Effects of Land Use and Land Cover Changes on Water Quality of the Upper uMngeni River, KwaZulu-Natal Province, South Africa

by

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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Hydrology, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Campus Pietermaritzburg, South Africa. The research was financially supported by the South Africa Water Research Commission (WRC K5/2354) and Umgeni Water under the uMngeni Ecological Infrastructure Partnership Project (UEIP). The Swedish Meteorological and Hydrological Institute (SMHI) has also assisted with attending the short-course training on HYPE Model.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

Signed: Prof. Graham P.W. Jewitt

Date: April 2017

DECLARATION 1: PLAGIARISM

I, *Jean Nepomuscene Namugize*, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written but the general information attributed to them has been referenced;

b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) this dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

Signed: Jean Nepomuscene Namugize

Date: April 2017

DECLARATION 2: PUBLICATIONS

This thesis is written in a paper format, starting from Chapter 3 to Chapter 6. Each paper includes its abstract, introduction, materials and methods, results and discussion, conclusion and recommendations and references at end of each chapter. My role in each paper published, submitted, presented or in preparation is indicated. The * indicates corresponding author.

Publication 1: Chapter 3 of this thesis

Namugize JN*, Jewitt GPW and Graham M (submitted). **Effects of land use and land cover changes on water quality in the uMngeni River Catchment, South Africa**. *Journal of Physics and Chemistry of the Earth*.

This paper is retrieved from an analysis of historical water quality database (1987-2015) provided by Umgeni Water. Land use land cover information were acquired from the National Land Cover of South Africa (for 1994 and 2000) and from the EZEMVELO KZN (2008 and 2011). I entirely conducted land use/land cover reclassification, water quality processing and writing of the paper, under the guidance of Prof Graham Jewitt and Dr Mark Graham. Additional editorial services were provided by Dr Sharon Rees. The results of this paper were presented at the 2015 Southern African Society of Aquatic Scientists Conference (28th June to 2nd July, 2015, Drakensburg, South Africa). I have also presented the results of this paper at the 16th WaterNet/WARFSA/GWP-SA Symposium, (28th-30th October 2015, Port Louis, Mauritius), under the sub-theme "Water, Land and Agriculture".

Publication 2: Chapter 4 of this thesis

Namugize JN* and Jewitt GPW (under review). **Sensitivity analysis of water quality monitoring frequency in the application of water quality index for the uMngeni River and its tributaries, KwaZulu-Natal, South Africa**. *Water SA.*

This paper is an analysis of a historical water quality dataset collected by the Umgeni Water in the upper reaches of the uMngeni Catchment from 1987 to 2015. Water samples and laboratory analyses of chemical determinants were carried out at Umgeni Water according to international standards ISO 9001 of their accredited laboratories. I designed the data processing and analysis and paper write-up with technical assistance of the supervisor. To calculate the water quality index, I downloaded an open excel macro at the Canadian Council of Ministers of Environment website (http://www.ccme.ca/en/.html).

Publication 3: Chapter 5 of this thesis

Namugize JN* and Jewitt GPW (submitted). **Bulk atmospheric deposition of nitrogen and phosphorus in the Midmar Dam Catchment, KwaZulu-Natal, South Africa**. *Water, Air & Soil Pollution.*

This paper is a result of analysis of bulk atmospheric samples collected in two years (from 1 November 2014 to 31 October 2016) and from 14 sampling sites along the uMngeni River and its tributaries in the Midmar Dam Catchment (from 1 June 2014 to 31 May 2016), following a bi-weekly frequency. I designed the river sampling programme and the collection of bulk atmospheric deposition samples. Technical assistance on manufacturing of the bulk atmospheric collectors was provided by Mr Cobus Pretorius. I did the grab collection of the samples, while laboratory analyses were conducted by Umgeni Water in Pietermaritzburg. Streamflow data from the gauging weirs (U2H007 and U2H013) were downloaded from the webpage of the Department of Water and Sanitation (www.dwa.gov.za/Hydrology). Rainfall data were provided by Umgeni water and the Agro-meteorology Instrumentation Mast System data of the School of Agriculture, Earth and Environmental Sciences, Pietermaritzburg. I was responsible for data processing, analysis and write-up with editing and technical assistance of the supervisor. In addition, the paper has been edited by Dr Sharon Rees.

Some of the results of this paper were presented at the 17th WaterNet/WRFSA/GWPSA Symposium (26th -28th October 2016, Gaborone, Botswana), under the sub-theme "Water, Land and Agriculture". I also presented this paper at the 18th SANCIAHS symposium (14-16th September 2016, Durban, South Africa) and this paper was judged to be among the best presentations.

Publication 4: Chapter 6 of this thesis

Namugize JN*, Jewitt GPW, Clark D and Stromqvist J (being submitted). **Assessment of the HYPE model for simulations of water and nutrients in the upper uMngeni River Catchment in South Africa**. *Hydrology and Earth System Sciences.*

This work is an analysis of data collected in the upper reaches of uMngeni Catchment. I selected the water quality model, I also did the collection and preparation of inputs data to the model, analysed the model outputs and wrote the paper with technical assistance of Prof Graham Jewitt. Climate data used was compiled by Dr Michele Warburton. Additional climate data were provided by the South African Weather Services (SAWS) while streamflow data were downloaded from the webpage of the Department of Water and Sanitation of South Africa (www.dwa.gov.za/Hydrology). Land use/land cover were acquired from the National Land Cover 2000, soil information from the Land Type Map of South Africa and water quality information from Umgeni Water and DWS. The model used was developed at the Swedish Meteorological and Hydrological Institute (SMHI), Sweden. Thus, initial set-up of the model was conducted at SMHI and model calibration was undertaken by me under the guidance of Johan Stromqvist who also fixed all model trouble shootings. All the co-authors commented on the manuscript of this paper and it has been edited by Dr Sharon Rees.

Signed: Jean Nepomuscene Namugize

Date: April 2017

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I would like to convey my heartfelt gratitude to the South African Water Research Commission, Umgeni Water for funding this research under the uMngeni Ecological Infrastructure Partnership Project (WRC K5/2354), the University of KwaZulu-Natal for school fees waiving, the Centre for Water Resources Research (CWRR) for making office space and facilities available and the Integrated Polytechnic Regional Centre of Kigali (IPRC), Rwanda for giving me a study leave.

Special thanks to my Supervisor Prof Graham P.W Jewitt, for his dedicated supervision, for his endless good mood, for his excellent feedbacks and for his continuous assistance through this long journey which started from the development of the research proposal, design of field work up to the writing of the thesis. I would like to thank Dr Bloodless Dzwairo from Durban University of Technology for having recommended me for this PhD admission and scholarship.

A special gratitude to Prof Berit Arheimer from the Swedish Meteorological and Hydrological Institute (SMHI) for funding my attendance to the HYPE short-course training in Sweden. Alena Bartosova, Jafet C.M. Andersson and René Capell are also acknowledged for providing technical assistance during the initial set-up of the model at SMHI. Thanks to Johan Stromqvist for accepting to co-author the 4th publication chapter.

Most importantly the staff of the University of KwaZulu-Natal who helped in a one way or another one, such as:

- Dr Michele Warburton, for permitting us to use her compiled catchment daily rainfall and temperature datasets
- Mr David Clark of the CWRR, for technical assistance in ArcGIS tools, HYPE configuration, without your assistance, it would have been difficult to test the model in the catchment.
- Mr Richard Kunz and Mr Mark Horan, for assistance in modelling processes and on sources of data
- Dr Mark Graham of GroundTruth, for technical advices and comments of the first paper

- Prof M S Savage and Dr Alistair Clulow, for providing the data from Agro-meteorology Mast System.

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- Mr Steve Terry for facilitation in acquisition of historical water quality data,
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- Mr Ronnie Thomas and Mr Nkosi, for assistance in collection of atmospheric deposition at Midmar Dam and provision of rainfall data,
- Mr Dinesh Rungasami for guidance during identification of the sampling sites

I also thank Mr Philemon Mhalaba from KZN Wildlife, for giving us access to the Midmar Nature Reserve and to the farmers, for giving access to their properties.

Most importantly to my wife Claudine Uwamahoro, my son Kelvin Impano Namahoro and my daughter Kylie Ikuzwe Namugize, for having accepted to miss me, most of the time when I was on field work, attending conferences and working day and night in the office. My brothers and sisters who kept on pushing me and motivating me. I would like also to extend my gratitude to the community of Rwandans living in Pietermaritzburg, especially to Dr Milindi Sibomana for his great motivation, the Family of Louis Kayonga, the family of Dr Faustin Habyarimana, family Jean Pierre Havugimana and family Dr Murekezi. In addition, I acknowledge the strong support I got from the late Mr Arnaud Rwankuba Kayonga and Late Ms Usanda Puta. Finally, this work could not finish without the Almighty God for the gift of life and my parents who motivated me to go to school.

ABSTRACT

Changes of land use and land cover are important drivers of the quality of water reaching a waterbody. These changes affect the catchment and modify the chemical composition of the atmosphere, and thus altering the cycle of nutrients and the flux of energy. With current developments in Geographic Information Systems (GIS) techniques, hydrological modelling and statistical analyses, one or a combination of many methods can be used to assess the relationships between land use and land cover (LULC) classes and water quality variables. However, all these approaches are reliant on the collection of field measurements, LULC data and water sampling. Typically funding for such long-term information is not generally available in Africa. A three-year study involving analysis of historical data, field work and desktop investigations was conducted in the upper reaches of the uMngeni Catchment (1653 km^2), South Africa, to assess the spatial and temporal variation of land use and land cover and its influence on the flux of water, nutrients (nitrogen and phosphorus) and *Escherichia coli (E. coli)* in the catchment. This involved the analysis of historical land use and land cover information (1994, 2000, 2008 and 2011), analysis and processing of historical datasets of *E. coli*, electrical conductivity, ammonium, nitrate, soluble reactive phosphorus (SRP), total phosphorus (TP), total suspended solids (TSS), temperature and turbidity. A water quality index based on a long-term data base of water quality emanating from existing monitoring programmes was assessed. In addition, stations were established for river sampling (14) and collection of bulk atmospheric deposition (3) of ammonium, nitrates, SRP and TP, in the Midmar Dam catchment (927 km^2). These were consolidated with the application and testing of the Hydrological Predictions for the Environment (HYPE) model in the catchment, in simulating streamflow, transport and dynamic of inorganic nitrogen and total phosphorus, resulting from LULC changes. Results showed that the natural vegetation declined by 17% between 1994 and 2011, coinciding with an increase in cultivated, urban/built-up and degraded lands by 6%, 4.5% and 3%, respectively. This resulted in high variability in the concentrations of water quality parameters, but Midmar and Albert Falls Dams retain over 20% of nutrients and sediment and approximately 85% of *E. coli.* It was concluded that these dramatic changes in LULC directly affect the chemical composition of water in the catchment. However, these linkages are complex, site-specific and vary from one sub-catchment to another and decision-making regarding water resources management in the catchment must recognise this. The level of *E. coli* in water is a major issue for human contact

during recreational activities in the entire study area. Higher concentrations of *E. coli*, ammonium, nitrates, SRP and TP were attributed to the poor or lack of sanitation facilities in the informal settlements, dysfunctional sewage systems, effluent discharged from wastewater works, expansion of agricultural activities, as well as a runoff from livestock farming and urban areas. Moreover, water quality in the catchment ranged between “marginal” and “fair”, predominantly “marginal” in 90% of the sites and completely poorer in the Mthinzima Stream, an important tributary of Midmar Dam. A declining monitoring frequency and resultant poorly reporting of water quality in the catchment, led to a recommendation for the establishment of automatic or event-based samplers, which should provide the optimum information on nutrient loadings to the waterbodies. Bulk atmospheric deposition and river inflows into the Midmar Dam studies were conducted under severe drought conditions. Higher concentrations of NH_4, NO_3 and TP in precipitation samples than those of rivers were found because of the high retention of nutrients in the landscape. In terms of loading, the bulk atmospheric deposition provided significant quantities of $NH_{4,}$ while TP, SRP and nitrates were predominantly from river flows. Specific loads of DIN (nitrate + ammonium) and TP in the catchment were slightly higher that the previously reported values for the catchment and are comparable to the other human-disturbed catchments of the world. HYPE model has successfully simulated streamflow (1961-1999), DIN and TP (1989-1999). For simulations of streamflow NSE values = 0.7 in four out of the nine sites (at a monthly time-step) and NSE > 0 in eight out of nine sites (at a daily time-step). Major floods and drought events were represented very well in the model, with a general over-simulation of baseflow events. The water balance was captured well at calibration sites with over-simulation of streamflow on the Lions River (PBIAS=28%) and their under-simulation in outlet sub-catchments (PBIAS < 0). This is ascribed to the simplification of some processes in the model i.e. evapotranspiration, water release, water abstraction and inter-basin transfer. There has been good fit between the simulations and observations of TP and streamflow with a lagging of the observed values. However, mismatches were noted for DIN. Evaluation of seasonal distribution of DIN suggested that denitrification, crop uptake of DIN and dilution were intensive during the period of rainfall and high temperatures in the catchment, while TP was highly mobilised during rainfall events, due to its strong binding with the soil. The information from this study highlighted the current state of LULC changes, the sub-catchments with the potentiality to export high levels of DIN and TP, the complexity of the relationship between LULC-water quality, the gaps in existing data collection programmes, the catchment responses to LULC changes and the usefulness of hydrological models which may apply beyond the upper reaches of the uMngeni Catchment.

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CHAPTER 1: INTRODUCTION

1.1 Rationale of the research

The global water volume is estimated at 1360 million km^3 and less than 3% of this volume is fresh water. Furthermore, only 0.014% of the fresh water is available for human consumption (Erol and Randhir, 2013). Worldwide, there has been a rapid decrease in the availability of usable fresh water in terms of water quality and quantity due to unsustainable land use practices (UNEP-GEMS/water, 2008; Zimmerman *et al*., 2008; Erol and Randhir, 2013). Rapid urbanisation, over-exploitation of agricultural land, conversion of natural vegetation to other land uses (residential, agriculture and forest) and climate change impacts are reported to be the key drivers of land use and land cover (LULC) changes (Miserendino *et al*., 2011; Yu *et al*., 2013; Ianis and Manuel, 2014). Changes in LULC have direct impacts on climate, geomorphology, soil properties, hydrological and biogeochemical processes, which in turn alter water quality at global, regional and local scales (Miserendino *et al*., 2011; Wan *et al*., 2014). Also, it has been difficult to attribute the chemical composition of a stream to the diffuse sources of pollution (Ahearn *et al*., 2005). Thus, LULC change and water quality variables have been used to assess these impacts (Ahearn *et al.*, 2004; Ahearn *et al*., 2005; Teixeira *et al.*, 2014). The transport of nutrients to a waterbody is strongly linked to LULC changes. Among land uses, agricultural, rural and urban land uses strongly increase the concentrations of nitrogen and phosphorus in the catchment while forest land use can have an opposite effect (Ngoye and Machiwa, 2004; Woli *et al*., 2004; Li *et al*., 2008; Yu *et al*., 2016).

Studies have concentrated on explaining the relationships between LULC and water quality, using water quality variables, such as dissolved salts, total suspended solid (TSS), nitrogen and phosphorus, as the basis for catchment management and ecological restoration (Hope *et al.*, 2004; Nie *et al*., 2011; Tang *et al*., 2011; Teixeira *et al*., 2014). Some authors demonstrate that there is a complex relationship between LULC changes and water variables by making comparisons from one region to another (Wan *et al*., 2014). Other studies show that across catchments, upstream areas are subject to fewer impacts than those downstream (Miserendino *et al*., 2011). The linkages between LULC and water quality are thus complex and site-specific. It has been reported that mining, urban and cultivation land uses lead to increased levels of phosphorus and nitrogen in water (Chang, 2008; du Plessis *et al*., 2014; Wan *et al*., 2014; Yu *et al*., 2016). For example, high levels of phosphorus correlated to soil texture and population habitation in a case where a wastewater treatment plant is constructed (Ahearn *et al.*, 2004). Elsewhere, nitrogen was linked to low flow conditions, agricultural practices and management (Pekárová and Pekár, 1996; Arheimer and Lidén, 2000). In some catchments, high levels of nitrogen and phosphorus were noted during baseflow and stormflow events (Ngoye and Machiwa, 2004; Schoonover and Lockaby, 2006), while in the others, they are noted during low flow events (Li *et al.*, 2009).

Moreover, investigations on the precipitation chemistry with regards to nitrogen and phosphorus have been undertaken in the northern hemisphere, but there is limited information on atmospheric deposition of these nutrients on the African continent (Bootsma *et al.*, 1999). In some regions of Africa where the monitoring of atmospheric deposition has occurred, its contribution to the levels of phosphorus and nitrogen of lakes was significant (Langenberg *et al.*, 2003; Tamatamah *et al.*, 2005; Muvundja *et al.*, 2009).

The uMngeni River catchment (4349 km^2) in KwaZulu-Natal province of South Africa is a stressed system, typical of many in fast-developing countries. The only atmospheric deposition studies of nitrogen and phosphorus in the catchment was carried out before 1983, indicating a lack of updated information (Hemens *et al.*, 1977; Breen, 1983). Expansion of agricultural activities, urban development, high density of livestock, informal settlements with poor sanitation, cattle feedlots, as well as effluents from significant waste water works in the catchment have already impaired different water uses. This has resulted in bacteriological pollution, eutrophication and algal blooms, as well as an increase in the cost of treating drinking water. All these are some of the major problems arising from water quality deterioration in the uMngeni Catchment (Kienzle *et al.*, 1997; Graham, 2004; Matthews, 2014; Matthews and Bernard, 2015). A locally developed runoff model, ACRU/ACRU-NPS was applied in the uMngeni Catchment to simulate streamflow, nitrate and phosphorus (Kienzle *et al.*, 1997; Schulze, 2000; Warburton *et al.*, 2012; Kollongei and Lorentz, 2015). However, lack of in-stream processes driving the transport and transformation of nitrogen and phosphorus in this model, has required the testing of the applicability of other water quality models in the catchment.

Due to the dynamic complexity of the association between LULC changes and chemistry of water which is spatial and scale-dependent, a firm conclusion cannot be drawn on its transferability from one catchment to another. Therefore, investigating the relationship between LULC changes and water quality responses will improve our understanding of the drivers of water quality deterioration in the fast-developing catchment of the upper reaches of the uMngeni River system. Additionally, opportunities for addressing the drivers of water quality deterioration in the uMngeni River system will be identified. This study will also fill the gaps of water quality data emanating from existing water quality monitoring plans and will provide insight on the possible sources of increased levels of nutrients in the catchment.

1.2 Justification

Rapid land use and land cover changes have occurred in the uMngeni Catchment over the past 20 years. These have direct negative impacts on the water quality of impoundments, regulating the stream flow and attenuating floods. To date, it has been 20 years since any comprehensive catchment study has been undertaken and in that time (Kienzle *et al.*, 1997), the catchment has developed more rapidly than expected. The uMngeni River is a microcosm of many catchments in the developing world, and as such, this study has a potential to provide findings applicable well beyond this basin.

This study was limited to the analysis of historical land cover and land use information available for the catchment, provided by the Centre of Water Resources Research (CWRR) of University of KwaZulu-Natal and KZN EZEMVELO. Also, historical water quality datasets for the uMngeni River and its tributaries upstream of the Albert Falls Dam have been provided by Umgeni Water. This dataset has been supplemented by a fortnightly river sampling programme, established by this study from June 1, 2014 to May 30, 2016, in 14 river sampling stations, upstream of the Midmar Dam. This study has also included the collection of bulk atmospheric deposition samples at four sites located in the proximity of the Midmar Dam over a period of 24 months from November 2014 to October 2016, on a fortnightly monitoring frequency.

The nutrient inputs of bulk atmospheric deposition considered in this study and their contribution to the total nutrient load has been evaluated. Furthermore, to the knowledge of the author, no peer-reviewed published article on the monitoring of the precipitation chemistry of nutrients for the catchment is available. The application of a modelling system for nitrogen and phosphorus will provide catchment-based knowledge on the transport and dynamics of nutrients. These are useful tools for decision-making, but they also provide information on the usefulness and applicability of catchment scale modelling systems and consider whether their use is justifiable or not in the upper reaches of the uMngeni Catchment.

1.3 Research objectives and approach

In this context, this study aims to assess the impacts of land use and land cover changes on the water quality in the fast-developing upper catchment areas of uMngeni. The specific objectives were to:

- assess the impacts of land use and land cover changes on the water quality of rivers entering impoundments with a focus on the upper reaches of the uMngeni Catchment,
- assess the effectiveness of the existing water quality monitoring programme for the uMngeni River and its tributaries and to recommend improvements if necessary,
- identify the contribution of atmospheric deposition to nutrient fluxes (nitrogen and phosphorus) in the upper reaches of the uMngeni River Catchment; and
- identify a suitable hydrological modelling system capable to represent the flow of water and nutrients in the upper reaches of the uMngeni Catchment.

To achieve the main aim and specific objectives, the study was undertaken in the upper reaches of the uMngeni Catchment, situated in KwaZulu-Natal Province. The study area represents approximately 38% of the surface area of uMngeni Catchment and is located between 29.78° and 30.42° longitude East and 29.23° and 29.63° latitude South, as presented in Figure 1.1. The major topographic features and land use and land cover types of the catchment are shown in Table 1.1 and the research approach in Figure 1.2.

1.4 Outline of the thesis

This thesis is written in paper format according to guidelines of the University of KwaZulu-Natal whereby each paper represents a chapter. It comprises seven chapters, including four papers intended for publication (Chapter 3 to Chapter 6). A list of reference is provided at the end of each chapter.

The thesis starts with an introduction, clearly defining the rationale for the research, justification, aim and research objectives and research approach (Chapter1).

Thereafter, a literature review on linkages between land use and land cover changes and water quality constituents, the current widespread of eutrophication process in the region, the role of atmospheric deposition of nutrients on water quality deterioration and candidate hydrological and water quality models commonly used, is provided (Chapter 2).

An analysis of the effects of land use and land cover changes on water quality in the upper reaches of uMngeni River Catchment, South Africa is then provided (Chapter 3). This chapter is based on historical land use and land cover information collected from the National Land Cover for South Africa and for KwaZulu-Natal province (1994, 2000, 2008 and 2011). Historical water quality data, spanning from 1987 to 2015 for the upper reaches of uMngeni Catchment was provided by the Umgeni Water at Pietermaritzburg. ArcGIS software used was provided by the Department of Geography of the University of KwaZulu-Natal. The author carried out land use reclassification, water quality processes and statistical analysis with technical advice from the supervisor and Dr Mark Graham.

A water quality index was applied to assess the effects of inconsistencies in water monitoring programmes on water quality decision-making (Chapter 4). For this chapter, the water quality dataset used in Chapter 1 was supplemented by other data including a bi-weekly sampling programme initiated by the author. Water quality indices were computed following the guidelines of the Canadian Council of the Minister of Environment Water Quality Index (CCME WQI). Open source software which was used for index calculation is freely available for download at CCME webpage. The analysis and writing of the chapter was solely by the author with support from the supervisor of this thesis.

