.

Various significant correlations between lagged rainfall and pollutant concentrations revealed that rainfall caused an increase in NH_3-N, PO_4^{3-}, TSS and flow after one hour. In the subsequent hour, rainfall caused a decrease in these parameters, indicating a possible dilution effect. The similar response of PO_4^{3-} and TSS suggested that PO_4^{3-} was transported to the river via sediment in runoff. Rainfall caused an increase in NO_3^--N after two hours, pointing to subsurface runoff as the likely transport mechanism of NO_3^--N to the river. Flow was most strongly correlated with rainfall lagged by three hours, indicating the modulating effect of the large pervious area in the catchment on the rainfall-runoff response time.

Multiple regression models demonstrated that if 10 and 20 year design rainfall depths increased, due to climate change, PO_4^{3-}, NH_3-N and flow would increase while DO would decrease. Of the two hypothetical climate change scenarios considered, the most significant impacts on water quality and flow were predicted to occur if the rainfall depth of a 20 year rainfall event increased by 15%. In this scenario, future climate changes would induce an increase in peak concentration of NH_3-N by 17% and PO_4^{3-} by 15%, while DO would decrease by 21%, and peak flow would increase by 21%. The results suggested that future climate changes would lead to the further contamination and potential flooding of the Stiebeuel River.

Concluding remarks

This thesis has strengthened the understanding of flow and water quality dynamics from an informal settlement through a high resolution monitoring program. Nyenje et al. (2010) note that in sub-Saharan Africa, the deterioration of rivers draining informally settled catchments is happening at an alarming rate. The authors assert that the uncontrolled disposal of wastewater in burgeoning informal settlements is the primary problem, and identify one of the most important research questions as "../where do the nutrients in wastewater end up?". The continuous monitoring of a series of rainfall events provided an answer, revealing insights into the dynamics of event-driven transport of nutrients stored at the surface of an informal settlement into an urban river. Moreover, the simultaneous measurement of water quality and flow allowed for the derivation of quantitative relationships over the rainfall events, addressing a key limitation identified by Schoeman et al. (2001) of hydrologic studies in informal settlements of South Africa.

The results also established quantitative relationships between an informal settlement and poor urban river water quality, confirming untreated wastewater as the primary source of contamination. Finally, the land use and climate change scenarios painted a bleak picture of water quality and flows in a future marked with the expansion of the informal settlement and more intense rainfall events. Without interventions, these scenarios are grave warnings of the long term consequences of inevitable land use and climate changes in informal settlements.

5.2 Recommendations for future study

The degradation of urban rivers draining informally settled catchments is a major problem in cities of the developing world. Considering this, an increasingly important research question is "how do we get a more comprehensive understanding of flow and water quality dynamics in informal settlements?".

This research has highlighted several key aspects for future research activity, namely:

- To continuously monitor water quality and runoff closer to the source of contamination within informal settlements
- To measure flow at multiple locations in a river flowing through an informal settlement
- To determine the effects of future land use and climate changes in tandem in informal settlements.
- To model climate change scenarios using GCM models and downscaling methods in informal settlements.

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