Chapter 5 presents the contribution of bulk deposition of nitrogen and phosphorus to nutrient loads and water quality in the Midmar Dam area. The author has designed the sampling programme and four bulk atmospheric deposition collectors. Collection of river and bulk atmospheric deposition samples was carried out by the author over a period of two years. Streamflow and rainfall data were acquired from the webpage of the Department of Water and Sanitation and the rain gauges of Umgeni Water, respectively. Laboratory analysis of phosphorus (soluble and total phosphorus), nitrogen (nitrate and ammonia) was carried by the laboratory technicians of the Umgeni Water, in Pietermaritzburg. Data processing, analysis, paper structure and write-up was undertaken by the author, with assistance from the supervisor of this thesis.

The focus of Chapter 6 is on testing a hydrological and water quality modelling system in simulating of streamflow, inorganic nitrogen and total phosphorus in the catchment. The author was responsible of collection and formatting of inputs data of the model. Initial set-up, calibration and validation of the model was done by the author with technical assistance of Johan Stromqvist. Writing and structure of the paper was done by the author with assistance of the co-authors. The Chapter 7 focuses on main conclusions and recommendations for further research.

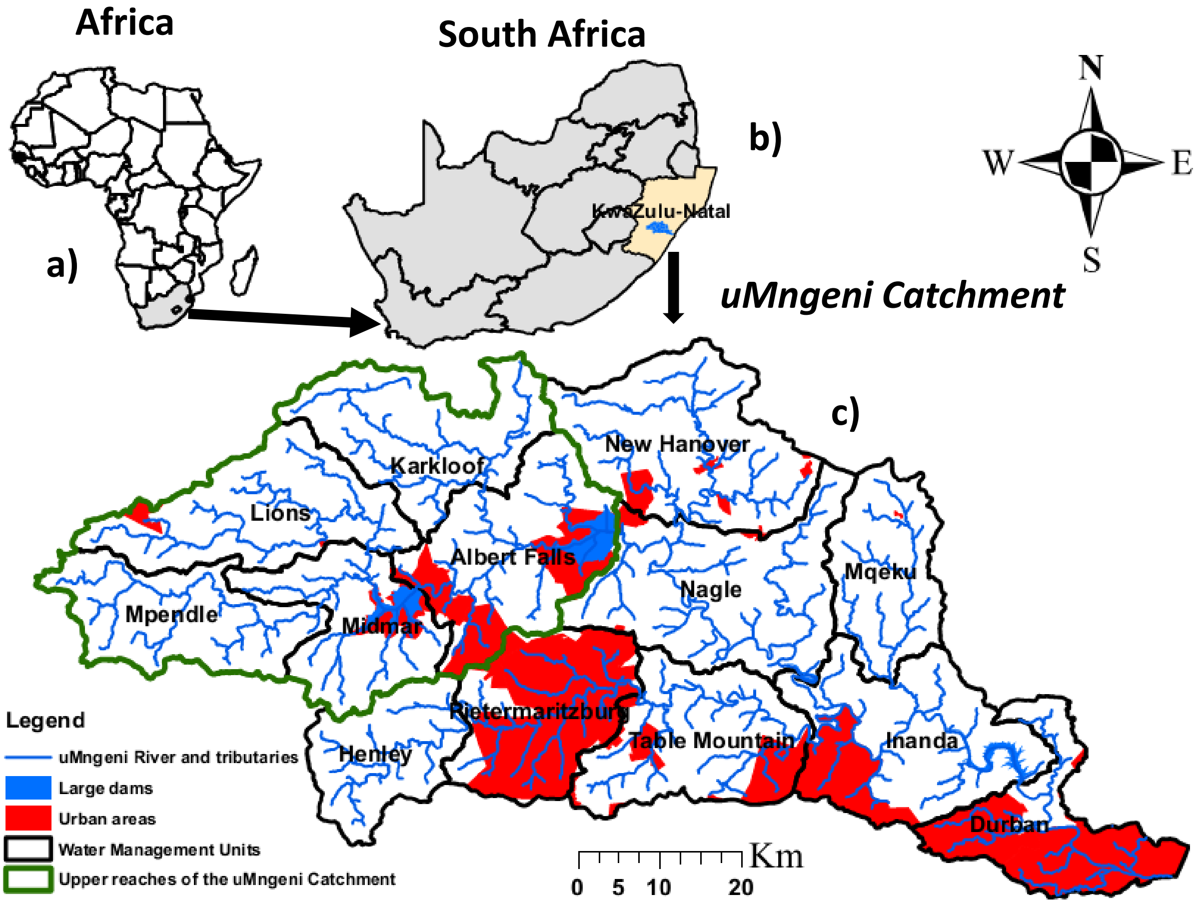

Figure 1.1 Map showing the location of South Africa in Africa (a), uMngeni Catchment in KwaZulu-Natal province (b) and the upper reaches of the uMngeni Catchment (c)

Table 1.1 The main topographic features and land use/land cover classes in the upper reaches of the uMngeni River Catchment, South Africa (after EKZNW, 2013)

Topography	
Catchment area (km^2)	1653
Range of altitude of outlet (masl)	653-2064
Annual evaporation of outlet (mm per annum)	1200
Mean annual precipitation (mm per annum)	1000
Annual runoff of outlet (million m^3 per annum)	131.1
LULC class (2011)	**% of area**
Natural vegetation	42
Cultivated land	17
Forest plantations	26
Urban/built-up (rural, urban and informal)	6
Waterbodies	4
Wetlands	2
Degraded land	3
Mines and quarries	0

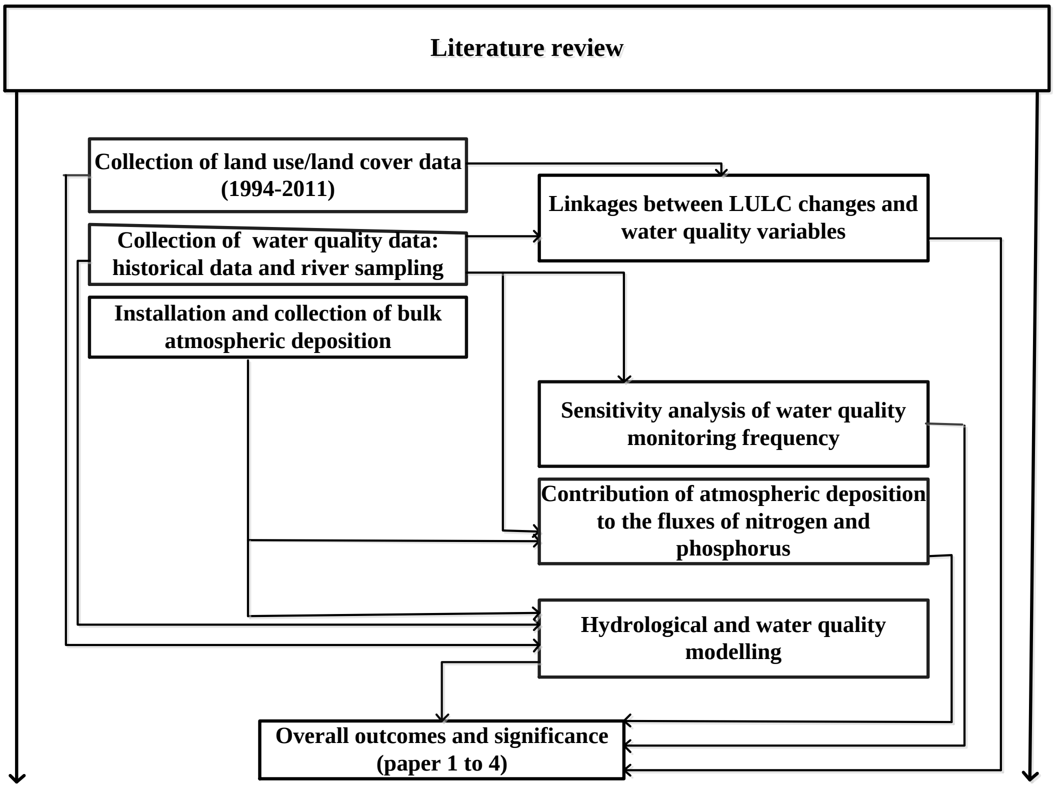

Figure 1.2 Research approach

1.5 Reference

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CHAPTER 2: LITERATURE REVIEW

This section provides an overview of the causes of land use and land cover (LULC) changes, information on reported linkages between land use types and water quality parameters, in catchments of different scales around the globe. Evaluation of water quality problems resulting from LULC changes, such as eutrophication of waterbodies is conducted, as well as the presentation of candidate rainfall-runoff modelling systems to test the simulation of the transport and transformations of nutrients in developing catchments typical of the upper uMngeni River.

2.1 Land use, land cover changes and water quality

Globally, from 1700 to 1990, cropland and grazing land areas increased five and six times respectively. This coincided with a decline of natural forest, savannah and grassland (Ramankutty *et al.*, 2006). A fast growing population in developing countries and the resultant urban expansion is transforming agricultural soil at a rate estimated to be one to three million hectares per year in favour of housing, industry, infrastructure and recreation (Ramankutty and Foley, 1999; Ramankutty *et al.*, 2006). Anthropogenic activities are reported to alter the fluxes of energy and the cycles of nutrients directly and this in turn affects local climate, biodiversity, quality and quantity of water, soil erosion and natural resource loss (Foley *et al.*, 2005; Liu *et al.*, 2013). Therefore, it is very important to understand that land use and land cover (LULC) are quite different[1] (Turner *et al.*, 1995; Schulze, 2000; FAO, 2005). Although the causes of land cover changes vary from one region to another, there are however several global factors like changes in forested areas, in agricultural areas, in pastoral areas and in urbanization that are said to contribute to land cover changes (Turner *et al.*, 1994; Lambin *et al.*, 2003). During the period of 1990-2015, studies show a global decline in total forest-cover (natural and planted forests) areas by 3% and an increase in planted-forest and a loss of natural forest (Keenan *et al.*, 2015; Sloan and Sayer, 2015). The rate of decline in natural forest which is related to increase of urbanisation is high in Africa (Lambin *et al.*, 2003; Sloan and Sayer, 2015). In contrast, land use is affected by

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[1] Scientists define land cover as a biophysical state of the earth's surface and subsurface for an area (Turner *et al.*, 1994) and land use is defined as the human employment of land (FAO, 2005).

multiple interacting drivers, which can be demographic, natural, economic, institutional and cultural (Lambin *et al.*, 2003). LULC are important drivers of changes in atmospheric composition, biogeochemical cycles, sustainability of agriculture, energy balance, biodiversity and water quality and have numerous negative effects on river water quality at a watershed scale (Tucker *et al.*, 1985; Foley *et al.*, 2005; Lepers *et al.*, 2005; Geza and McCray, 2008; Teixeira *et al.*, 2014). For example, fertiliser application for crop production causes an increase in the concentration of phosphorus and nitrogen and alteration of soil properties, which may lead to the eutrophication of a water body (Wan *et al.*, 2014).

Worldwide, studies linking LULC and water quality have been carried out at different spatial scales, including at micro-plot (Pekárová and Pekár, 1996), experimental farm (Honisch *et al.*, 2002), sub-catchment (Arheimer and Lidén, 2000; Schoonover and Lockaby, 2006), and catchment and large river basins (Chang, 2008; Li *et al.*, 2009; Yu *et al.*, 2016). These studies have contradicted the traditional belief which considered a change in-stream flow as the key driver that determines the hydrochemistry of a water body (Hem, 1948; Durum, 1953). For example, an assessment on four rivers in Norfolk, England, found a significant correlation between the concentration of nitrate and sulphate and a high stream flow (Edwards, 1973). However, in a British Columbian river, sulphate was inversely proportional to high stream flow (Ahearn *et al.*, 2004) and this highlighted the complexity of the relationship between LULC and water quality. As a consequence, researchers have affirmed that there is a complex relationship between land use and water quality (Tang *et al.*, 2011; Wan *et al.*, 2014), while others have inferred direct relationships (Gyawali *et al.*, 2013; Le Maitre *et al.*, 2014). There are other key factors that also play a big role in the water quality of a river, such as soil properties, slope, permeability and river basin size; although, these are not directly linked to land use, but to land cover (Wan *et al.*, 2014).

Many studies have reported that urban and agricultural land uses have a direct relationship with high concentration of pollutants in a water body, while natural forest and grassland uses have positive impacts on the water quality of a stream (Wang, 2001; Ren *et al.*, 2003; Wijesekara *et al.*, 2012; Gyawali *et al.*, 2013; Wan *et al.*, 2014). The relationship between land cover change and evapotranspiration, an initiation of runoff, a wash out of nutrients from soil and other hydrological processes have also been studied (Honisch *et al.*, 2002; Linderman *et al.*, 2005; Rieger *et al.*, 2010; Tang *et al.*, 2011; Sterling *et al.*, 2013; Mutema *et al.*, 2016).

In a study carried out in the Luvuvhu Catchment in South Africa, the authors confirmed that upstream land use activities and geology have a direct impact on water quality and quantity, which in turn may positively or negatively affect the livelihoods of the population (Hope *et al.,* 2004). Therefore, it has been shown that assessing the impacts of LULC changes on hydrology provides a useful input for catchment management and ecological restoration. An assessment usually embraces the spatial patterns of the hydrological concerns of different LULC maps, a comparison of the catchment values of simulated hydrological constituents to LULC, changes at the watershed scale and an examination of temporal responses in-stream flow with changes in LULC (Nie *et al.*, 2011). With the current development of Geographic Information System (GIS) techniques and software and the availability of land use information, many researchers have tried to understand the relationship between LULC and water quality using GIS spatial analysis, statistical methods, process-based hydrological and water quality models or a combination of different methods (Carey *et al.*, 2011; Wan *et al.*, 2014). A summary of selected studies which considered this relationship between LULC and water quality constituents, especially nitrogen and phosphorus compounds, at different spatial scales and in different countries is presented in Table 2.1.

2.2 LULC Changes in sub-Saharan Africa

In Africa, rapid urbanisation and crop intensification in agricultural areas puts pressure on the land resources for food and energy production (Teklu, 1996; Brückner, 2012; Brink *et al.*, 2014). The population of Africa is projected to reach up to two billion in 2045 (UNPD, 2010; Linard *et al.,* 2013). In 2005, approximately 72% of the urban population in sub-Saharan Africa (SSA) were living in slums, without access to potable drinking water and sanitation facilities (Linard *et al.*, 2013). The population in SSA continues to grow faster than other continents (Drechsel *et al.*, 2001). This has serious negative impacts on the hydrological cycle and on water quality and quantity (Linard *et al.*, 2013). Ramankutty *et al.* (2008) showed that 8% of African land area is crop land and 30% is pasture and range land. Several investigations showed that food production in SSA is not enough to supply the demand (Larson and Frisvold, 1996; Teklu, 1996; Alcamo *et al.*, 2011). SSA alone has a population of over 800 million, representing 12% of the world's population (Prasad, 2011). Three-fifth of the population of SSA live in rural areas and extract their daily subsistence from natural resources, and this is said to be the highest percentage in the world (UNEP, 2008). Growth in population (average growth rate ~ 2.9% per annum) and national income and rapid urbanisation in SSA have changed the traditional management and use of land which were mainly hunting, gathering, pastoral activities, shifting cultivation and crop rotation (Teklu, 1996; Larson and Frisvold, 1996; Ramankutty *et al.*, 2006).

Table 2.1 Selected studies of the relationship between land use/cover and water quality in selected catchments across the globe: where TN: total nitrogen, TP: total phosphorus, NOx (nitrate and nitrite), N: nitrogen and P: phosphorus

Country	**Catchment area (Km^2)**	**Major findings**	**Reference**
China	95,200	Urban and agricultural lands are main source of NO3 use, low levels of nitrate are noted during high flow events	(Li *et al.*, 2009)
China	2,400	Urban, rural and residential lands are associated with high levels of TN and TP, natural grassland and forest contribute to lower levels of nitrogen and phosphorus, variability of the relationship LULC-water quality across the catchment	(Wan *et al.*, 2014)
China	1, 343,000	Water quality variables were associated with agricultural, forest, grassland and urban areas	(Yu *et al.*, 2016)
Germany	1.6	High phosphorus is associated with agricultural practices Topography, soil type and farming system influence NOx	(Honisch *et al.*, 2002; Rieger *et al.*, 2010)
Japan	1,010-1,309	Increase of NO_3 with increasing of agricultural lands	(Woli *et al.*, 2004)
Slovakia	0.08-574.05	Decline in NO_x contents of water with reduction in use of inorganic fertilizers, high phosphate in mixed catchments with wastewater treatment plants	(Pekárová and Pekár, 1996)
South Africa	1858	Water quality deterioration is a result of cultivation, mining and urban/built-up land covers in the area	(du Plessis *et al.*, 2014)
South Korea	26,219	Urban land use is associated with high levels of water pollutants, except for pH	(Chang, 2008)
Sweden	2-35	NOx levels strongly correlate with land use change Phosphorus levels are linked to soil texture. High levels of P and N are noted during low flow conditions	(Arheimer and Lidén, 2000)
Tanzania	17,900	High levels of NH_3 and NO_3 are associated with urban and agricultural lands	(Ngoye and Machiwa, 2004)
USA (Calfornia)	1,989	Correlation between the levels of nitrate in water with grassland and urban areas having WwTPs	(Ahearn *et al.*, 2005)
USA (Ohio State)	5,840	P, N are significantly associated with urban and agricultural land uses and mostly after storm events	(Tong and Chen, 2002)
USA (South Florida)	2,500	TP correlates with human disturbance, the dominant land use type influences NO_x	(Carey *et al.*, 2011)
USA (West Georgia)	5-25	High levels of N and P are associated with impervious land use during baseflow and storm flow events	(Schoonover and Lockaby, 2006)
Zimbabwe	1,600	Increase of settlement and agricultural areas coincides with high levels of TP, TN, forested land is associated with lower levels of P and N	(Kibena *et al.*, 2014)

A land cover change investigation carried out in sub-Saharan Africa, using remote sensing techniques estimated a change in vegetation cover by 4% between 1982 and 1991 (Lambin and Ehrlich, 1997; Wasige *et al.*, 2013). The land degradation in Africa is justified by an increase of other land uses and a decline in natural forest as observed since 1980 (UNEP, 2008). For example, in SSA agricultural land use has increased by 57% between 1975-2000 (Brink and Eva, 2009).

Land cover in South Africa is dominated by shrubland, grassland and savannah woodland, while forestry occupies less than 1% of the country's surface area. The country has experienced a rapid increase of an estimated 8750 alien plant species (of which 180 are invasive) and which occupy 8% of the South African surface area (DEA, 2011). Therefore, if nothing is done to reduce their expansion, 60 to 80% of the indigenous plant species may disappear. This has a great impact on the nutrient-cycling in the country, as the growth of commercial forests is interrelated with fertilizer application and change in water circulation in the soil (DEA, 2011). The KwaZulu-Natal Province (where the uMngeni River is located) is considered to be an area affected by an excessive human disturbance (Harris *et al.*, 2014). The natural vegetation of the province has declined by 20%, from 1994 to 2011, in respect to increased afforestation and cultivated lands (Fairbanks *et al.*, 2000; Jewitt, 2012; Jewitt *et al.*, 2015). Moreover, an increase in the urban population around the uMngeni Catchment was noted, with further expansion in the future (Mauck and Warburton, 2013). However, in South Africa, LULC changes, riverine systems and water quality services fall under different systems, agricultural governance, natural environmental governance and water quality governance, respectively (Le Maitre *et al.*, 2014), This complicates coordination in decision-making, as each system makes its decisions without consulting others, as it also occurs in other countries (Wang, 2001; Le Maitre *et al.*, 2014).

2.3 Atmospheric deposition as source of nutrients in the catchment

In addition to land use practices, other factors that change the water quality of a water body, include precipitation and the resulting runoff, atmospheric deposition (dry and wet deposition), fertilizers and manure and point sources of pollution (Lorenz *et al.*, 2009; Muvundja *et al.*, 2009; Kratzer *et al.*, 2011).

The impact of atmospheric deposition on nutrient fluxes within a water body has also attracted the attention of researchers (Jassby *et al.*, 1994; Zhang *et al.*, 2012). It can serve as a source of nitrogen and phosphorus for the plants to grow. However, excessive input of nutrients in the ecosystems can modify the biogeochemical cycles leading to eutrophication and acidification of aquatic and terrestrial ecosystems (Zhang *et al.*, 2012; Im *et al.*, 2013; Qi *et al.*, 2013). It has been reported that nitrogen concentrations in the atmosphere have increased since 1860, suggesting that the global riverine inputs of nitrogen equate its atmospheric deposition (Qi *et al.*, 2013). This has also been confirmed in research carried on the Neuse River Catchment in North Carolina, USA (Whitall *et al.*, 2003), and on the Kattegat sea between Denmark and Sweden (Spokes *et al.*, 2006). These studies have concluded that the emission of phosphorus in the atmosphere is relatively smaller than that of nitrogen. In addition to natural processes, human activities, such as industrial emissions and agricultural practices and land management, combustion of fossil fuels, wild fires and livestock farming are the main sources of emission of nitrogen and phosphorus into the atmosphere (Naqvi *et al.*, 2008; Nyaga *et al.*, 2013). The monitoring of atmospheric deposition has many challenges related to data collection and data coverage. This varies with the geographic area, wind patterns and meteorological conditions of a region (Zobrist *et al.*, 1993; Nyaga *et al.*, 2013).

The atmospheric deposition of nitrogen and phosphorus in South Africa is reported to be low, compared to the global situation. However, due to increasing urbanization, agricultural activities and regional phosphate mining activities, it is expected to increase in the future (Nyaga *et al.*, 2013). The contribution of atmospheric deposition to the nutrient budget in the uMngeni Catchment is considered small, but may be significant (Hemens *et al.*, 1977; Breen, 1983). A few studies on atmospheric deposition in the uMngeni Catchment have been done and have shown high values of both nutrients, nitrogen and phosphorus, loading to the Midmar Dam as shown in Table 2.2.

Table 2.2 River and atmospheric nutrient loading to the Midmar Dam

Period	**Source of nutrients**	**Total Phosphorus (tonsN.yr^{-1})**	**Total Nitrogen (tonsN.yr^{-1})**	**Source**
1973-1974	Atmospheric input to the dam surface	0.542	15,356	(Hemens *et al.*, 1977)
	Riverine inputs	5,661	132,402	
1981-1982	Bulk precipitation to the dam surface	0,64	12,017	(Breen, 1983)
	Riverine inputs	5,262	62,9	

From Table 2.2, in the season 1973-1973, bulk atmospheric deposition contributed 9% and 10% respectively for total phosphorus and total nitrogen to the Midmar Dam. However, an increase in the contribution of atmospheric deposition was noted in 1981-1982, 11% and 16% respectively for total nitrogen and total phosphorus. The current trends of nutrient loading via atmospheric deposition will be assessed in this study.

2.4 Eutrophication and water quality

Eutrophication is a worldwide environmental issue induced by anthropogenic activities (Wang *et al.*, 2013) and natural processes (Prepas and Charette, 2004; Graham *et al.*, 2012). It is defined as a state in which rivers, lakes and coastal waters are enriched in primary production (biomass) resulting from excessive plant nutrient inputs, mainly nitrogen and phosphorus (Smith *et al.*, 1999; Prepas and Charette, 2004; Duan *et al.*, 2009; Nyenje *et al.*, 2010; Wang *et al.*, 2013). The negative impacts of eutrophication on water quality for different uses, such as the disparity between primary production and decomposition, the decrease in light penetration, the growth of duckweed and creation of anoxic conditions, which leads to anaerobic mineralisation, an increase in turbidity and particulate matter contents of water and production of bad odour and taste for human consumption have been highlighted by many authors (Janse and Van Puijenbroek, 1998; Cheng and Chi, 2003; Karadžić *et al.*, 2010; Xu *et al.*, 2012).

Investigations on eutrophication of water ecosystems in South Africa started in 1970 and later in 1980, as a management plan, a law on orthophosphate effluent discharge 1mg/L was gazetted (Walmsley, 2000; Van-Ginkel, 2011). This process was mainly dominant in most developed and industrialized areas, such as Shongweni Dam in KwaZulu-Natal, Buffalo River in Eastern Cape, and rivers draining south and north of Pretoria and Johannesburg (Walmsley, 2000). Therefore, the Haartbeespoort, Rietvlei and Roodeplaat Dams, all located near the City of Pretoria, were rated among the most eutrophic systems in the world, due to municipal sewage and industrial effluents (Walmsley *et al.*, 1978; Wiechers and Heynike, 1986) and the use of synthetic laundry detergents comprising about 70 $gP.kg^{-1}$ (Wiechers and Heynike, 1986).

The effects of eutrophication in South Africa, such as algal blooms, the high cost of drinking water treatment (Graham *et al.*, 2012), taste and odour problems, growth of nuisance aquatic macrophytes have also been noted in many South Africa water bodies (Dennison and Lyne, 1997; Walmsley, 2000; Matthews and Bernard, 2015). Furthermore, it was estimated in 2008 that 35% of water stored in South African dams have declined in quality, due to nutrient loading (Graham *et al.*, 2012).

In the upper uMngeni Catchment, studies regarding nutrient effects on the water quality of rivers and dams have been documented. Major findings indicate that: (1) there is a continual deterioration of water of rivers and dams, due to increasing levels of nitrogen and phosphorus in the water (Ngubane, 2016), (2) the Midmar Dam has shifted from oligotrophic-mesotrophic to mesotrophic-eutrophic conditions in a period of 30 years and the dam may become eutrophic by 2028 (Hemens *et al.*, 1977; GroundTruth, 2012), (3) bacteriological pollution (*Escherichia coli)* is an issue in management of quality of river waters in the catchment, ascribed to dysfunctional sewage networks, overgrazing and an increase of habitation in informal settlements with poor or without sanitation facilities (Kienzle *et al.*, 1997; GroundTruth, 2012; Gakuba *et al.*, 2015; Taylor *et al.*, 2016), (4) a high variability in load and concentration of nitrogen and phosphorus can be attributed to irregularities in existing water quality monitoring programmes (Kienzle *et al.*, 1997; Ngubane, 2016); and (5) conversion of natural vegetation to commercial forestry, agricultural and urban land uses (Jewitt, 2012; Mauck and Warburton, 2013; Jewitt *et al.*, 2015). A reported increase in population of *cyanobacteria* (in winter months of 2005) and periodic occurrence of *Ceratium* algae (since 2004) in Midmar and Albert Falls Dams, respectively, result in high levels of nitrogen and phosphorus in water (Matthews, 2014; Matthews and Bernard, 2015).

2.5 Water quality models

Computer models have proven to be useful tools in predicting and simulating the transport of non-point sources of pollutants and hydrologic processes in watershed. They are known to be cheaper and time effective, compared to the cost and time involved in water quality data collection and analysis, but high uncertainties in output are recognised (Dayyani *et al.*, 2010). Several hydrological models are currently in use, for example the ACRU agro-hydrological modelling system (Smithers and Schulze, 2004), the Soil and Water Assessment Tool (SWAT) (Arnold *et al.*, 2011), the Hydrological Predictions of the Environment (HYPE) (Lindstrom *et al.*, 2010; Arheimer *et al.*, 2011; Dhami and Pandey, 2013), the Watershed Analysis Risk Management Framework (WARMF) (Chen *et al.*, 2012), the MIKE SHE (Graham and Butts, 2005), and the Better Assessment Science Integrating Point and Non point Sources (BASINS) (Tong and Chen, 2002; Crossette *et al.*, 2015). Water quality models describe spatial and temporal variations of chemical constituents in the catchment and their principle is based on the mass balance equation encompassing the processes involved (Rauch *et al.*, 1998; Loucks and Van-Beek, 2005). Apart from the ACRU model developed in South Africa, the other modelling systems mentioned above originate from the northern hemisphere. However, for this study, three models i.e. ACRU, SWAT and HYPE are briefly presented.

2.5.1 ACRU Agro-hydrological modelling

The ACRU agro-hydrological modelling system is a daily time-step, physical conceptual and multi-purpose model developed in the Agricultural Research Catchment Unit (ACRU) of the Department of Agricultural Engineering, currently known as the School of Agriculture, Earth and Environmental Science of the University of KwaZulu-Natal, in the Republic of South Africa (Jewitt and Schulze, 1999; Kienzle and Schmidt, 2008; Mugabe *et al.*, 2011; Kusangaya *et al.*, 2013).

The ACRU model has been used to simulate streamflow, peak discharge, total evaporation, reservoir status, water supply and demand for irrigation, LULC changes, seasonal crop yield and sediment yield for a specific catchment (Jewitt and Schulze, 1999; Schulze *et al.*, 2000; De Winnaar and Jewitt, 2010; Warburton *et al.*, 2010; Le Maitre *et al.*, 2014). ACRU has been applied in many catchments, for example in South Africa (Kienzle *et al.*, 1997; Jewitt and Schulze, 1999; Schulze *et al.*, 2000; Everson, 2001; Jewitt *et al.*, 2004; De Winnaar and Jewitt, 2010; Warburton *et al.*, 2010; Dye, 2013; Le Maitre *et al.*, 2014), Zimbabwe (Mugabe *et al.*, 2011), Swaziland (Sidorchuk *et al.*, 2003), in Ghana (Aduah *et al.*, 2016) and in New Zealand, USA and Canada (Kienzle and Schmidt, 2008; Kienzle, 2011; Kienzle *et al.*, 2012).

The input dataset in ACRU includes information on catchment characteristics, such as location, climatic variables, soil, land cover and rainfall data, which have been shown to be imported input model characteristics (Gyawali *et al.*, 2013). The ACRU model, as a daily time-step, also has the capability of transforming monthly data into daily data using Fourier analysis. ACRU has a component of water budget which includes land cover, land use and management changes and can assess the effects of land use change and alien vegetation clearance on the riparian zone. It can simulate daily, monthly and annual sediment yields and reservoir sedimentation (Smithers and Schulze, 2004; Warburton *et al.*, 2012). The minimum of data and information required to run the ACRU model in South Africa is found in Smithers and Schulze (2004).

To increase the simulation capabilities of the ACRU model, the phosphorus, nitrogen, and sediment transport processes were extended in the model to simulate the water quality which is called ACRU-NPS (Campbell *et al.*, 2001). The principle of ACRU-NPS sub-model is based on Groundwater Loading Effects on Agricultural Management Systems (GLEAMS) (De Paz and Ramos, 2002). Prior to Kollongei and Lorentz (2015), ACRU has been used to simulate sediments, phosphorus and *Escherichia coli (E. coli)* loadings in the uMngeni Catchment, (Kienzle *et al.*, 1997). But the model approach was not from GLEAMS. Results indicated that the model over-estimated phosphorus and *E. coli* loadings and a satisfactory calibration of phosphorus in this application was not achieved, largely due to the reliability of observed data which was questionable (Kienzle *et al.*, 1997; Cullis *et al.*, 2005).

ACRU-NPS has been applied in a few studies related to water quality modelling in South Africa and elsewhere in the world (Kollongei and Lorentz, 2015). In the Mkabela sub-catchment (41.5 km^2), ACRU-NPS was used to predict the fate and transport of sediments, nitrate and soluble phosphorus in wetlands, dams and buffer strips. The model performance for NO_3^- and soluble phosphorus has been assessed by the goodness-of-fit criterion (NSE) and the coefficient of determination (R^2) which were in acceptable level of accuracy (R^2 = 0.98, NSE = 0.96 for NO_3- and R^2 = 0.95 and NSE = 0.90 for Soluble-P) (Kollongei and Lorentz, 2015). The model only simulates the delivery of nutrients, but no in-stream processes.

2.5.2 Soil and Water Assessment Tool (SWAT)

The SWAT is a semi-distributed, continuous hydrological and water quality model developed by the United States Department of Agriculture-Agriculture Research Service (USDA-ARS). The model is used to predict impacts of management practices on hydrological processes and non-point source of pollution in large ungauged basins, with varying land use, soils and management practices (Arnold *et al.*, 1998; Neitsch *et al.*, 2011; Arnold *et al.*, 2012). The model operates at a daily time-step and is designed to predict impacts over long periods of time (Fohrer *et al.*, 2001). The SWAT model is an extension of the BASINS, a hydrological model developed at the United States Environmental Protection Agency (USEPA) (Di Luzio *et al.*, 2002). The SWAT model has been extensively used worldwide in surface, riverine hydrology and water quality (Santhi *et al.*, 2006). To improve the performance of the SWAT water quality sub-model, the CREAMS, GLEAMS, Erosion Productivity Impact Calculator (EPIC) and Enhanced Stream Water Quality (QUAL2E) models have also been added (Zhang *et al.*, 2013).

The major applications of the SWAT model are climate change impacts, hydrology, pollutant loss assessments and as an interface with other models (Gassman *et al.*, 2007). An evaluation and calibration of the SWAT model in 115 hydrologic and 37 water quality assessment basins have been reported by Gassman *et al.* (2007). The regression correlation coefficient (R^2) and the Nash-Sutcliffe Efficiency (NSE) statistics have shown good results of the model in predicting hydrologic and pollutant loss. The limitation in the long-term application of the SWAT model in developing countries and in South Africa in particular, is related to intensive forcing data requirements, which are lacking in the country. For surface runoff calculations, SWAT uses the Soil Conservation Service runoff Curve Numbers (SCS CN) which have not been established in South Africa and the Green and Ampt infiltration method (Stehr *et al.*, 2008), the non-spatial integration of hydrological research units (HRUs), it ignores the groundwater entering the deep aquifer and the non-inclusion of the flow and pollutant loading in sub-basins (Gassman *et al.*, 2007; Stehr *et al.*, 2008; Schoumans *et al.*, 2009; Jiang *et al.*, 2014; Kollongei and Lorentz, 2015). Moreover, in SWAT model, in-stream processes of transformation of nutrients have been made optional and over-simplified (Heathman *et al.*, 2008; Neitsch *et al.*, 2011).

2.5.3 Hydrological Predictions for the Environment (HYPE)

The HYPE model is a conceptual hydrological and water quality model developed at the Swedish Meteorological and Hydrological Institute (SMHI) between 2007 and 2008. The model is used to simulate stream flow, transport and turnover of nitrogen and phosphorus, dissolved organic carbon and conservative chemicals, such as chloride and ^{18}O at large and small scale catchments, at a daily time step (Lindström *et al.*, 2010; Jiang *et al.*, 2014; Hundecha *et al.*, 2016; Jomaa *et al.*, 2016). The model structure has four components: (1) the hydrological simulation system (HYSS) encompassing water balance and other hydrological models; (2) Monte Carlo simulations; (3) a water quality framework with simple routing; and (4) nutrient transformation and regional groundwater flow components. The model includes some parts of the HBV-NP model also developed in Sweden to simulate the dynamics, residence and transformation of nitrogen and phosphorus, in rivers, lakes and in groundwater (Andersson *et al.*, 2005). The HYPE model has been applied in different nutrient simulation studies across small sub-basins and large regions with many basins in European countries, mostly in Sweden (Lindström *et al.*, 2010; Arheimer *et al.*, 2011; Strömqvist *et al.*, 2012; Pers *et al.*, 2016), in a nested meso-scale catchment in Germany (Jiang and Rode, 2012; Jiang *et al.*, 2014; Jomaa *et al.*, 2016), in agricultural lands with crop rotation in China (Yin *et al.*, 2016), in climate change and land use evaluation studies in India (Pechlivanidis *et al.*, 2015) and in the Baltic Sea Catchment (Donnelly *et al.*, 2011). The HYPE model has been applied in few regions of Africa, i.e. Niger Basin to simulate streamflow and climate change and in the Middle East and North Africa (Andersson *et al.*, 2014).

2.6 Discussions

2.6.1 Land use/cover change and water quality

Population growth, rapid urbanisation in developing countries and crop intensification are regarded as the main drivers of LULC changes. LULC changes are important drivers of change in the biogeochemical cycle of nutrients and they have several negative impacts on water quality and raise management issues (Gyawali *et al.*, 2013). The relationship between LULC and water quality parameters is complex, site-specific and scale dependent (Wan *et al.*, 2014). In Africa, investigations regarding the relationship between LULC and water quality have faced big challenges due to a lack of sufficient and relevant information (Wasige *et al.*, 2013).

Population growth, rapid urbanisation and increase in formal and informal settlements in uMngeni River Catchment because of the socio-economic and political changes in South Africa after apartheid and increasing agricultural activities and forestry, have resulted in a decline of natural vegetation in favour of agricultural and urban land uses, with corresponding water quality deterioration. Thus, water quality is gradually deteriorating in the uMngeni Catchment, as it is elsewhere in the world (Silva and Williams, 2001; DWAF, 2008; Tang *et al.*, 2011; Chen *et al.*, 2012; GroundTruth, 2012; Lam *et al.*, 2012; Yang *et al.*, 2012). An increase in nutrient loading and bacteriological pollution of water in the catchment is also noted. This review has shown that it is of great importance to combine LULC and water quality information to get a better understanding of the driving forces of water quality deterioration in the uMngeni River Catchment as recent studies are lacking.

2.6.2 Atmospheric deposition

Many studies regarding the chemical composition of precipitation have been carried out in the northern hemisphere, but there is limited information of this on the African continent (Bootsma *et al.*, 1999). In the few African regions where studies have been done, they showed its significant contribution to the total loading of phosphorus and nitrogen at catchment level (Bootsma *et al.*, 1999; Tamatamah *et al.*, 2005; Muvundja *et al.*, 2009). The most recent studies regarding atmospheric deposition of nutrients in the upper reaches of uMngeni Catchment were carried out in 1983 and they indicated a lower contribution to the load of phosphorus and nitrogen in comparison to river inputs (Hemens *et al.*, 1977; Breen, 1983). Since then, the uMngeni Catchment has lost approximately 20% of its natural landscape; and the levels of nitrogen and phosphorus have increased in the Midmar and Albert Falls Dams. This is indicated by high counts of algal population in these two dams of the catchment (DWAF, 2008), and this further revealed the economic implications at the drinking water treatment works (Graham *et al.*, 2012) and impairment of the recreational water uses in the area. Therefore, the collection of atmospheric deposition can supplement existing river water monitoring plans and can assist in drawing reliable conclusions on all possible sources of nutrients in the basin.

2.6.3 Selection of a water quality modelling system

The uMngeni Catchment has been subjected to a few water quality modelling systems. Some have been applied in the whole catchment to simulate a selected number of water constituents. For example, ACRU (Kienzle *et al.*, 1997), contribution of Agriculture to Non Point Sources of Pollution (ANPS) (Cullis *et al.*, 2005), the pollutant loading estimator (PLOAD) and Bayesian decision networks to assess the effects of land use practices on water quality respectively (Dabrowski *et al.*, 2013) and ACRU-NPS (Kollongei and Lorentz, 2015). The choice of a suitable model to use among the three candidate models briefly presented above, was based on: (1) flexibility or complexity and ease of use of the model, (2) input data requirements and model predictions, (3) the spatial and temporal resolution of the model, (4) availability of supporting information for the modeller and peer-reviewed publications on the model to simulate nutrient transport and turnover in the catchment; and (5) information on the results of calibration and validation of the model was also considered. Where possible, communication with the model developers was undertaken for the ACRU-NPS and the HYPE models, as the SWAT model has sufficient online documentation available to download.

ACRU has been extensively used in many South African catchments, in neighbouring countries and overseas, as mentioned above. Although, it would have made sense to use the locally developed model in South Africa (ACRU-NPS), this model was excluded, due to a lack of sufficient applications of the model in simulation of water quality locally or at regional levels (Kollongei and Lorentz, 2015) and in particular, because of the non-inclusion of in-channel nutrient transformation processes in the model.

SWAT is a powerful model in simulation of land use change effects and water quality. Therefore, this model requires an intensive forcing database which is not available in the country. Additionally, it would take a lot of time to populate the model (Dabrowski *et al.*, 2013). Although HYPE is a new model, recently developed in Sweden; its focus on nutrient simulation applications, makes it a most promising model to apply in the upper reaches of the uMngeni Catchment. The model has provided satisfactory simulations of stream flow and phosphorus and nitrogen in several other catchments. In terms of input data, the model requires a maximum of 10 inputs data files regardless of the spatial scale. Each of these three models i.e. ACRU NPS, SWAT and HYPE are physically-based, semi-distributed, having in common the process of dividing the basin in sub-basins, which in turn are divided into hydrological response units (HRUs). A comparison of the three models, considering the spatial and time scales, input data requirements, and model simulations is presented in Table 2.3.

Table 2.3 Comparison of the three models: ACRU-NPS, SWAT and HYPE

Parameter	ACRU-NPS	SWAT	HYPE
Input data	Daily rainfall and temperature. Daily potential evaporation. Monthly land cover information, soil physical variables, geohydrological data (specific retention, specific yield, hydraulic conductivity, gradient of water table and initial water table data) agricultural practices and management	Maximum and minimum daily temperature, daily rainfall, solar radiation, relative humidity and wind speed, topographical, soil physical properties (texture), land use information, best management practices, land use management information (fertilizer amounts, timing, planting harvesting)	Daily air temperature and rainfall, land use information, soil texture, elevation and slope, soil layer depths and number of horizons, water holding capacity, manure and inorganic fertilizer application, crop husbandry, timing and amount of fertilization, timing of sowing and harvesting for the area, other sources of nutrients
Model simulations	Total evaporation, soil water and reservoir storage, land cover and abstract impacts on water resources, snow water dynamics, stream flow, surface runoff, infiltration, nitrogen, phosphorus and sediment dynamics in wetlands, dams and buffer strips	Land use management processes, stream flow, erosion and sediment yield, evapotranspiration, total groundwater recharge, water quality variables including pesticides and heavy metals, over-simplification of in-stream processes	Stream flow, snowpack, lake water level, evapotranspiration, groundwater level transport and turnover of nitrogen and phosphorus in-stream processes
Computational time-step	Daily	Daily	Daily
Spatial scale	Flexible	Flexible	Flexible
Disadvantages	Data intensive, lack of in-stream dynamics of nutrients, limited publications on water quality assessments	Data intensive Use of the runoff curve numbers not established in South Africa, no specific lake routine (dams),	Error checking is very limited in the model set-up; crop rotation is not simulated New model in South Africa The model is still under continuous development

2.7 Conclusion

This review shows that land use and land cover is affected by both human and biophysical factors. In addition to climate change, LULC changes are important factors that influence the water quality of a waterbody. Relationships between LULC changes and water quality variables exist, but, they are complex and vary in different parts of the world. However, conclusive decisions on water quality deterioration in the uMngeni Catchment cannot be drawn without considering land use changes. Moreover, it is shown that LULC change affects local climate and the chemical composition of the atmosphere. There is generally limited information on atmospheric deposition of nutrients on the African continent. In a situation where information has been collected in Africa, provided useful information on its significant contribution to nutrient loading of the lakes (Tamatamah *et al.*, 2005; Muvundja *et al.*, 2009). This indicates that monitoring water quality of rivers, regardless of the contribution of the atmospheric deposition of nutrients lacks relevant information associated to land use changes and precipitation chemistry in the area.

This review also assessed three hydrologic and water quality modelling systems (ACRU-NPS, SWAT and HYPE). The assessment of the models was based on model structure, data requirements, capability, reported use and the temporal and spatial scale of the model to capture nutrient dynamics in a fast-developing catchment, typical of the uMngeni. The HYPE model has been selected to be tested in the area, considering its capabilities in simulating stream flows, nutrient transport and turnover in soil, river channels and dams (Lindström *et al.*, 2010). The model has not been applied in South Africa, but was proved economical with regards to data requirements compared to the ACRU-NPS and SWAT models.

Finally, to the author's knowledge, there is a lack of peer-reviewed published articles linking land use and water quality in the uMngeni Catchment. The few studies undertaken have focused on simulations of stream flow (Warburton *et al.*, 2012), while the ACRU-NPS model applied in the catchment by Kollongei and Lorentz (2015) does not include the processes of transformation of nutrients in a water body. Thus, this study adds value to the findings of Hemens *et al*. (1977) and Breen (1983), in the uMngeni Catchment and updates them. It also provides catchment responses in terms of water quality deterioration that results to rapid LULC changes.

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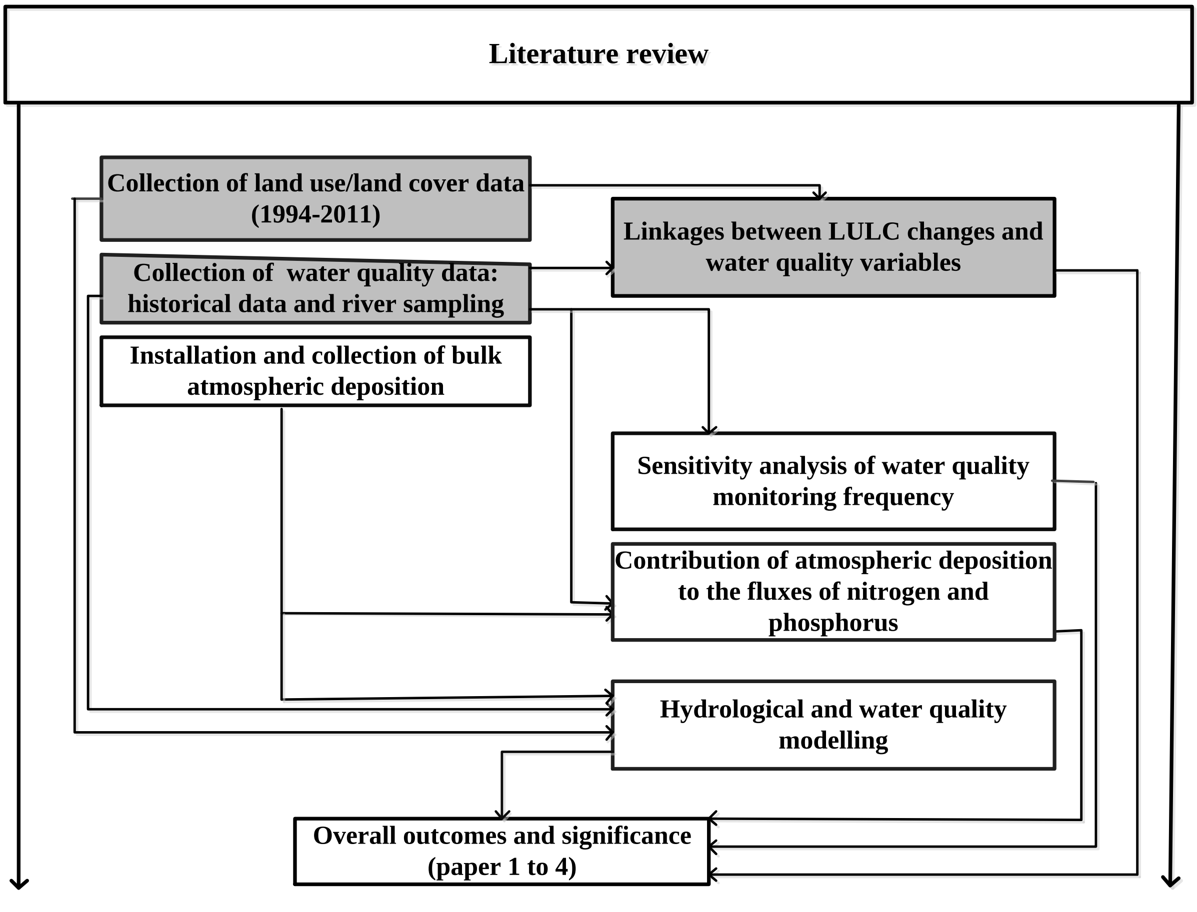
Preface to Chapter 3

Land use and land cover changes are key drivers of water quality deterioration in a catchment (Chapters 1 and 2). In order to improve our understanding of the relationships between LULC types and water parameters in the upper reaches of the uMngeni Catchment, an assessment involving the collection of historically available land use information (for the period 1994-2011) and water quality data was conducted (Chapter 3). This evaluation involved the delineation of the catchment, reclassification of LULC types, assessment of rates of LULC changes, assessment of water quality variations, following the hydrological year and analysis of associations between LULC and the selected water quality variables.



CHAPTER 3: EFFECTS OF LAND USE AND LAND COVER CHANGES ON WATER QUALITY IN THE UPPER REACHES OF UMNGENI RIVER CATCHMENT, SOUTH AFRICA

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3.1 Abstract

Land use and land cover change are major drivers of water quality deterioration in watercourses and impoundments. However, understanding of the spatial and temporal variability of land use change characteristics and their link to water quality parameters in catchments is limited. The linkages between biophysical chemical water quality parameters and land use and land cover classes in the upper reaches of the uMngeni Catchment, a rapidly developing catchment in South Africa, were assessed using Geographic Information Systems tools and statistical analyses for the years 1994, 2000, 2008 and 2011. Natural vegetation, forest plantations and cultivated areas occupy 85% of the catchment. The noted increase in cultivated, urban/built-up and degraded areas by 6%, 4.5% and 3%, respectively, and other land uses (plantations, mines, wetlands and waterbodies) coincides with a decrease in natural vegetation by 17%. Variability in the concentration of water quality parameters from 1994 to 2011 and a decline in water quality were observed. *E. coli* levels exceeding the recommended guidelines for recreation and public health protection were noted as a major issue in seven of the nine sampling points. In overall, water supply reservoirs in the catchment retained over 20% of nutrients and over 85% of *E. coli*. A relationship between land use types and water quality variables exists. However, the degree and magnitude of these associations vary among sub-catchments and is difficult to quantify. This highlights the complexity and the site-specific nature of relationships between land use types and water quality parameters in the catchment. Thus, this study provides useful findings on the general relationship between land use and land cover and water quality degradation, but highlights the risks of applying simple relationship or adding complex relationship in management of the catchment.

Key words: *Land use/ land cover; uMngeni Catchment; Nutrients; South Africa; Water quality deterioration*

3.2 Introduction

Over 50 % of the global population now lives in urban areas (Aguilera *et al.*, 2012; Maimaitijiang *et al.*, 2015) and it is expected that urbanisation will continue to increase in future decades, with associated land use and climate change impacts (Ianis and Manuel, 2014; Maimaitijiang *et al.*, 2015). Land Use and Land Cover (LULC) changes affect geomorphology, soil properties, hydrological processes and water quality at global, regional and local scales (Wan *et al.*, 2014) and thus, the ecological integrity of aquatic ecosystems (Miserendino *et al.*, 2011). The key anthropogenic drivers of LULC changes are the over-exploitation of agricultural land use, the conversion of natural vegetation to commercial forestry or pasture land and rapid urbanisation (Miserendino *et al.*, 2011; Yu *et al.*, 2013). Agricultural land use activities lead to an increase in nutrient loads, sediments and organic matter in rivers, lakes, impoundments and estuaries, which create major problems for catchment managers (Foley *et al.*, 2005; Shrestha *et al.*, 2008).

Many research studies on the linkages between LULC and stream water quality have concluded that a significant relationship exists between land use and water quality parameters at a catchment level (Kibena *et al.*, 2014), while others have shown a complex and direct relationship, varying from one region in the world to another and depending on the depth of analysis (Miserendino *et al.*, 2011; Dabrowski *et al.*, 2013; du Plessis *et al.*, 2014; Wan *et al.*, 2014; Yu *et al.*, 2015). Wan *et al.* (2014) highlighted the importance of temporal, spatial and scale variations and noted that upstream reaches are subject to fewer impacts, compared to those downstream. Fewer impacts in steeper areas, compared to flatter areas, have also been reported and LULC impacts in large streams differ greatly from those in small streams (Buck *et al.*, 2004; Duncan, 2014; Wan *et al.*, 2014). Du Plessis *et al.* (2014) found that LULC changes have various negative impacts on the water quality of a watercourse, as they lead to both increases and declines in the concentration of water quality variables.

Researchers have demonstrated that cultivated land use produces five times more sediment in a watercourse than in forests, as a result of lower runoff coefficients (Fiquepron *et al.*, 2013). Sediment yield in South Africa (SA) is estimated to be between 100-400 tons.km^{-2}.a^{-1}, a value which is not high globally, but which is critical, due to climatic variations in the country (Brink *et al.*, 2005). Healthy forests and grasslands tend to limit sediment flow and turbidity, discharge less nutrients into waterbodies and play a major role in water purification, filtering and trapping nitrogen, phosphorus and potassium (Fiquepron *et al.*, 2013; Kibena *et al.*, 2014).

A study carried out in 95 administrative departments of France, for example, concluded that forest cover has a positive impact on water quality, while agricultural runoff is the main source of water pollutants (Foley *et al.*, 2005; Fiquepron *et al.*, 2013). However, this contradicts an investigation in Zimbabwe, which showed that settlements and agricultural land uses have a positive impact on water quality of local streams (Kibena *et al.*, 2014). However, land development, in the form of agricultural and urban use, have a direct impact on the deterioration of stream water quality, by increasing runoff and discharging nutrients and heavy metals (Pratt and Chang, 2012). Buck *et al.* (2004) showed that agricultural land use in New Zealand is the major source of nutrients and faecal coliforms to rivers and streams of the country. While over half of the global population of developing countries live in urban areas, most of them live in urban sprawl, much of which can be considered as slums, which have significant impact on water quality (Duh *et al.*, 2008; Linard *et al.*, 2013). In 2010, the percentage of urban population, living in slum conditions, without adequate water, sanitation and other basic infrastructures, such as sewage and electricity, was over 60% in sub-Saharan Africa (Linard *et al.*, 2013; Fox, 2014). In 2005, the proportion of South African population living in slum conditions was estimated to be 28.7% (Fox, 2014).

LULC change is a key driver affecting catchment hydrology in South Africa (Albhaisi *et al.*, 2013). The continuation of land development will likely result in the shrinkage of a potable water supply and other water-related ecological services (recreational purposes and aquatic biodiversity) (Pratt and Chang, 2012). Masubelele *et al.* (2014) assessed historical land use and rainfall data and concluded that there has been a decline in shrublands in favour of grassland in the semi-arid areas of South Africa. On a national scale, a land cover change assessment that was carried out for the period 1995-2005 showed an increase of 1.2 % in transformed land (forestry, urban, mining and plantation forestry) and a decrease in cultivated land by 0.5% (Schoeman *et al.*, 2013; Masubelele *et al.*, 2014). In the KwaZulu-Natal (KZN) Province, from 1994 to 2011, the natural vegetation decreased from 73% to 53%, coinciding with increased afforestation and cultivation lands (Fairbanks *et al.*, 2000; Jewitt, 2012). The period from 1995-2005 was characterized by an increase in the percentage of urban, forest plantations and other land cover classes in KZN, except cultivation, mining and quarries which decreased in the same period (Schoeman *et al.*, 2010, 2013). If the transformation of natural landscape to other land uses continues with the current trends, KZN will retain only 22% of its current natural vegetation in 2050 and this will inhibit the delivery of ecological goods and services in the province, which are estimated to be 149 billion South African Rands (Jewitt, 2012).

The KZN Province (in South Africa) is considered to be a highly ecologically disturbed region, due to human activities. The population of the KZN Province has increased by 22% in the period between 1996-2009. Over the half of this population lives in the uMngeni Catchment (Beires, 2010) and relies on water supplied from the upper reaches of the catchment. The natural vegetation in the catchment of the major river, uMngeni, has been highly modified as a result of anthropogenic activities such as population growth, a change in food and energy demands and socio-economic and policy drivers (Figure 3.1) (Warburton *et al.*, 2010; Mauck and Warburton, 2013). Land use and land cover change activities in the uMngeni Catchment affect the major water uses in the catchment, namely, agriculture, industry, domestic water supply, recreation as well as environmental flows (Dabrowski *et al.*, 2013).

The uMngeni Catchment can be broadly divided into three reaches with different land uses, where the upper reach is dominated by commercial forestry and agriculture, the middle reach by sugarcane plantations and the urban areas of Pietermaritzburg along the uMsunduzi tributary, and the lower reaches encompassing the industrial and urban areas of Durban at the river mouth. Formal and informal settlements concentrated around emerging urban centres (Warburton, 2012; Dabrowski *et al.*, 2013). Evidence of water quality deterioration in the uMngeni River is ascribed to increased population pressures, the improvement of living standards, the threat of industrial pollution (CSDS, 1990) and agricultural intensification. It is important to better understand the dynamics of development in the uMngeni Catchment and the water quality consequences, to provide information the decision-makers and planners in the catchment.

Numerous studies linking LULC change to water quality have been undertaken (Miserendino *et al.*, 2011; Aguilera *et al.*, 2012; Li *et al.*, 2012; Dabrowski *et al.*, 2013; du Plessis *et al.*, 2014; Ianis and Manuel, 2014; Kibena *et al.*, 2014; Wan *et al.*, 2014) and these approaches may be applicable to the uMngeni catchment. However, the rapid development in uMngeni River catchment system suggests that the collection of timely and accurate land use and land cover information, to assist in the detection of impacts on water resources and to inform management actions is necessary. However, per the authors' knowledge, no study linking the spatial and temporal variations of LULC and water quality has been undertaken in the uMngeni Catchment. Consequently, the aim of this study is to assess the linkages between the land use and land cover types and the biophysical chemical water quality parameters. Three specific objectives were set: (1) the assessment of spatial and temporal LULC changes in the uMngeni River Catchment for the period 1994-2011, using Geographic Information System (GIS) techniques, (2) understanding the temporal variability of biological and physico-chemical water quality parameters in the upper reaches of the uMngeni Catchment, based on data collected by Umgeni Water (UW), and (3) to establish a relationship between LULC classes with water quality variables at key sites in the upper catchment. This paper contributes to the knowledge of LULC changes in a fast-developing catchment, which is typical of many in developing countries, with water quality deterioration, and it provides information for policy makers and land use planners in the catchment.

3.3 Materials and Methods

3.3.1 Study area

The study was conducted in the upper reaches of uMngeni River Catchment, located between longitudes 29°78´ and 30°42´ East and latitudes 29°34´ and 29°63´ South, in the KZN province, South Africa (Figure 3.1). The uMngeni River Catchment has a surface area of 4349 km^2, produces over 20% of the gross national product of South Africa and accommodates over 4.5 million inhabitants, representing 45% of the KZN population and 65% of the total economic production in KZN (Graham *et al.*, 1998; Graham, 2004; Warburton, 2012; Mauck and Warburton, 2013; WWF-SA, 2013). The length of the uMngeni River is estimated at 225 km. It rises at the uMngeni vlei, a wetland area at an altitude of 1760 m above sea level and discharges to the Indian Ocean, near the City of Durban (DWAF, 2008). The river flow is regulated by four large dams from upstream to downstream viz. Midmar, Albert Falls, Nagle and Inanda (Figure 3.1). These dams are the major sources of water supply to the towns of Pietermaritzburg and Durban, to informal settlements scattered in the catchment and to agricultural water users (Kienzle *et al.*, 1997).The Midmar and Albert Falls Catchments produce three-quarters of the runoff that enters the uMngeni River system (Breen, 1983) and they therefore form the focus of this study. The Lions River is the major tributary of the uMngeni River upstream of Midmar Dam and includes water transfer schemes from the adjacent Mooi River Catchment (UW, 2013). Downstream, the uMsunduzi River drains Pietermaritzburg and joins the uMngeni River upstream of the Inanda Dam.

The annual rainfall across the catchment is highly variable, ranging between 600 mm to 1500 mm per annum, with most of the rainfall occurring during the summer months (October to March). The average annual temperature ranges from 12 to 20°C and the high mean annual evaporation ranges between 1567 and 1737 mm per annum (Clark *et al.*, 2009; Warburton *et al.*, 2012; Mauck and Warburton, 2013).The altitude across the uMngeni Catchment varies from 0 to 2013 m above sea level, from the Indian Ocean in the East, to the mountainous areas in the West (Clark *et al.*, 2009).

Based on climate, soil type, land use and land cover, the uMngeni Catchment has been subdivided into 13 Water Managements Units (WMUs) by the erstwhile Department of Water Affairs and Forestry (DWAF), currently known as the Department of Water and Sanitation (DWS) (Figure 3.1). All surface waters generated from each WMU converge to the same point, which is generally a water monitoring site or a gauging weir (Warburton *et al.*, 2012). This study encompassed the five WMUs located upstream of the Albert Falls Dam viz. Albert Falls, Karkloof, Midmar, Lions and Mpendle, covering an area of 1653 km^2 (Figure 3.1).

3.3.2 Data collection

3.3.2.1 Water quality data

For this study, water quality data were provided by Umgeni Water (UW), the entity responsible for the bulk potable water supply in the catchment. As part of its business, UW monitors sections of the uMngeni River and its tributaries. The dataset covers a period of 27 years, extending from 1987 to 2013. The sampling frequency over this period varies from weekly to monthly. Many chemical constituents are monitored, but for this study, the water quality parameters related to LULC changes, the eutrophication of a waterbody and human health were selected viz. electrical conductivity (EC), pH, ammonium, nitrate, soluble reactive phosphorus (SRP), total phosphorus (TP), total suspended solids (TSS), temperature, turbidity and *E. coli* (Yu *et al.*, 2013; du Plessis *et al.*, 2014). All biological, physical and chemical water parameters were sampled, following the standard methods described by the DWS, and analysed according to international standards in the UW ISO9001 accredited laboratories. Based on UW water sampling sites, the study area was subdivided in two areas, namely uMngeni catchment upstream of the Midmar Dam which includes: the sites S1, S2, S3 and S4 and uMngeni River downstream of the Midmar Dam, encompassing the sampling sites S5, S6, S7, S8 and S9 (Figure 3.1).

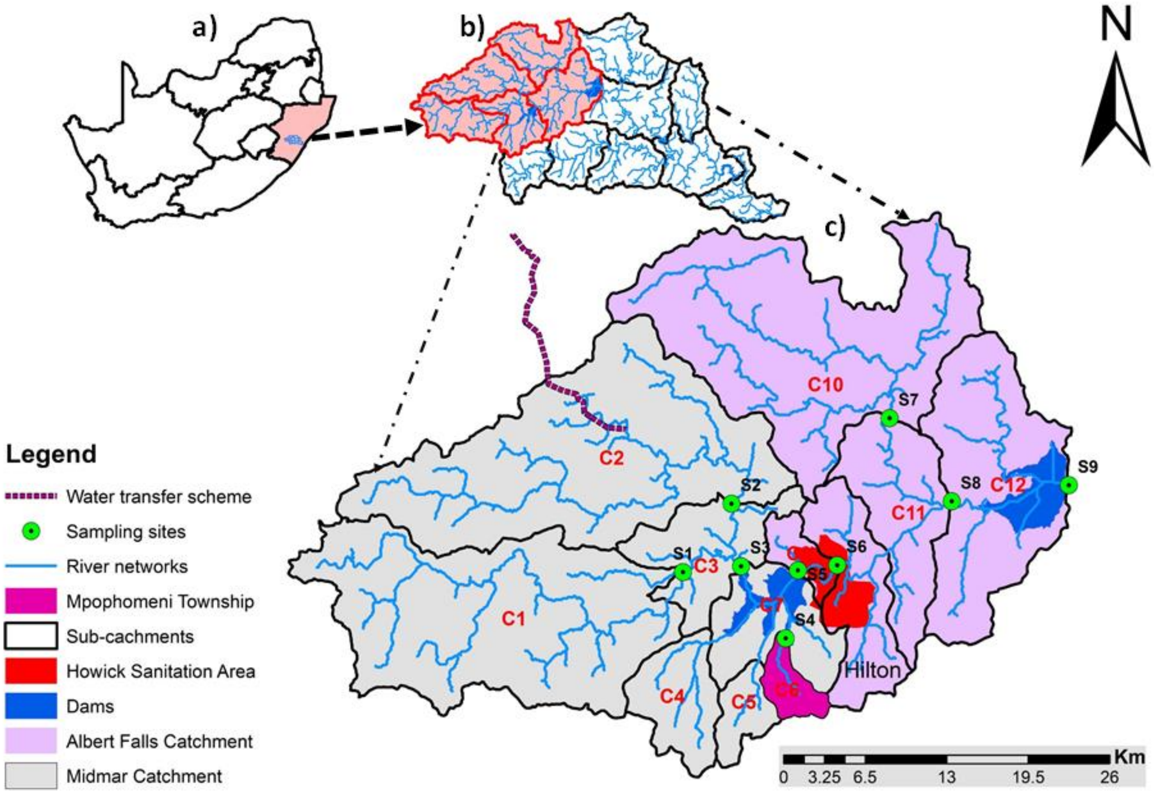

Figure 3.1 Map showing the location of the study area: A: Location of the uMngeni Catchment in KwaZulu-Natal Province of South Africa, B: Location of the five water management units (WMUs) out of 13 WMUs of the uMngeni Catchment and C: the upper reaches of uMngeni Catchment, showing 12 delineated sub-catchments (Ci), nine water monitoring sites (Si) and two large dams (from upstream to downstream, the Midmar and Albert Falls Dams, respectively)

3.3.2.2 Land use and land cover information

Historical LULC maps used in this study were sourced from various private and public institutions in the country. The maps were processed and land cover classes from each source were aligned, using ArcGIS 10.1 (ArcMap^{TM} 10.1, ESRI, 2012) to calculate the percentage of each LULC class in uMngeni Catchment (Table 3.1).

Table 3.1 Source of land use and land cover information

Date of data capturing	Source of land cover information	Data type	Year of publication
1994	South African National Land Cover (NLC1994)	Shape file of uMngeni Catchment land cover	1996
2000	South African National Land Cover (NLC2000)	Shape file of National Land cover map	2005
2008	Provincial land cover imagery sourced from Ezemvelo KZN Wildlife (EKZNW) produced by Geoterraimage (pty) Ltd	Raster file, cell size 20mx20m for KZN Province	2010
2011	Provincial land cover imagery sourced from Ezemvelo KZN Wildlife (EKZNW) produced by Geoterraimage (pty) Ltd	Raster file, cell size 20mx20m for KZN Province	2013

3.3.3 Data processing and analysis

3.3.3.1 Statistical analysis

Descriptive statistical methods were used to determine the average, standard deviation, standard errors, minimum and maximum values and the number of water quality samples for different time periods. Monthly and annual concentrations of parameters for each site in Table 3.2 were also determined. Following the approach of Taylor, 1990; Li *et al.*, 2012; Pratt and Chang, 2012; du Plessis *et al.*, 2014; and Kibena *et al.*, 2014, a Pearson correlation analysis was undertaken to establish whether a linear relationship between LULC variables, considered as independent variables, and water quality variables, as dependent variables, exists. STATISTICA 7.0. (StatSoft, Inc., Tulsa, OK), was used to calculate the Pearson correlation coefficient r, to give more precision to the relationship between bivariate data, depending on whether there is a positive, negative or no-relationship between the two variables. Based on the Pearson correlation coefficients, the relationship between two variables was considered as strong, medium, weak and none, depending on whether the absolute values of r were, from 1-0.68, 0.67-0.36, 0.35-0.10 and 0.09-0.00, respectively.

The average annual concentration of each water quality parameter per site, for the years 1994, 2000, 2008 and 2011, i.e. those years for which LULC information exists, were analysed and are reported in Appendices 3.A and 3.B. They were then correlated to LULC information for upstream areas contributing sub-catchments, where they exist. Umgeni Water provided water quality data for 17 sampling sites, of which 12 sites are located downstream and four sites upstream of the Midmar Dam. Inconsistency in the frequency of sampling was observed, varying from monthly, weekly, quarterly, once per year, and even zero sampling per year at some sampling sites after 2000. Only water quality parameters measured in all sites were included in the database developed in this study. This has resulted in a reduction of the useful analysis sites to nine, as shown in Table 3.2. Seasonal variation of water quality was assessed, following a typical hydrological year for the catchment, starting from October to September, namely, 1993-1994, 1999-2000, 2007-2008 and 2010-2011, coinciding with available LULC information.

3.3.3.2 Land use and land cover reclassification

A catchment delineation exercise was carried out upstream of each sampling point, to quantify the proportion of land use types that contributed to a particular sampling site. Automated hydrology and arc hydro tools of ArcGIS 10.1, for a digital elevation model (DEM) of 20 m x 20 m resolution were combined with delineated sub-catchments by Warburton *et al*. (2012). A combination of these methods was applied to overcome the problems of the over-estimation of sub-catchment areas, which occurred in automated delineation method (Khan *et al.*, 2014). Based on nine sampling points, the catchment was divided into 12 sub-catchments (Figure 3.1, Table 3.2).

From the national land use and land cover data, using ArcGIS 10.1, a reclassification of land use and land cover (LULC) in the uMngeni Catchment was carried out, to merge all LULC classes into eight classes *viz*. natural vegetation, cultivation, degraded, urban/built-up, waterbodies, plantations, mine and wetlands. Percentages of the LULC class were then calculated for each sub-catchment upstream of the Albert Falls Dam.

Table 3.2 Water quality monitoring sites and sub-catchments

Sub-catchment ID	Area (km^2)	Site ID	Site code (UW)	Latitude	Longitude	Sampling site description
C1	326	S1	RMG-001	-29.4918	30.108360	uMngeni at Petrus Stroom
C2	353	S2	RLN-001	-29.4427	30.148702	Lions river at Weltevreden Weir
C3	74	S3	RMG-002	-29.4878	30.156225	uMngeni inflow of the Midmar Dam
C4	57	NA	*	*	*	Gqishi inflow of the Midmar Dam
C5	25	NA	*	*	*	Nguklu inflow of the Midmar Dam
C6	18	S4	RMT-006	-29.5402	30.193235	Mthinzima river influent of the Midmar dam
C7	73	S5	RMG-003	-29.4911	30.202900	uMngeni outflow of the Midmar Dam
C8	22	S6	RMG-006	-29.4875	30.235300	uMngeni at Howick
C9	83	NA	*	*	*	*
C10	334	S7	RKK-003	-29.3820	30.279000	Karkloof River upstream of the confluence with uMngeni
C11	98	S8	RMG-008	-29.4421	30.329710	uMngeni at Morton’s Drift after confluence with Karkloof tributary
C12	189	S9	RMG-010	-29.43109	30.42593	uMngeni River outflow of Albert Falls Dam

*: A sub-catchment without an outlet water monitoring site or without available water quality data, Ci: sub-catchment, Si: water sampling point and NA: non-applicable

3.4 Results

3.4.1 Distribution of land use and land cover changes

The natural vegetation, plantations, cultivation and urban/built-up classes were the major land use types in the 12 sub-catchments, representing 25 to 60%, 0.1 to 49%, 1 to 43% and 4 to 41 %, respectively (Figure 3.2 and Table 3.2). Other land use classes (degraded, waterbodies, mines and wetlands) represent less than 15% of the catchment area. It was noted that decreases of natural vegetation coincided with increases of urban/built-up areas, plantations and cultivated land uses, as presented in Table 3.3. Based on the 2011 LULC reclassification, natural vegetation, cultivated, degraded, urban/built-up and plantation land uses occupied large areas in sub-catchments C1, C3, C5, C6 and C12, respectively, waterbodies in C7 and C12 and wetlands in C3 (Figures. 3.2 and 3.3). The overall land use changes in the upper reaches of uMngeni Catchment from 1994 to 2011 were a decline of natural vegetation by 17%. The cultivated, urban/built-up, degraded and wetland areas increased by 6%, 4.5%, 2.8% and 2% respectively. The other land uses (forest plantations, mines/quarries and waterbodies) did not largely change (Table 3.3).

Table 3.3. Distribution of land use and land cover changes in the catchment from 1994 to 2011 (Thompson, 1996; NLC, 2000; EKZNW, 2010, 2013)

		1994		2000		2008		2011		% of
ID	LULC class	Area, Km2	Area, %	Area, Km2	Area, %	Area, Km2	Area, %	Area, Km2	Area, %	Change 1994-2011
1	Natural	973.69	58.90	886.46	53.62	758.54	45.90	697.82	42.23	-16.67
2	Cultivated	180.51	10.92	216.28	13.08	252.32	15.27	282.78	17.11	6.19
3	Plantations	431.47	26.10	398.03	24.08	430.43	26.04	433.73	26.25	0.15
4	Urban/built-up	17.52	1.06	22.73	1.37	84.36	5.10	91.44	5.53	4.47
5	Waterbodies	46.71	2.83	56.08	3.39	58.31	3.53	62.44	3.78	0.95
6	Wetlands	3.25	0.20	44.76	2.71	24.62	1.49	36.29	2.20	2.00
7	Degraded	0.00	0.00	28.71	1.74	43.89	2.66	47.64	2.88	2.88
8	Mines&quarries	0.00	0.00	0.10	0.01	0.30	0.02	0.28	0.02	0.02
	Total	**1653**		**1653**		**1653**		**1653**		

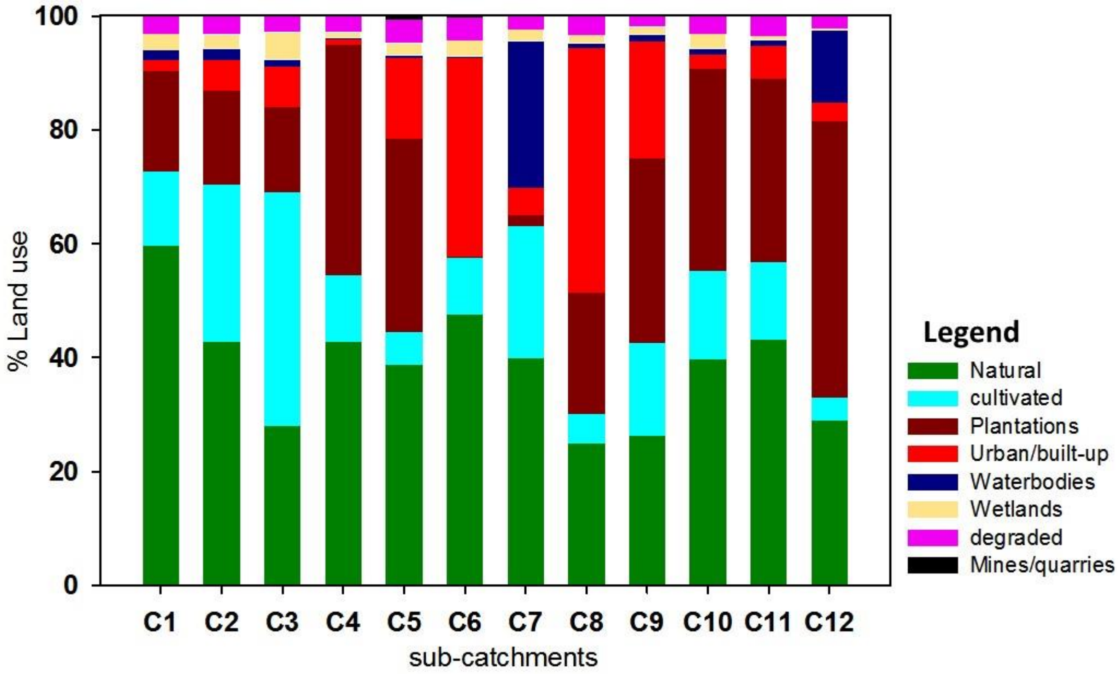

Figure 3.2 Percentage of land use distribution in 12 sub-catchments for 2011 (EKZNW, 2013)

In sub-catchments C5, C6, C8, C3 and C2, the proportion of natural vegetation converted to other land uses over a period of 17 years is 37%, 36%, 26%, 24% and 23%, respectively. In these sub-catchments, there has been an increase in urban/built-up areas by 21%, 14% and 13% for C6, C5 and C8. Increases in cultivated areas were noted in C2, C11, C6 and C10 (Figure 3.3 and Table 3.3). The potential point sources of pollution are not included in the LULC maps provided, but information on these, has been collected from various sources and are shown in Table 3.4.

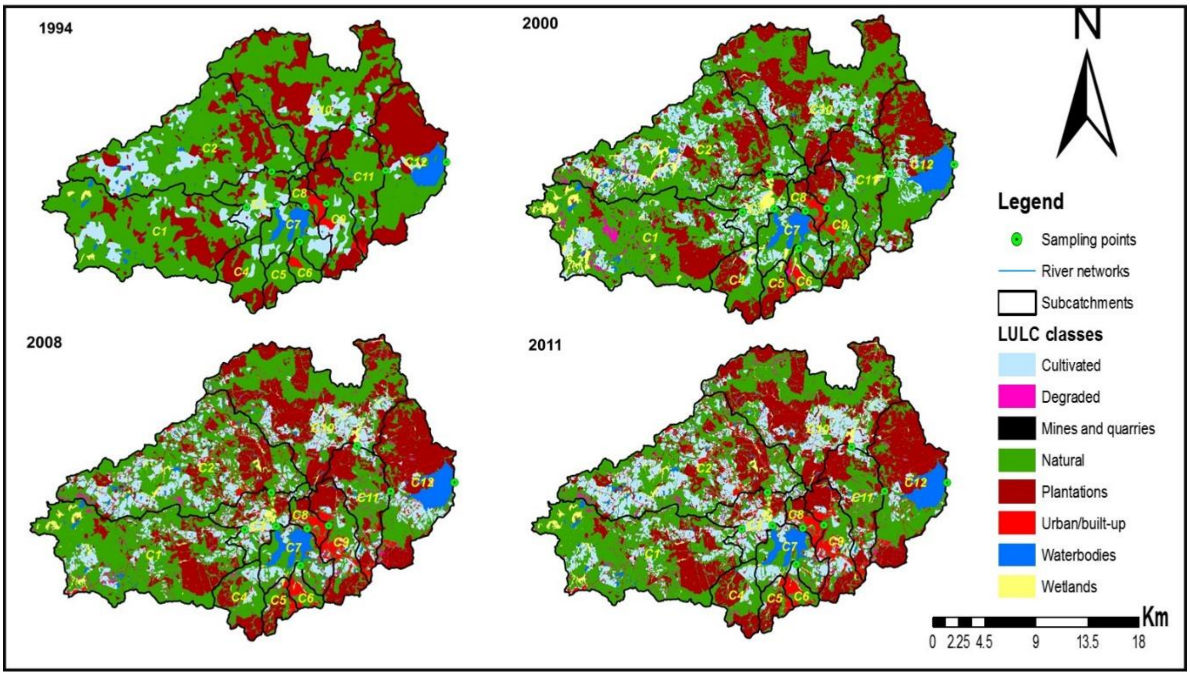

Figure 3.3 Historical land use and land cover maps of upstream of the Albert Falls Dam (Thompson, 1996; NLC, 2000; EKZNW, 2010, 2013)

Table 3.4 Location of major point sources in the upper reaches of uMngeni Catchment (Hudson *et al.*, 1991)

Catchment	Point sources	Sub-catchment	Average concentration (mgTP/L)
Midmar	Mpophomeni	C6	4.8
Albert Falls	Hilton	C9	19.5
	Howick	C9	2.5
	Midlands	C9	5.7
	St. Annes	C9	5.7
	Cedara	C9	1.7

3.4.2 Biophysical and chemical trends of water quality variables

The recorded pH was slightly alkaline, ranging between 7.4-7.6 across seven sampling sites with an average value of 7.5±0.1, while data are missing for the two remaining sites. Electrical conductivity ranged between 5.1 ms/m and 29.5 ms/m. Concentrations of NO_3-N in the nine sampling sites ranged between 0.20-0.45 mgN.L^{-1} and high levels of 2.6 mgN.L^{-1} and 0.57 mgN.L^{-1} were found at S4 and S8, respectively. High levels of nutrients at S4 highlighted the effects of the Mthinzima Stream in introducing poor quality water to the Midmar Dam, despite the small size of the Mpophomeni sub-catchment (Appendix 3.A). Descriptive statistics of water quality parameters are presented in Appendices 3.A and 3.B.

3.4.2.1 Water quality upstream of the Midmar Dam

A decline in *E. coli* levels, from 1993-1994 to 1999-2000, was noted at Site S1, with a fluctuation at S2, S3 and S4, and sharp increase in all four sites for the hydrological years 2007-2008 to 2010-2011. In general, high levels of *E. coli* were observed in all sites during the summer period (October to March), the period of highest rainfall in the catchment (Figure 3.4). Higher concentrations of TP and *E. coli* were noted in the rainy season (October to March), compared to the dry season (April to September). Fluctuations in nutrient concentrations from 1994 to 2011 vary by an order of magnitude in all nine sites. TP concentrations ranged between 35µgP.L^{-1} at Site S3 to 1667µgP.L^{-1} at Site S4. The values at S4 exceeded the recommended eutrophication thresholds (Figure 3.5).

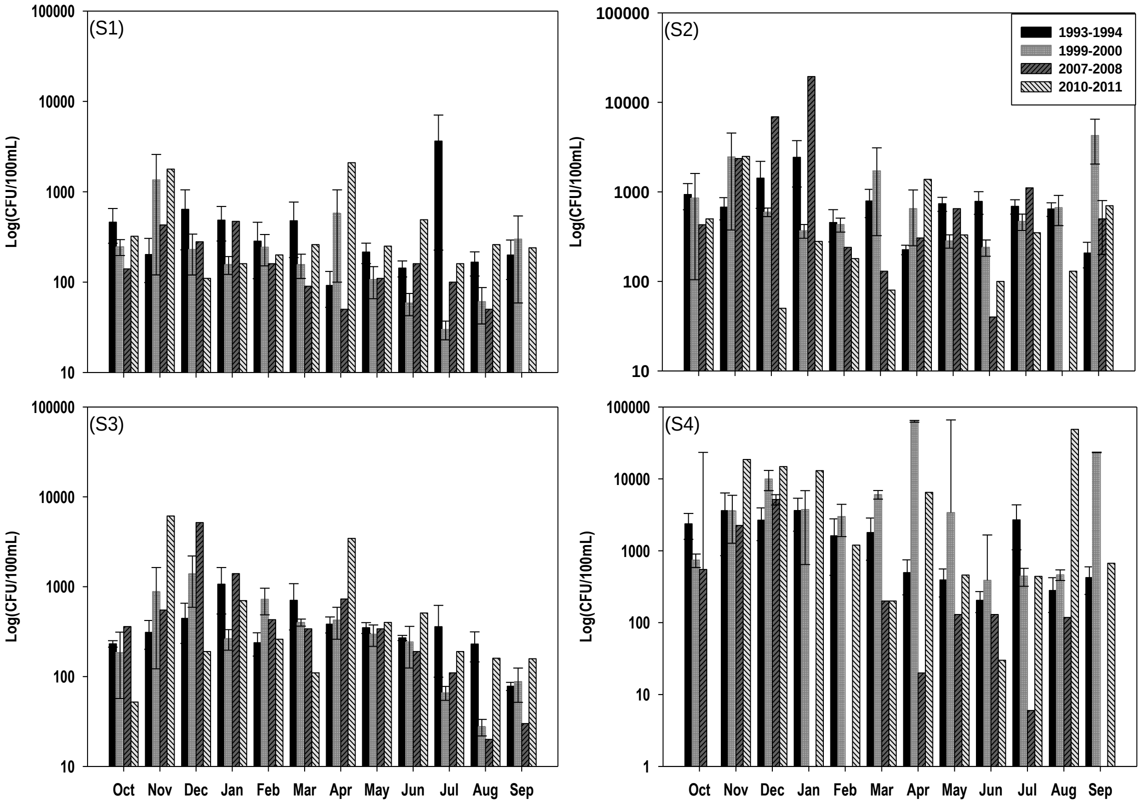

Figure 3.4 Log scale average monthly concentrations of *E. coli* (CFU/100ml) at four sites, upstream of the Midmar Dam: (S2) Lions River at the Weir, (S1) uMngeni at Petrus Stroom, (S3) uMngeni inflow of the Midmar and (S4) Mthinzima inflow to the Midmar Dam. Error bars illustrate the standard error of the mean and where error bars do not appear, less than two samples were taken per month

However, this study also found higher *E. coli* levels at Site S2, compared to Sites S1 and S3 (Figure 3.4). Nutrient contents of water at Site S1 were low, in comparison to S2 and S3, owing to less activity in the catchment. The mean annual TP concentrations were compared with the DWS threshold for eutrophication of 55µgP/L, and high values exceeding the DWS threshold were noted at S1, S2 and S3 (in 2008)**.** At Site S4, this benchmark value was always exceeded for TP and nitrate (limit of 55µgP/L and 0.6 mgN/L) (Figures 3.5 and 3.6).

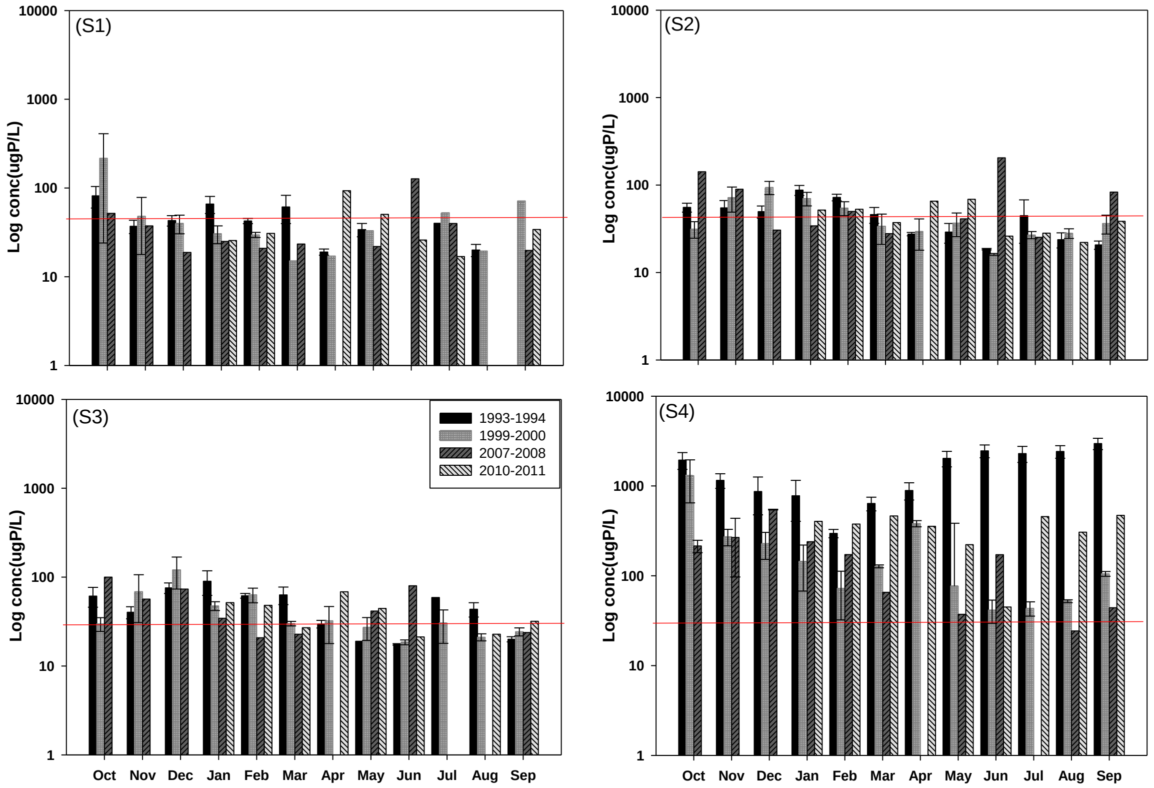

Figure 3.5 Average monthly concentrations of TP in four sites: (S1) uMngeni at Petrus Stroom, (S2) Lions River at the weir, (S3) uMngeni inflow of the Midmar and (S4) Mthinzima inflow of the Midmar Dam. Error bars illustrate the standard error of the mean and where, error bars do not appear, less than two samples were taken per month

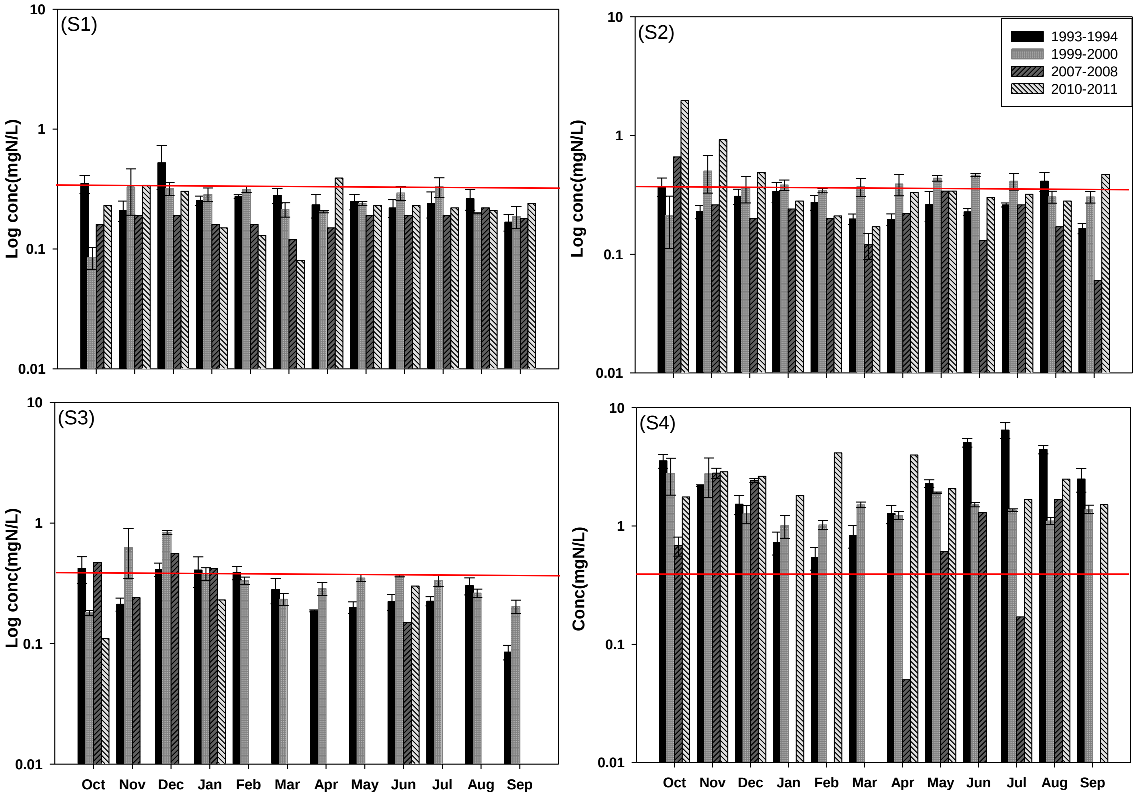

Figure 3.6 Average monthly concentration of nitrate: (S1) uMngeni at Petrus Stroom, (S2) Lions River at the weir, (S3) uMngeni inflow of the Midmar Dam and (S4) Mthinzima inflow of the Midmar Dam. Error bars illustrate the standard error of the mean and where error bars do not appear, less than two samples were taken per month

3.4.2.2 Water quality downstream of the Midmar Dam

Site S5 (outflow of Midmar Dam) showed low levels of *E. coli*, nitrate and TP (Figures 3.7, 3.8 and 3.9). Concentrations increased at S6 after the inflow of Howick Waste Water Works effluent, which is likely to be the main source of contamination. However, it is important to mention irregularities in water quality monitoring at Sites S6 and S7; for example, there was no data at Site S6 for 2010-2011 and missing data from October to January for 2007-2008, while at Site S7, there was no water quality information for 2007-2008 and 2010-2011 (Figures 3.7, 3.8 and 3.9). Hence, seasonality does not appear to affect *E. coli*, TP and nitrate levels in Sites S6, S7, S8, but this could be a result of inconsistent monitoring in those three sites downstream of the Midmar Dam. High *E. coli* counts are found in summer at Site S5, coinciding with the rainfall period in the catchment and the possibility of farm dams flushing. High levels of both nutrients at S7 could be associated with commercial forestry in Karkloof (Figures 3.7 and 3.8).

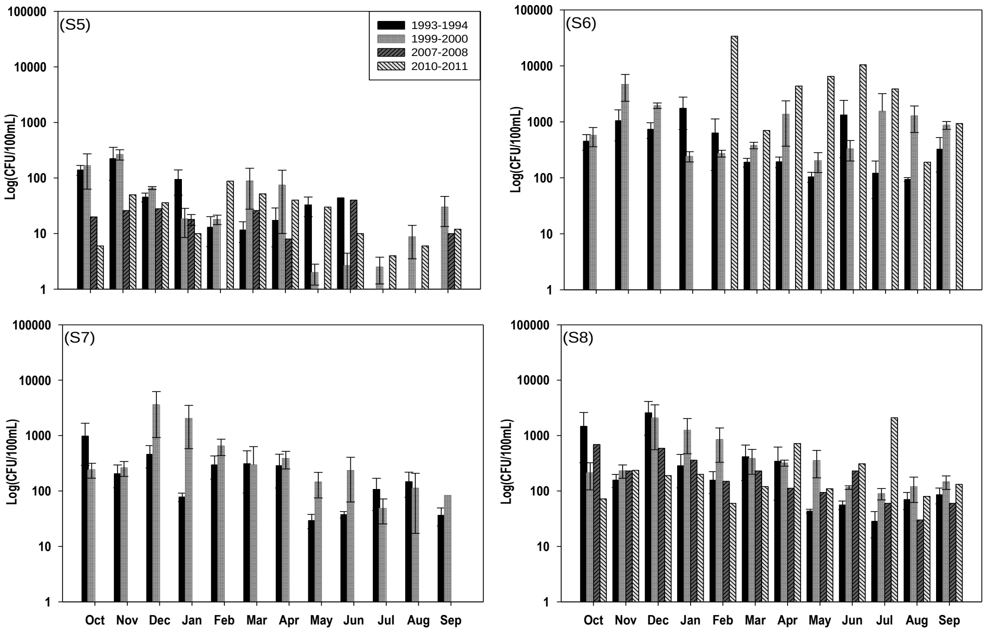

Figure 3.7 Log scale average monthly concentration of *E. coli* (CFU/100ml) at (S5) uMngeni outflow of the Midmar Dam, (S6) uMngeni at Howick, (S7) Karkloof upstream of uMngeni confluence, (S8) uMngeni at Morton's Drift. Error bars illustrate the standard error of the mean and where error bars do not appear, less than two samples were taken per month

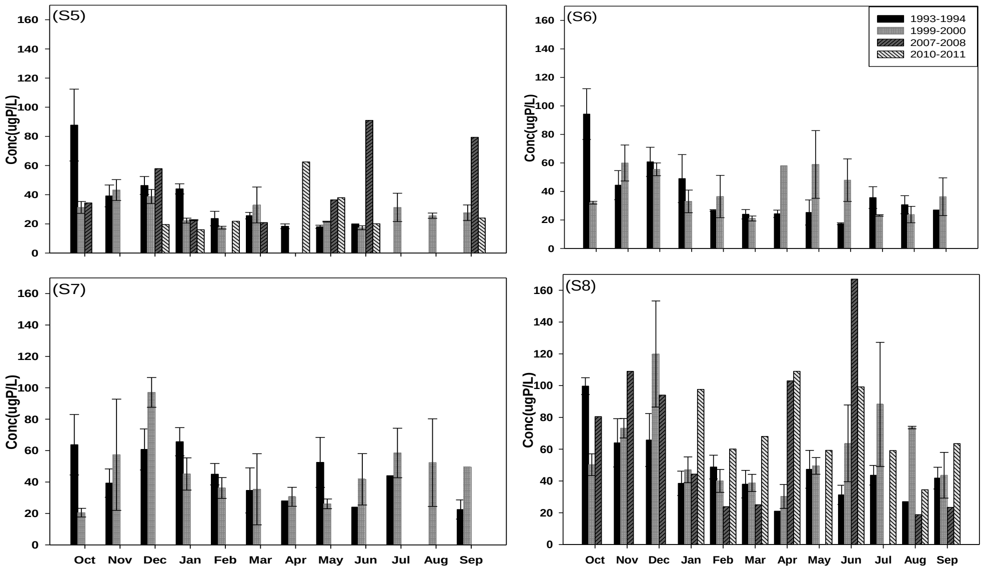

Figure 3.8 Average monthly TP concentration at (S5) uMngeni outflow of the Midmar Dam, (S6) the uMngeni at Howick, (S7) Karkloof upstream of the uMngeni confluence, (S8) uMngeni at Morton's Drift. Error bars illustrate the standard error of the mean and where error bars do not appear, less than two samples were taken per month

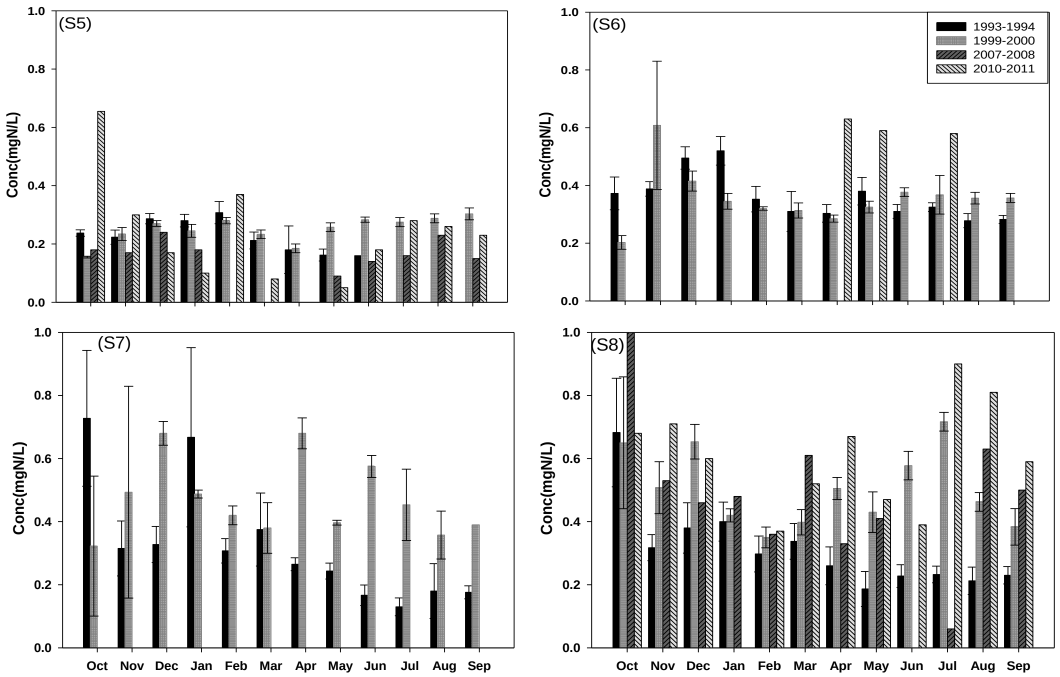

Figure 3.9 Average monthly nitrate concentrations at (S5) uMngeni outflow the Midmar Dam, (S6) the uMngeni at Howick (S7) Karkloof upstream of the uMngeni confluence, (S8) uMngeni at Morton's Drift. Error bars illustrate the standard error of the mean and where error bars do not appear, less than two samples were taken per month

3.4.3 Spatial and temporal variation of water quality parameters

A comparison of the four sites upstream of the Midmar Dam (S1, S2, S3 and S4), shows that S1 (uMngeni River at Petrus Stroom) was of good quality, compared to S2 (Lions River at the weir) and at the inflow of the Midmar Dam (S3), a reduction in nutrients concentration and *E. coli* levels was evident (Figure 3.10). This may be attributed to in-channel processes and interactions between the river and the surrounding wetlands. High levels of nitrate and *E. coli* at S2 could be attributed to the water transfer scheme from Mooi River to Mpofana, which is a tributary of the Lions River (DWAF, 2008), as well as agricultural practices in the catchment. It is important to note that the Mthinzima Stream (S4) is highly polluted, as confirmed by other investigations (DWAF, 2008; Dabrowski *et al.*, 2013).

The deterioration of water quality of the uMngeni River from S6 to S8, in terms of nutrients and *E. coli,* has been noted by DWAF (2008) and may be attributed to urban development in Hilton, formal and informal resettlements in Howick and Hilton, effluent discharge from the Howick Waste Water Treatment Plant and other point and non-point sources of pollution in the area (Dabrowski *et al.*, 2013) (Figure 3.10). Total phosphorus concentrations, exceeding the DWS threshold for eutrophication at S8 and S4 were consistent with the findings of Quayle *et al.* (2010). An increase in turbidity and TSS at S3 and S8, was also comparable to other studies (DWAF, 2008) (Appendices 3.A and 3.B).

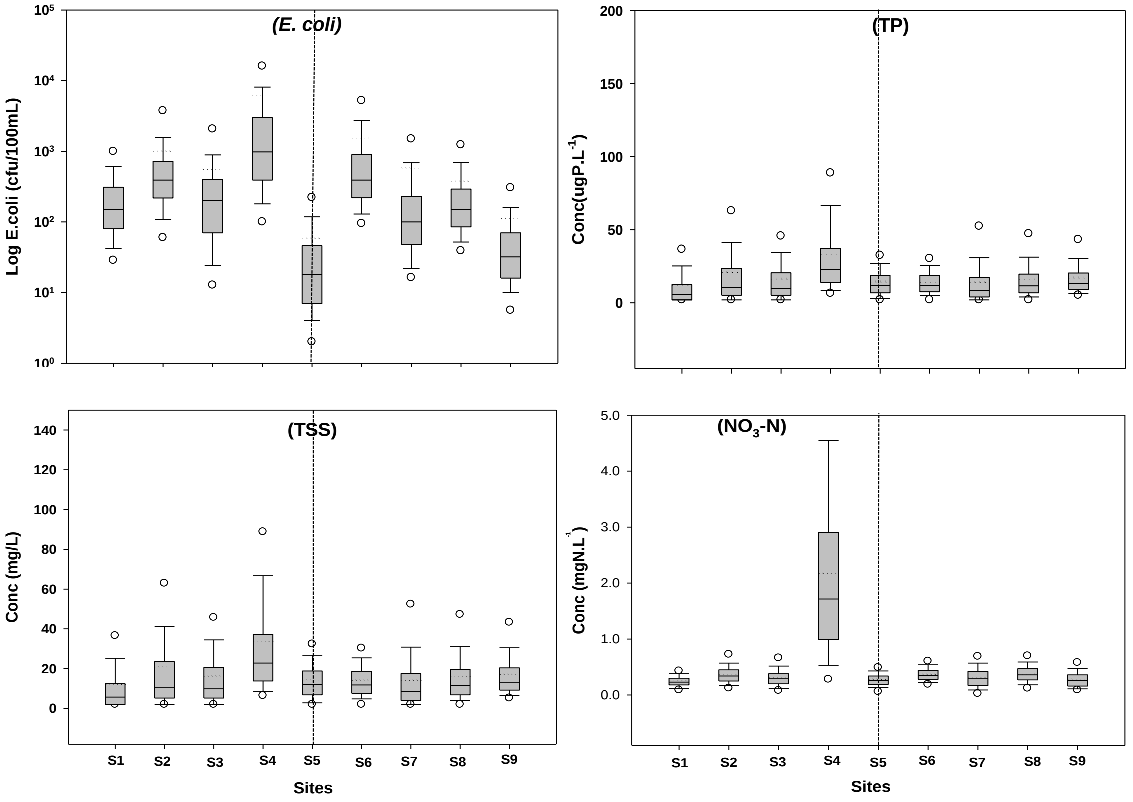

Figure 3.10 Boxplots/whiskers without outliers representing 5th and 95th percentiles, median value, minimum and maximum and mean values for *E. coli*, TP, TSS and NO_3-N in nine sampling sites. Data distribution (1987-2011), the dotted vertical line shows the Site S5 (outflow of the Midmar Dam)

According to water quality data from the sampling sites with a consistent sampling frequency, water quality change over time in the area is presented in Figure 3.11. The levels of *E. coli* increased over time from 1994 to 2011 in four selected sites (S2, S3, S4 and S8), as shown in Figure 3.11. The concentration of TP followed the same trend at Sites S2, S3 and S8, but, declined at Site S4.

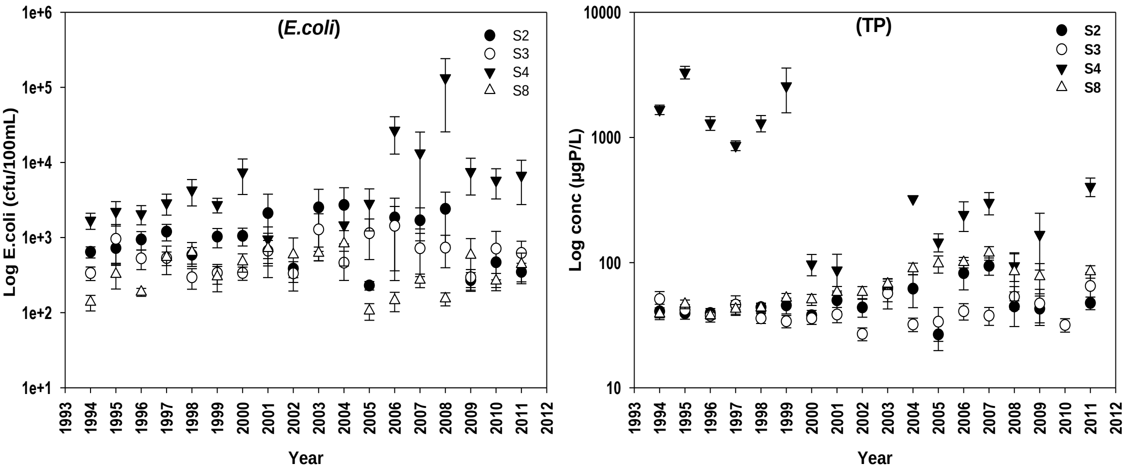

Figure 3.11 Average annual concentrations of TP and *E. coli* at four selected sites (S2, S3, S4 and S8) in the catchment from 1994 to 2011. Error bars represent the stand error of the mean.

Water quality sampling from 1987 to 2000, was carried out on a weekly basis over the whole catchment, with a cumulative number of samples of 48 to 60 per year. However, inconsistencies have been noted since a monthly sampling programme (12 samples/year) was implemented since 2001 for a number of sampling sites and, in some instances, even for non-sampling (Figure 3.12). The impact and sensitivity analysis of this is part of another study (Namugize *et al.*, in preparation). In this study, this influence was seen at Sites S6 and S7 where only analyses for 1993-1994 and 1999-2000 are possible.

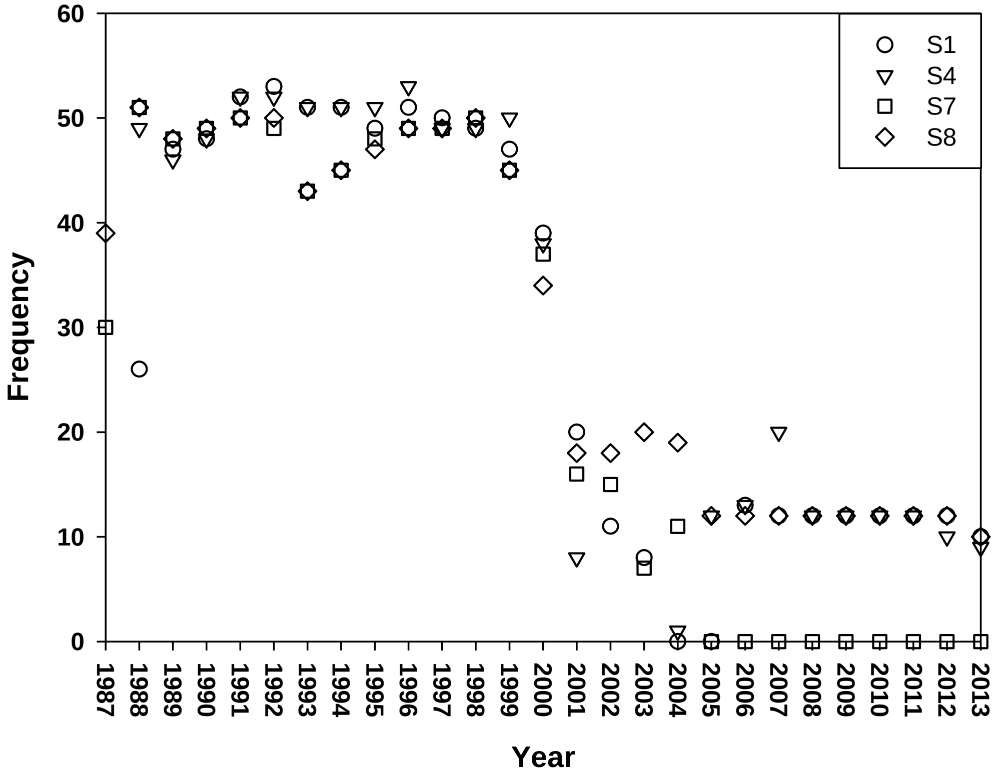

Figure 3.12 Cumulative annual monitoring frequency in the catchment

3.4.4 Relationship between LULC changes and water quality variables

In order to assess whether there is a relationship between LULC and water quality parameters in the catchment, eight independent variables were applied and assessed (natural, urban/built-up, cultivated, plantations, waterbodies, mines, degraded and wetland) and nine water quality variables were selected as dependent variables. For the sub-catchments without upstream contributing sub-catchments (C1, C2, C6 and C10), which all represent sites upstream of the large dams of Albert Falls and Midmar and where the impoundments have no influence, the correlation coefficients were calculated at outlet sampling sites (S1, S2, S4 and S7). In other sub-catchments, all upstream land use areas were combined, to assess the cumulative effects of upstream land use areas in relationship to land use-water quality (C1, C2 and C3 for the site S3; C8, C9, C10 and C11 for Site S8). As the Midmar and Albert Falls Dams are significant sinks of chemicals and die-off *E. coli*, their outflow Sites S5 and S9 were excluded in the correlation analyses (Figure 3.13).

The Pearson correlation coefficients showed that the degree of association between LULC classes and water quality varies from one sub-catchment to another (Tables 3.4 and 3.5). For example, at Site S8 (including sub-catchments C8, C9, C10 and C11), increases in urban/built-up and degraded land uses are strongly associated with an increment of TP concentration, while plantation and waterbodies positively influence EC and NO_3-, respectively, ($P<0.05$). In this sub-catchment, a decline in natural vegetation and forest plantations is strongly associated with the high levels of TP in-streams ($P<0.05$) (Table 3.5). In C2, a significant negative association exists between waterbodies and TSS, a strong association between mines/quarries and urban/built-up and temperature, forest plantations and TSS, while the degree of association of other land uses and *E. coli*, EC and SRP is medium, or non-existent (Table 3.4).

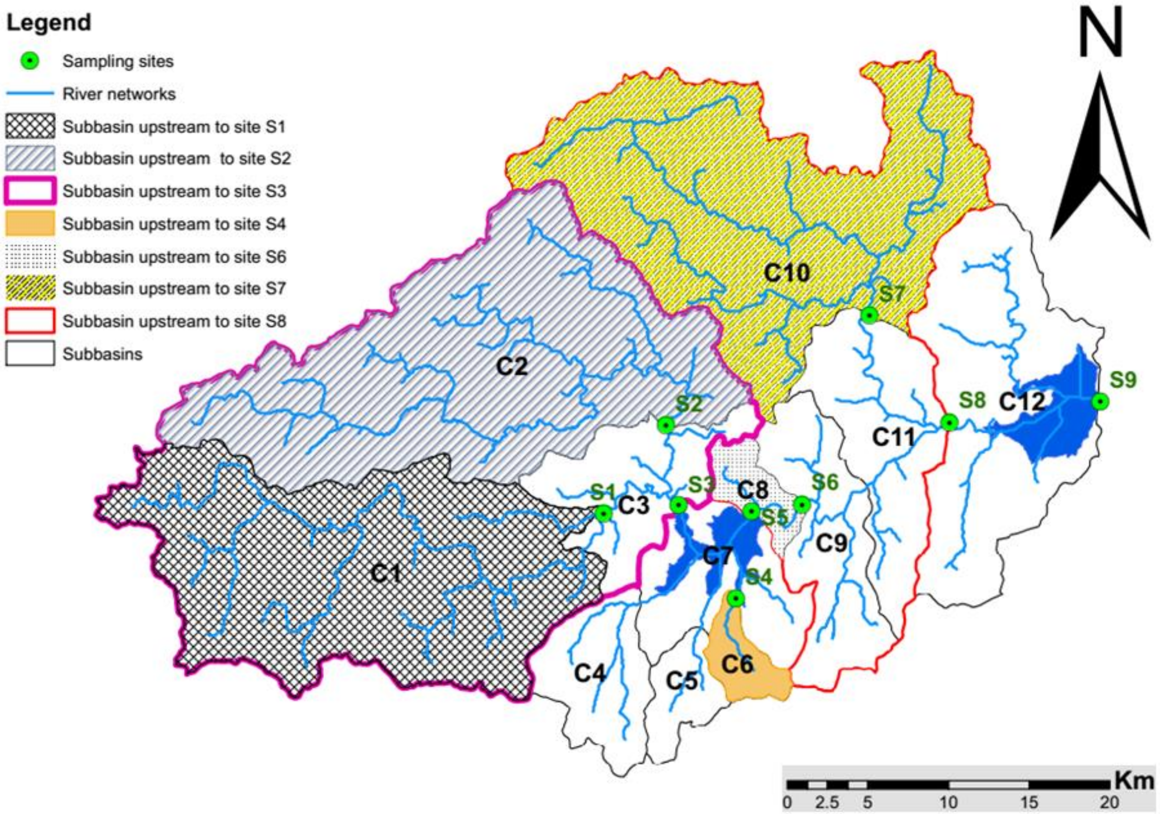

Figure 3.13 Location of the sampling sites where the correlation analysis was done. The sites at the outlets of the two dams (Midmar and Albert Falls) were excluded in correlation analysis

Table 3.5 Results of Pearson correlation analysis for change in LULC area to change of water quality variables, n=4

Site	Area (km^2)	LULC class	*E.coli*	EC	NH_4	NO_3	TSS	SRP	Temp	TP	Turb
S1	C1 (326.2)	Natural	0.44	0.78	-0.31	0.18	0.79	-0.77	-0.31	-0.37	0.81
		Cultivated	0.11	-0.32	0.42	-0.45	-0.86	0.95	0.31	0.40	-0.66
		Plantations	0.91	0.68	-0.45	0.22	0.61	-0.44	-0.57	-0.55	0.84
		Urban/built-up	-0.10	-0.18	0.72	-0.72	**-0.98**	**1.00**	0.64	0.71	-0.84
		Waterbodies	0.18	-0.63	-0.10	0.09	-0.53	0.65	-0.19	-0.10	-0.35
		Wetlands	-0.79	-0.87	-0.21	0.45	-0.04	-0.10	-0.06	-0.09	-0.32
		Degraded	-0.84	-0.86	0.20	0.04	-0.50	0.37	0.31	0.31	-0.72
		Mines/ quarries	nd	nd	nd	nd	nd	nd	nd	nd	nd
S2	C2 (352.2)	Natural	-0.13	-0.01	-0.49	0.17	0.83	-0.01	-0.76	-0.17	-0.34
		Cultivated	0.02	-0.07	0.41	-0.16	-0.89	-0.11	0.72	0.13	0.24
		Plantations	0.00	-0.08	-0.42	0.52	0.94	0.20	-0.79	-0.41	0.16
		Urban/built-up	0.28	0.32	0.66	-0.61	-0.82	0.08	0.93	0.57	0.05
		Waterbodies	-0.16	-0.20	0.25	-0.16	**-0.97**	-0.31	0.64	0.08	0.03
		Wetlands	0.00	-0.33	0.09	0.59	-0.26	0.08	0.12	-0.48	0.77
		Degraded	0.26	0.08	0.56	-0.08	-0.68	0.18	0.74	0.14	0.55
		Mines /quarries	0.49	0.53	0.80	-0.73	-0.67	0.29	**0.99**	0.73	0.12
S3	C1+C2 + incremental C3 (753.2)	Natural	-0.77	0.00	-0.28	-0.50	0.08	0.29	-0.61	-0.15	0.54
		Cultivated	0.81	-0.04	0.22	0.37	0.09	-0.45	0.62	0.23	-0.33
		Plantations	-0.40	-0.01	-0.28	-0.67	0.44	-0.12	-0.35	0.13	0.81
		Urban/built-up	**0.98**	0.36	0.56	0.00	0.44	-0.13	0.88	0.60	-0.47
		Waterbodies	0.68	-0.23	0.03	0.51	-0.08	-0.59	0.45	0.05	-0.22
		Wetlands	-0.07	-0.35	-0.14	0.87	-0.80	-0.01	-0.13	-0.57	-0.55
		Degraded	0.56	0.01	0.29	0.64	-0.33	-0.04	0.47	-0.03	-0.75
		Mines/ quarries	**1.00**	0.55	0.73	-0.16	0.56	0.08	**0.96**	0.74	-0.57
S4	C6 (18.2)	Natural	-0.38	0.78	-0.67	0.66	-0.27	0.94	-0.28	0.92	-0.25
		Cultivated	0.25	-0.29	**0.97**	-0.18	-0.30	-0.59	0.35	-0.55	-0.35
		Plantations	0.07	**-0.98**	0.06	-0.77	0.85	-0.88	-0.22	-0.89	0.77
		Urban/built-up	0.49	-0.49	0.84	-0.46	-0.12	-0.77	0.51	-0.73	-0.09
		Waterbodies	0.10	-0.49	0.90	-0.28	-0.03	-0.73	0.13	-0.68	-0.14
		Wetlands	0.08	**-0.95**	-0.16	-0.80	0.94	-0.79	-0.24	-0.82	0.89
		Degraded	0.06	**-0.96**	-0.07	-0.78	0.91	-0.82	-0.25	-0.84	0.84
		Mines/quarries	0.58	-0.19	0.84	-0.27	-0.44	-0.52	0.70	-0.48	-0.35

Where: nd: not determined, bold: correlation is significant at 0.05 level (2tailed), where temp: temperature, Turb: turbidity

Table 3.6. Results of Pearson correlation analysis for change in LULC area to change of water quality variables, n=4

Site	Area (km^2)	LULC class	*E. coli*	EC	NH4	NO3	TSS	SRP	Temp	TP	Turb
S6	C8 (21.5)	Natural	-1.00	-0.96	-0.99	-1.00	0.34	-0.99	**-1.00**	1.00	0.80
		Cultivated	0.80	0.67	0.79	0.81	-0.78	0.79	0.82	-1.00	-1.00
		Plantations	0.77	0.63	0.76	0.77	-0.81	0.76	0.79	-1.00	**-1.00**
		Urban/built-up	0.95	0.99	0.96	0.95	0.05	0.96	0.94	1.00	-0.50
		Waterbodies	0.77	0.62	0.75	0.77	-0.82	0.76	0.78	-1.00	**-1.00**
		Wetlands	**1.00**	0.99	**1.00**	**1.00**	-0.22	**1.00**	**1.00**	nd	-0.72
		Degraded	0.71	0.55	0.69	0.71	-0.86	0.70	0.72	-1.00	**-1.00**
		Mines/quarries	nd	nd	nd	nd	nd	nd	nd	nd	nd
S7	C10 (334.2)	Natural	nd	-0.46	nd	nd	nd	nd	-0.06	nd	nd
		Cultivated	nd	0.39	nd	nd	nd	nd	0.09	nd	nd
		Plantations	nd	0.71	nd	nd	nd	nd	-0.23	nd	nd
		Urban/built-up	nd	0.54	nd	nd	nd	nd	0.00	nd	nd
		Waterbodies	nd	0.13	nd	nd	nd	nd	0.31	nd	nd
		Wetlands	nd	0.31	nd	nd	nd	nd	0.24	nd	nd
		Degraded	nd	0.44	nd	nd	nd	nd	0.10	nd	nd
		Mines/quarries	nd	nd	nd	nd	nd	nd	nd	nd	nd
S8	C8+C9 +C10+ incremental C11 (536.9)	Natural	-0.11	-0.84	-0.87	-0.72	0.76	-0.29	0.43	**-0.97**	0.25
		Cultivated	0.34	0.68	0.78	0.87	-0.57	0.50	-0.54	0.93	-0.01
		Plantations	-0.53	**0.99**	0.80	0.10	-0.97	-0.32	0.02	0.74	-0.77
		Urban/built-up	-0.01	0.90	0.91	0.64	-0.83	0.18	-0.40	**0.97**	-0.36
		Waterbodies	0.67	0.31	0.52	**0.99**	-0.19	0.75	-0.66	0.73	0.37
		Wetlands	0.44	0.63	0.65	0.89	-0.49	0.61	-0.38	0.84	0.10
		Degraded	0.17	0.78	0.88	0.77	-0.70	0.33	-0.55	**0.98**	-0.19
		Mines/quarries	a	a	a	a	a	a	a	nd	nd

Where *: the correlation coefficient at S6 is high because it has been calculated for only three years (lack of 2008 water quality data), at S7 water quality data for 2008 and 2011 were missing, nd: not determined, bold: correlation is significant at 0.05 level (2tailed), a. cannot be computed because at least one of the variable is constant, temp: temperature and Turb: turbidity

3.5 Discussion

3.5.1 Land use distribution

A decline of the natural vegetation occurs, relative to large increases of urban/built-up, cultivation and other land uses in four of the 12 sub-catchments, while a small decline of forest plantations was noted in C1, C2, C9 and C12. Hence, C5, C6 and C8 were the most disturbed sub-catchments, with higher increases of urban/built-up land uses, while C1 and C4 were the least affected sub-catchments, with a low rate of urbanisation (Figure 3.3 and Table 3.3). This is supported by a growing urban population in the areas surrounding the Midmar Dam toward Albert Falls, with further expansion predicted by 2050, as reported in Mauck and

Warburton (2013). Our findings on the decline of natural vegetation in the uMngeni Catchment are consistent with the KZN natural vegetation loss of 7% in the period between 2005 and 2011 (Jewitt *et al.*, 2015). These changes in LULC have direct negative impacts on runoff and water quality of surface water, due to alteration of hydrological systems (Pratt and Chang, 2012; Yu *et al*., 2013; du Plessis *et al*., 2014; Wan *et al*., 2014; Aduah *et al*., 2015; Su *et al*., 2015).

3.5.2 Water quality trends in the catchment

Overall, there has been a decline and fluctuation of EC values at sites upstream Midmar Dam, i.e. S1, S2, S3 and S4 (Appendix 3.A). However, average EC values for 2011 were higher than those from previous studies in the catchment, for example, Graham *et al.* (1998) and Graham (2004). Four Sites (S1, S2, S3 and S4) showed high concentrations of *E. coli*, exceeding the human full contact with water threshold of 250 CFU/100mL, which indicates pollution by warm blooded animals (Figure 3. 4) (DWAF, 1996). A comparison of water pollution in the four sites upstream of the Midmar Dam, from the most to the least polluted, showed that S4 is the most polluted, then S2, S3 and finally S1. Very high *E. coli* counts were recorded at the Sites S2 and S4, with a maximum value of 146000 CFU/100mL. Only Sites S5 and S6, immediately downstream of Midmar Dam showed *E. coli* concentrations of less than 130 CFU/100mL, the threshold for recreational purposes (DWAF, 1996). This further highlights the role of the Midmar Dam in the reduction of *E. coli*. Higher concentrations of *E. coli* are linked to rapid urbanisation, which is associated with the expansion of informal settlements, stray livestock and poor sanitary systems, particularly at Site S4, located downstream of the Mpophomeni Township (Figures 3.4, 3.5 and 3.6).

The presence of *E. coli* in water suggests the presence of other pathogens that can infect humans through ingestion or skin cuts. The main sources of *E. coli* in the catchment may be attributed to grazing livestock and poor sewerage systems in the Mpophomeni settlement (DWAF, 2008). High concentrations of TP, nitrate, ammonia and SRP at S2 are attributed to a piggery, dairy cattle and poultry farming activities in the Lions River sub-catchment, supporting the suggestions of Dabrowski *et al*. (2013).

The findings and links to LULC provide more insight into the study by Graham *et al.* (1998), which concluded that water entering the Midmar Dam was of good quality when considering nutrients, TSS, electrical conductivity and turbidity. Midmar Dam is the source of water for the urban areas of Hilton, Howick and Pietermaritzburg. Nutrient concentrations at S4 (Mthinzima) are higher than other sites, confirming results from previous studies (Graham *et al.*, 1998; GroundTruth, 2012; Dabrowski *et al.*, 2013). This reflects the reality that the Mthinzima Stream is contaminated by sewage spilling and waste dumping from the Mpophomeni Township, while low level of nutrients at S1 indicates the dominance of pristine vegetation upstream of this site (Figures 3.4, 3.5 and 3.6).

There was a decline in nutrient and *E. coli* levels from S2 to S3, which could be attributed to biological, chemical, physical and hydrological processes within the stream, interactions of the stream-wetlands (Rücker and Schrautzer, 2010; Hesse *et al.*, 2013) and river self-purification processes (DWAF, 2008), highlighting the role that naturally functioning ecological infrastructure can play in water quality. Seasonality had no effect at Sites S1, S2 and S3, but at S4 higher concentrations occurred in winter (Figures 3.4, 3.5 and 3.6). Site S4 exhibited high levels of TP, SRP, NH_4-N, TSS and turbidity, resulting from dysfunctional sewer networks in Mpophomeni and a high density of unsewered informal and low cost housing in the area (Deventer, 2012).

Midmar Dam plays a big role in the improvement of the water quality of uMngeni River, through internal bio-physical and chemical processes occurring within the dam, such as increasing water residence time, die-off of *E. coli,* sedimentation of phosphorus and denitrification of nitrogen (Suwarno *et al.*, 2015). *E. coli* entering Midmar Dam are killed by solar ultra-violet radiation (DWAF, 2008) and between 10 to 50% of TP, nitrate, turbidity and TSS is retained (Figure 3.11). This effectively reduces the cost of water treatment at the DV Harris Water Works, which increases with the rising concentration of *E. coli* (Graham *et al.*, 1998). However, increases in temperature and SRP were recorded at S5. These findings confirm the role of reservoirs in trapping sediment and nutrient loads, which results in improvement of water quality and, in turn, impacts on aquatic biodiversity downstream of the dam, as noted in other research studies (Dabrowski and deKlerk, 2013; Liu *et al.*, 2015; Suwarno *et al.*, 2015). It is also consistent with other studies, which show the influence of impoundments on riverine nutrient transport and their role in nutrient retention (Bosch, 2008) (Figure 3.10).

The Midmar and Albert Falls Dams act as large sinks of phosphorus, nitrate, TSS and *E. coli*, with exception of increases of ammonium, which are ascribed to the mineralisation of organic matter in a waterbody (Figure 3.10). This has implications for downstream water users, as fluxes of chemicals from upper part of the catchment are reduced (Ahearn *et al.*, 2005). In contrast, this retention of nutrients and TSS accelerates the decline of water quality of impoundments, with the possibility of eutrophication of the two dams in the future which are already in mesotrophic-eutrophic condition (GroundTruth, 2012). This has negative implications for different water uses. The concern that impoundments of the uMngeni Catchment could become eutrophic has been raised by previous studies (Wiechers and Heynike, 1986; Walmsley, 2000; GroundTruth, 2012). Furthermore, sediment retention reduces the lifespan of the reservoir. These results are in agreement with a study noting that reservoirs globally withhold 20-50% of all sediments (WCD, 2000; Vörösmarty *et al.*, 2003) and play a major role in the transformation and removal of nutrients during their transport within the catchments (Bosch, 2008). It was noted that dam storage capacity reduces annually by 1%, due to siltation, sedimentation and other climate change issues (Thothong *et al.*, 2011).

In summary, water quality in the study area was gradually deteriorating over time, with respect to *E. coli* and nutrients, which was also confirmed independently of this study by reported chlorophyll-a in the Midmar and Albert Falls Dams (Quayle *et al.*, 2010; Matthews, 2014). The magnitude of water quality deterioration is pronounced upstream of the Midmar Dam and from the uMngeni River at Howick (S6) to the uMngeni River at Morton's Drift (S8) (Figure 3.11). An increase in sediment-related variables (turbidity, total suspended solids and total phosphorus) has a direct impact on water treatment processes. Based on the concentrations of SRP and TP since 1975, the Midmar Dam became an oligo-mesotrophic system and the mean annual TP of 9 $\mu g.L^{-1}$ (Hemens *et al.*, 1977). Another study carried out in 2010 analysed water quality data sets for 1995 to 2008 and demonstrated that the annual average concentrations of TP entering the Midmar and Albert Falls Dams were 42.5 $\mu g.L^{-1}$ and 68.1 $\mu g.L^{-1}$, respectively, (Quayle *et al.*, 2010). These values are lower than our findings of 45.3 $\mu gP.L^{-1}$ and 84.7 $\mu gP.L^{-1}$, at S3 and S8, respectively, for the year 2011 (Figure 3.11, Appendices 3.A and 3.B).

3.5.3 Linkages between LULC and water quality

In sub-catchment C1, which contains most natural vegetation, high levels of SRP were positively influenced by increases of cultivated and urban/ built-up areas, while *E. coli* counts were influenced by forest plantations, and TSS was negatively affected by urban/built-up areas (Table 3.5). These land uses in C1 did not notably affect NO_3-N, temperature, TP and NH_4-N. In sub-catchment C3, there was a significant association between urban/built-up, mines and quarries, and concentrations of *E. coli* (Table 3.5). This could be ascribed to the fact that this sub-catchment has the combined effects from C1 and C2, after flowing through the Lions River wetland. In addition, medium, weak and non- relationships existed between SRP, TP, NH4 and EC with all land use classes in this catchment. This evidence is supported by the multifaceted relationships between LULC and water quality parameters, which are site-specific. The interpretation of our results at C7 and C12 was hindered by the location of the sampling sites at the outflows of the Midmar and Albert Falls Dams, respectively. The influence of other land use types in these sub-catchments are likely to be masked by the dams. Thus, no analysis was done at these sites (Figure 3.13).

A comparison of the two sub-catchments C8 (Howick and Hilton formal and informal settlements) and C6 (Mpophomeni Township), both with high urbanization areas, suggested that high levels of EC, NH_4-N, NO_3-N, TSS, SRP and TP were linked to a shrinkage of natural vegetation in favour of urban/built-up areas in sub-catchment C6. This supported the findings of Yu *et al.* (2013), suggesting that conversion of natural vegetation to residential land uses increases impervious areas and runoff, which leads to high level of pollution. However, in C8, all water variables were associated with a decline of natural land uses, despite the lack of water quality data for the year 2008 (Table 3.6). These finding were consistent with observations in the Blesbok Spruit Catchment in South Africa (du Plessis *et al.*, 2014) and also on the humid north west Shikoku island of Japan, where an increase of urban/built-up areas was associated with water quality deterioration (Mouri *et al.*, 2011; Wan *et al.*, 2014; Zhao *et al.*, 2015).

Furthermore, high levels of NH_4-N are positively influenced by an increase in urban/built-up areas and cultivated land use types (in C6) and a decline in natural vegetation (in C8) (Table 3.6). At least two findings in the literature support this interpretation, namely: (1) an increase in cultivated land uses, with the application of fertilizers, increases nitrates in the water (Foley *et al.*, 2005), and (2) urban/built-up land cover increases the inorganic nitrogen concentration in water, which was evident in the case where a wastewater treatment plant was constructed, which could be an explanation for the C6 and C8 sub-catchments (Ahearn *et al.*, 2005; Foley *et al.*, 2005). At Sub-catchment C11, significant positive correlations noted between plantations and EC, waterbodies and NO_3 are ascribed increases in cultivated areas and to an incremental contribution from the upstream sub-catchments. Strong associations between TP and degraded and urban/built-up areas in Sub-catchment C11 could be attributed to a decline of natural vegetation and to the major point sources of pollution in the tributary sub-catchments C9 and C10. In this study, the lack of outlet sampling sites in sub-catchments C4, C5 and C9 (excluded in our correlation matrix) and inconsistency in water quality monitoring in C10 (lack of 2008 and 2011 water quality data), were the major challenges (Appendices 3.A and 3.B). This limits the confidence in the findings and the extent to which firm conclusions can be drawn.

3.6 Conclusion and recommendations

The main objective of this study was to assess the spatial and temporal effects of land use and land cover changes on bio-physical chemical water quality parameters, in the rapidly developing uMngeni Catchment. From the data of this study, it is evident that land use and land cover have changed greatly across the uMngeni Catchment since 1994, because of the clearing of natural vegetation and the increase in urban/built-up and cultivated areas. In 2011, the natural vegetation, cultivation and forest plantations are the major land use types upstream of the Albert Falls Dam, occupying approximately 85% of the catchment area. From 1994 to 2011, the natural vegetation declined by 17%, coinciding with the expansion of urban/built-up areas, cultivation and other land uses. The most disturbed sub-catchments are in the areas surrounding the Midmar Dam, where there is a high population density, due to urbanisation.

A general increase in concentrations of nutrients was observed in some sites, with fluctuation in others, from 1994 to 2011, owing to increased population, the expansion of informal resettlements and the conversion of natural vegetation to other land uses. Results strongly showed a higher concentration of nutrients in the Mthinzima Stream, which drains Mpophomeni Township. Water quality improves from the Lions River weir to the uMngeni River inflow of the Midmar Dam, owing to interactions between river channels and wetlands. At the uMngeni River outflow of the Midmar Dam to Howick, water is of good quality, with respect to the South African guidelines for eutrophication and recreational waters. Nutrients are assimilated and, from Howick to Morton's Drift, an increase in nutrients was ascribed to the Howick Wastewater Treatment Works effluent, to point sources of pollution downstream of Midmar Dam, as well as runoff coming from formal and informal resettlements of upper Howick and Hilton urban areas.

Water quality has deteriorated over time and an increase in nutrients and *E. coli* to water bodies was noted, although concentrations fluctuated with time. The seasonality of water quality parameters varies among water sampling sites; greater concentrations of *E. coli* and nutrients were noted in the rainy season. The Midmar and Albert Falls Dams are the largest sinks of pollutants, as they retain over 85% of *E. coli* and over 20% of TSS, TP, SRP and nitrate. This has negative implications on the lifespan of a dam, as well as downstream aquatic biodiversity, but has economic benefits in reducing the cost of treating water at the DV Harris Water Works. The relationship between LULC changes and water quality parameters is complex and site-specific, while the correlation coefficients vary among sub-catchments. These findings are in conformity with other research studies carried out in the USA (Maimaitijiang *et al.*, 2015), China (Li *et al.*, 2012; Wan *et al.*, 2014), Zimbabwe (Kibena *et al.*, 2014) and in South Africa (du Plessis *et al.*, 2014).

The lack of uniformity in land cover classification in South Africa presented a challenge. The various LULC information used had different numbers of land use classes, which hindered the reclassification. There is, therefore, a need for the harmonization of land use classification in the uMngeni Catchment and in South Africa in general. Inconsistency in the frequency of water quality monitoring, as well as water quality parameters, has resulted in the exclusion of many water parameters, which were therefore not analysed at each sampling site. To obtain better information on the linkages between land use types and water quality parameters, a water sampling point per sub-catchment is required, as well as an increase in monitoring sites, so that information on smaller sub-catchments is available. The Mthinzima Stream sub-catchment, with high concentrations of nutrients and *E. coli*, despite it draining less than 3% of the catchment area and to a larger extend Howick, indicates that sewerage inflow is a major problem and that repair and maintenance of infrastructure must be a priority. The establishment of continuous long-term campaigns, for raising the awareness of the local population on waste and water resource management is suggested. Water quality results presented here are from grab samples, which give a snapshot of the water concentration. Automatic samplers that can monitor continuously and capture all high flow events are recommended where gauging weirs exist and at the inflow and outflow of the Midmar and Albert Falls Dams. To achieve long-term river water quality management, it is important to identify the external sources of nutrient loads in the catchment, such as runoff, groundwater, atmospheric deposition and point sources of pollution.

3.7 References

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3.8 Appendices

Appendix 3.A

Descriptive statistics of water quality in the upper reaches of the uMngeni River Catchment for the years 1994, 2000, 2008 and 2011, where m stands for the average annual concentration, sd: standard deviation, n: number of samples and EC: electrical conductivity, Turb: turbidity, and Temp for temperature

		E-coli (CFU)			EC (ms/m)			NH4-N (mg/L)			NO3-N (mg/L)			SRP (µgP/L)			TP (µgP/L)			TSS (mg/L)			Temp (°C)			Turb (NTU)		
Site	***Year***	***m***	***sd***	***n***	***m***	***sd***	***n***	***m***	***sd***	***n***	***m***	***sd***	***n***	***m***	***sd***	***n***	***m***	***sd***	***n***	***m***	***sd***	***n***	***m***	***sd***	***n***	***m***	***sd***	***n***
S1	1994	555	1947	*51*	6.3	1.5	*51*	0.03	0.04	*49*	0.23	0.09	*51*	7	7	*50*	44	26	*50*	27	43	*50*	16	6	*49*	19	45	*50*
	2000	201	309	*39*	5.1	0.8	*39*	0.03	0.02	*38*	0.26	0.08	*39*	7	4	*38*	44	62	*37*	24	41	*38*	16	5	*38*	14	31	*38*
	2008	249	309	*12*	5.9	0.7	*12*	0.09	0.05	*12*	0.17	0.05	*12*	13	13	*12*	48	40	*12*	12	10	*12*	18	5	*12*	9	7	*12*
	2011	437	566	*12*	5.2	0.7	*12*	0.05	0.02	*12*	0.22	0.10	*12*	14	25	*12*	45	34	*12*	13	15	*12*	16	6	*12*	11	15	*12*
	1994	643	768	*50*	8.4	1.9	*51*	0.03	0.02	*50*	0.27	0.19	*51*	9	5	*51*	49	42	*51*	23	25	*51*	16	6	*49*	17	22	*51*
S2	2000	1052	1734	*38*	7.4	1.0	*38*	0.05	0.03	*38*	0.38	0.09	*38*	11	5	*38*	41	21	*38*	23	30	*38*	16	5	*38*	22	30	*38*
	2008	2620	5805	*12*	11.9	13.8	*15*	0.14	0.12	*14*	0.19	0.10	*14*	15	10	*14*	59	54	*14*	22	31	*14*	17	5	*15*	21	36	*14*
	2011	348	367	*12*	7.0	1.5	*15*	0.06	0.02	*12*	0.28	0.09	*12*	7	2	*12*	48	19	*12*	17	12	*12*	17	6	*15*	18	12	*12*
	1994	336	491	*51*	7.5	1.5	*51*	0.04	0.03	*48*	0.24	0.13	*51*	8	5	*50*	47	30	*50*	22	26	*49*	17	6	*49*	20	35	*49*
S3	2000	324	403	*39*	6.5	0.8	*37*	0.04	0.02	*37*	0.32	0.09	*37*	8	3	*37*	35	20	*37*	16	12	*37*	17	5	*37*	18	24	*37*
	2008	682	1080	*12*	10.7	14.4	*15*	1.03	3.08	*12*	0.24	0.12	*4*	10	7	*12*	60	49	*12*	23	24	*12*	18	4	*15*	17	21	*12*
	2011	623	933	*12*	6.4	0.7	*14*	0.11	0.12	*12*	0.30	0.20	*4*	6	2	*12*	45	19	*12*	20	14	*12*	18	5	*14*	19	13	*12*
	1994	1695	2931	*51*	28.6	8.7	*51*	0.06	0.11	*50*	2.62	2.01	*51*	1087	911	*50*	1667	1025	*51*	24	17	*51*	16	5	*49*	30	30	*51*
S4	2000	7428	22683	*38*	15.2	1.9	*38*	0.10	0.13	*37*	1.29	0.33	*38*	44	31	*35*	97	113	*36*	51	159	*36*	15	5	*38*	63	190	*37*
	2008	145674	432885	*12*	18.8	9.3	*12*	0.94	1.61	*12*	0.74	0.81	*12*	49	68	*12*	111	78	*12*	31	48	*12*	18	6	*12*	47	94	*12*
	2011	6728	13768	*12*	21.3	6.0	*12*	2.43	1.81	*12*	1.78	1.35	*12*	181	124	*12*	405	237	*12*	25	17	*12*	16	5	*12*	26	17	*12*
S5	1994	62	142	*24*	6.7	0.8	*24*	0.04	0.02	*22*	0.23	0.08	*24*	5	1	*23*	27	12	*23*	14	10	*23*	21	3	*23*	13	11	*23*
	2000	30	58	*39*	6.4	0.4	*39*	0.04	0.03	*39*	0.27	0.04	*39*	7	3	*39*	27	13	*39*	12	6	*39*	17	5	*39*	13	8	*39*
	2008	30	27	*12*	7.1	0.8	*12*	0.22	0.22	*12*	0.17	0.05	*12*	20	16	*12*	56	31	*12*	7	3	*12*	18	4	*12*	8	7	*12*
	2011	28	24	*12*	7.2	0.8	*12*	0.25	0.23	*12*	0.26	0.16	*12*	4	2	*12*	32	15	*12*	13	10	*12*	15	4	*12*	13	9	*12*

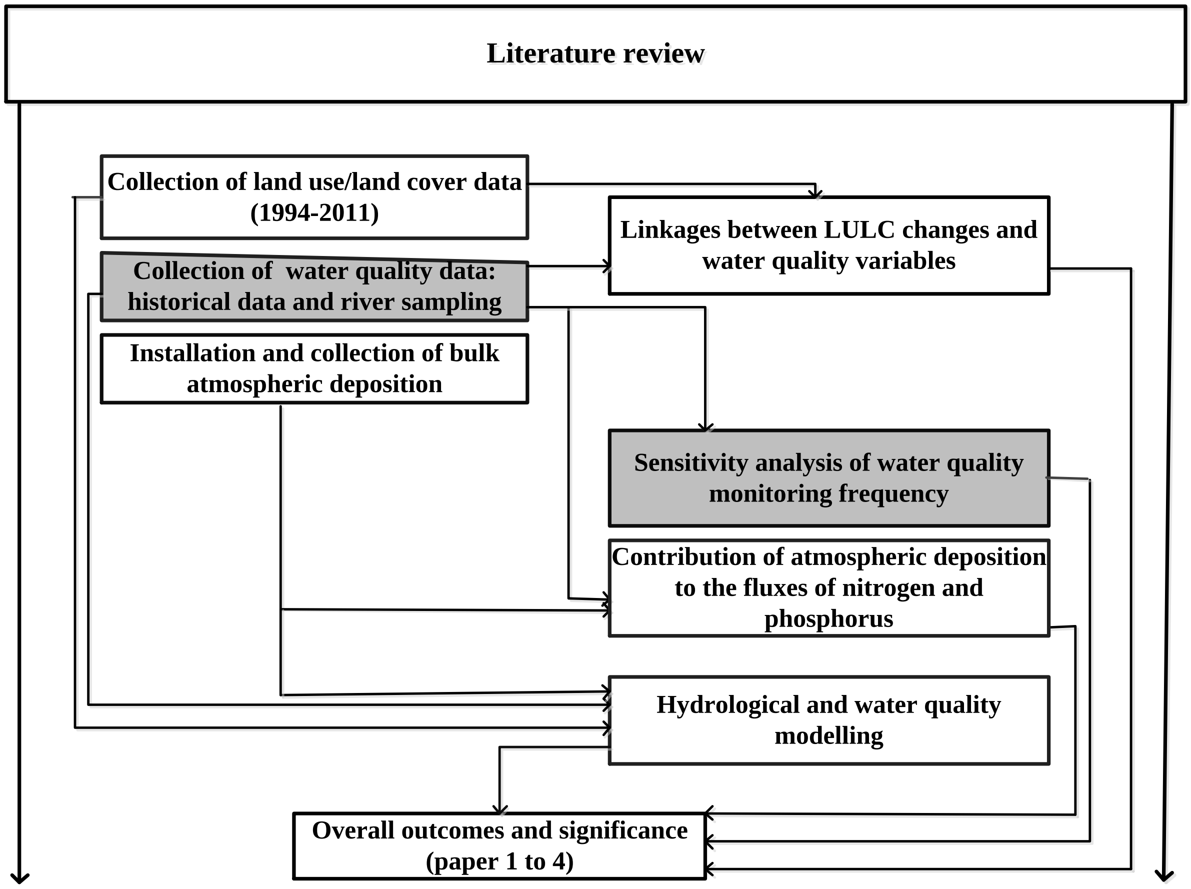
Appendix 3.B

Descriptive statistics of water quality in the upper reaches of the uMngeni River Catchment for the years 1994, 2000, 2008 and 2011, where m stands, for the average annual concentration, sd: standard deviation, n: number of samples, EC: electrical conductivity, turb: turbidity, temp: temperature and nd: for missing data

		E-coli (CFU)			EC (ms/m)			NH4 (mg/L)			NO3 (mg/L)			SRP(µg/L)			TP (µg/L)			TSS (mg/L)			Temp (°C)			Turb (NTU)		
Site	*Year*	*m*	*sd*	*n*	*m*	*sd*	*n*	*m*	*sd*	*n*	*m*	*sd*	*n*	*m*	*sd*	*n*	*m*	*sd*	*n*	*m*	*sd*	*n*	*m*	*sd*	*n*	*m*	*sd*	*n*
S6	1994	62	142	24	6.7	0.8	24	0.04	0.02	22	0.23	0.08	24	5	1	23	27	12	23	14	10	23	21	3	23	13	11	23
	2000	30	58	39	6.4	0.4	39	0.04	0.03	39	0.27	0.04	39	7	3	39	27	13	39	12	6	39	17	5	39	13	8	39
	2008	30	27	12	7.1	0.8	12	0.22	0.22	12	0.17	0.05	12	20	16	12	56	31	12	7	3	12	18	4	12	8	7	12
	2011	28	24	12	7.2	0.8	12	0.25	0.23	12	0.26	0.16	12	4	2	12	32	15	12	13	10	12	15	4	12	13	9	12
S7	1994	142	193	45	7.3	1.1	45	0.03	0.01	43	0.26	0.24	45	7	5	44	38	19	44	15	11	44	17	5	45	10	14	44
	2000	456	1060	37	6.5	1.0	37	0.04	0.06	37	0.45	0.13	37	16	16	36	43	25	37	19	17	37	17	5	37	19	20	37
	2008	nd	nd	nd	29.5	36.8	3	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	15	4	3	nd	nd	nd
	2011	nd	nd	nd	7.8	0.5	3	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	19	6	3	nd	nd	nd
S8	1994	138	217	45	8.1	0.9	45	0.04	0.02	44	0.26	0.10	45	12	5	45	43	15	45	15	14	45	18	5	45	12	10	45
	2000	476	759	34	7.2	0.7	34	0.03	0.02	33	0.46	0.12	34	24	24	32	51	28	31	18	18	34	17	5	33	15	14	34
	2008	153	104	12	9.2	1.0	14	0.14	0.07	12	0.43	0.16	12	13	13	12	92	125	12	12	4	12	17	4	14	11	3	12
	2011	439	628	12	8.9	1.0	15	0.09	0.07	12	0.57	0.17	12	27	15	12	85	34	12	14	9	12	18	5	15	14	9	12
S9	1994	258	1335	45	8.3	0.6	45	0.03	0.02	44	0.23	0.11	45	4	5	44	37	19	44	22	19	43	19	4	45	29	16	44
	2000	100	174	42	7.4	0.5	40	0.08	0.06	40	0.16	0.12	40	6	4	39	21	10	40	10	6	41	18	4	42	11	9	40
	2008	143	273	12	15.2	23.9	14	0.20	0.22	12	0.28	0.15	12	4	6	12	48	92	12	14	10	12	17	4	14	20	20	12
	2011	83	127	12	8.6	0.6	15	0.13	0.14	12	0.29	0.20	12	4	3	12	33	13	12	12	7	12	18	3	15	14	6	12

Preface to Chapter 4

In the uMngeni River catchment, water quality deterioration is highly influenced by anthropogenic activities which alter landscapes (Chapter 3). However, inconsistencies in the monitoring frequency of existing monitoring programmes may compromise the ability to provide firm conclusions on the state of water in the catchment. In Chapter 4, the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) was applied to assess the sensitivity of monitoring frequency on water quality reporting as well as on WQIs.



CHAPTER 4: SENSITIVITY ANALYSIS OF WATER QUALITY MONITORING FREQUENCY IN THE APPLICATION OF A WATER QUALITY INDEX FOR THE UMNGENI RIVER AND ITS TRIBUTARIES, KWAZULU-NATAL, SOUTH AFRICA

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4.1 Abstract

Water quality deterioration is a global issue which is ascribed to both non-point and point sources of pollution. Lack of funding and changing mandates for water quality monitoring results in reduced monitoring frequency and then sampling, and thus in critical gaps in knowledge to inform management in order to create a secure water future. This study aims to assess the effect of water sampling frequency on water quality index reporting in the upper uMngeni Catchment. A twenty-eight-year time series of water quality data from eleven sampling stations was assessed for pH, electrical conductivity, temperature, turbidity, total suspended solids, *Escherichia coli* counts, NH_4-N, NO_3-N, PO_4-P and total phosphorous. Statistical packages were used to process the data and water quality indices (WQIs) for eutrophication and recreational water were calculated. It was found that in ten of the eleven stations, the water quality status ranged from marginal to fair for human recreational and eutrophication of waterbodies. However, WQI scores were consistently poor at one site i.e. the Mthinzima Stream. Importantly, it was found that the higher the monitoring frequency, the lower the WQI calculated, at all sites. This suggests that water quality, due to a declining monitoring frequency is poorer than reported. The findings showed that *Escherichia coli* and turbidity are influential variables lowering the recreational and eutrophication WQIs, respectively. WQIs are shown to be a useful tool for monitoring the changes of water quality in space and over time in the uMngeni Catchment. However, the use of WQIs should complement not substitute other tools for water quality data interpretation.

Key words: *Eutrophication; monitoring frequency; sensitivity analysis; uMngeni Catchment; water quality guidelines; water quality index*

4.2 Introduction

Water quality problems are associated with natural processes and anthropogenic activities such as urbanisation, industrial development (UNEP-GEMS/Water, 2008), wastewater discharge and expansion of agricultural activities (Chilundo *et al*., 2008; UNEP, 2010). Globally, contribution of human activities to water quality deterioration outweighs the natural sources of water pollution (UNEP-GEMS/Water, 2008). Safe and adequate water is a primary need for all living organisms, environment and ecosystem protection and the lack of sufficient, safe and clean water is a socio-economic limitation to development in many countries (Liu *et al.*, 2013). Water, energy and food popularised now as the food-water-energy nexus, are the primary needs for human well-being (Karabulut *et al.*, 2016) and the natural ecosystem plays a key role in their provision (Jewitt, 2002, Kumar and Saroj, 2014).

Three fundamental solutions to water quality issues include pollution prevention, water treatment and restoration of ecosystems. These must be supported by water monitoring programmes aiming to identify sources of pollution to guide responses (Zhao *et al.*, 2014). Sampling strategy is a key component of any monitoring programme and is intended to guide the collection of water quality records that can be used to understand the changes that occur in a water body and to make management decisions for pollution prevention or response to pollution events (Chang *et al*., 2014; Wang *et al*., 2015). A water quality sampling plan must take into consideration the water users, intended water quality, has to be cost-effective and must provide reliable and representative information (Roig *et al*., 2007). However, limited monitoring or alterations to monitoring programmes may compromise these ideals. A high sampling frequency is deemed to be the best option for waterbodies with high variation of water quality and provides data for estimates of pollutant flux (Tate *et al.*, 1999; Absalon *et al*., 2014; Bieroza and Heathwaite, 2015). The high cost of physical water collection and subsequent laboratory analysis costs have lead to rationalisation or limited monitoring and thus curtail information on water quality in developing countries (Murphy *et al.*, 2015).

In South Africa, 12 million of the rural South African population do not have access to safe drinking water and rely on untreated water directly from rivers for domestic water usage

(Thwala, 2010; Gakuba *et al*., 2015). Water from many SA rivers is of poor quality as it has high turbidity owing to dominant clay and silt soil types (CSIR, 2010) and this has been further compromised by development in the country's catchments. The promulgation of the high phosphorus limit of 1 mg/L from all Wastewater Treatment Works (WwTWs) in 1980 was an attempt to address concerns that SA has some of the most eutrophic aquatic systems in the world (Van Ginkel, 2011; Coetzee and Hill, 2012; Matthew, 2014). Villiers and Thiart (2007) reported enrichment in dissolved inorganic nitrogen ($NO_3^- + NO_2^-$) and soluble reactive phosphorus (SRP) in the 20 largest catchments of South Africa.

High levels of nutrients, sediment and microbial contamination have been identified as major water quality problems of uMngeni River (Lin *et al*., 2012; Matongo *et al*., 2015). These are ascribed to poor catchment management, growth of unsewered human settlements, poor sanitation (Olaniran *et al*., 2014; Gakuba *et al*., 2015), population growth in rural areas, agricultural malpractices, dysfunctional sewage networks and the use of powdered laundry detergents (Villiers and Thiart, 2007; Quayle *et al*., 2010).

4.2.1 Water Quality Index (WQI)

A Water Quality Index (WQI) is a quantitative method for aggregating a complex data set of water quality parameters and converting pollutant concentrations into sub-index values and combining them into a single number or index (Cude, 2001; Yan *et al*., 2015). A WQI is intended to facilitate interpretation of water quality information by scientists (Dobbie and Dail, 2013), the general public, managers and decision-makers (Terrado *et al*., 2010; Hurley *et al*., 2012; Allam *et al*., 2015), who require concise information about water bodies (Boyacioglu, 2010). A WQI helps to assess the performance of water quality monitoring programmes, to identify water pollution problems which need particular emphasis, to provide a water quality baseline and highlights its spatial and temporal variation (Terrado *et al*., 2010). WQIs can bridge the gap between water experts and other people and so contribute to human development and ecological stability (Hurley *et al*., 2012).

The concept of WQI was first applied in Germany in 1848, using microorganisms as water quality indicators (Terrado *et al*., 2010). Since then, a number of WQIs have been developed in different regions of the globe (Allam *et al*., 2015; Yan *et al*., 2015), such as a "modern" WQI in 1965 (Jacobs *et al*., 1965; Allam *et al*., 2015), Oregon water quality index (OWQI) in 1970 (Cude, 2001), the US National Sanitation Foundation Water Quality Index (NSFWQI)

(Wills and Irvine, 1996), the Canadian Council of Ministers of Environment Water Quality Index (CCME WQI) (CCME, 2001a, b; CCME, 2006, Lumb *et al*., 2006), the Florida Stream Water Quality Index (FWQI) (Boyacioglu, 2010), the Universal Water Quality Index (UWQI) (Boyacioglu, 2006) and the "new" WQI (Said *et al*., 2004). The number of water constituents included in these indices ranges from four to four hundred (CCME, 2001a; Cude, 2001; Said *et al*., 2004). It should be noted that several authors argue that WQIs are inconclusive due to a lack of biological, physical and chemical data, cannot be generally used in predictive models (Cude, 2001) and do not substitute other methods of water quality data analysis (Khan *et al*., 2005).

Global studies undertaken assessed the overall river water quality score in SA as fair in 2008, using the global Water Quality Index (WQI), which is part of Environment Performance Index (EPI) based on five parameters i.e. pH, dissolved oxygen, total phosphorus, total nitrogen and and electrical conductivity (Srebotnjak *et al*., 2012). Catchment wide studies have also been undertaken for example, a Water Quality Index for Biodiversity (WQIB) was computed at Vaal and Orange Rivers. The outcome was that WQIB of the Orange River ranged from good to excellent, while the Vaal River ranged from marginal to poor score (Carr and Rickwood, 2008). A River Health Water Quality Index (RHWQI) has been applied at the inflow and outflow of each of the three dams of the uMngeni River (Midmar, Nagle and Inanda) using a dataset spanning between 2005 and 2012 and it was concluded that water quality was acceptable for the aquatic biodiversity of the river (Rangeti, 2014). In addition, an in-house WQI of the Umgeni Water (UW) has been used since 1990s to characterize rivers and impoundment water sources in its operation area (WES, 2012; Hodgson, 2016).

4.2.2 The Canadian Council of Ministers of Environment Water Quality Index (CCME WQI)

The flexibility and simplified calculation of the CCME WQI has made it the most globally used of the various WQIs (Lumb *et al*., 2006; Rickwood and Carr, 2009; Terrado *et al*., 2010; Akkoyunlu and Akiner, 2012; Abtahi *et al*., 2015) and it has been the subject of many modifications according to the objectives at the waterbodies investigated (Hurley *et al*., 2012). Applications have been intended to assist in the identification of water pollution hotspots that need emphasis in the catchment and major water quality parameters influencing its deterioration. The CCME WQI can accommodate a large database of water quality information. This index is easily adaptable to different legal requirements and to the selection of input variables (Rickwood and Carr, 2009). It also provides the possibility of changing water quality objectives to be met according to different water uses (Rickwood and Carr, 2009; Terrado *et al*., 2010). However, this index has some disadvantages, such as assigning all variables the same weight in index calculations, regardless of their different effects on water quality deterioration and it does not accommodate the biological and hydro-morphological components of a waterbody (Terrado *et al*., 2010).

Given its wide acceptance, it could be a useful tool to provide information on spatial and temporal variations of water quality of uMngeni River and its tributaries. Information to be generated by this index could be easily disseminated to all uMngeni water resources management stakeholders and could help policy and decision-makers to draw relevant conclusions on water pollution issues within the area. WQIs are important tools for communicating catchment water quality data, but they are reliant on good quality data. Despite deterioration in water quality, monitoring programmes are declining and data availability is problematic. Therefore, it is likely that WQIs and useful information they provide are compromised by declining availability of data. We tested this assumption, using the CCME WQI under South Africa conditions. Thus, the overall objective of this study was to assess how inconsistency in river monitoring sampling frequency may compromise the decision-making on water quality information collected. To achieve this objective, the eutrophication and recreational WQIs have been calculated, following the CCME QWI system and the influence of changes in frequency of monitoring on the results was assessed.

4.3 Material and Methods

4.3.1 Study area and sampling sites

The uMngeni River Catchment plays a vital role in the economy of the KwaZulu-Natal (KZN) province. This catchment is one of the five components of the Mvoti to Umzimkulu Water Management Area (WMA), supplying drinking water to over 4.5 million inhabitants of the province (DWAF, 2004). Water demands in the catchment exceed the available water resource and as a result, water transfer schemes from the Mooi River to the uMngeni River were constructed with others planned for the future (UW, 2013). It is estimated that 70% of the population in the WMA is concentrated in uMngeni Catchment, attracted by developmental infrastructure and employment opportunities, largely in and around the cities of Durban and Pietermaritzburg (DWAF, 2003). The Midmar and the Albert Falls Dams, both located in the upper reaches of the catchment, produce three quarters of the runoff generated in the whole uMngeni catchment system (Breen, 1983; Jewitt *et al.*, 2015). The area is characterized by an annual rainfall greater than 700 mm p.a and the study area covers five water management areas of the upper reaches of the uMngeni River.

Major land uses as in 2011 were natural vegetation, forest plantations, cultivation and urban/built-up, representing, 42%, 26%, 17% and 5% respectively (Namugize *et al.*, submitted). Occurrence of eutrophication and resulting increase in algal population at the Midmar and Albert Falls Dams are the foremost concerns, with the potential for impairing recreational water use and the cost of drinking water treatment in the catchment (Graham, 2004; Matthews, 2014). Water quality indices were computed for the 11 monitoring sites of the uMngeni River and its tributaries, upstream of the Albert Falls Dam (1653 Km^2), representing 38% of the surface area of uMngeni Catchment (Figure 4.1 and Table 4.1). Detailed descriptions of the study area are presented in (Hay, 2017) and (Namugize *et al.*, submitted) and this paper provides only a brief description of the sampling points.

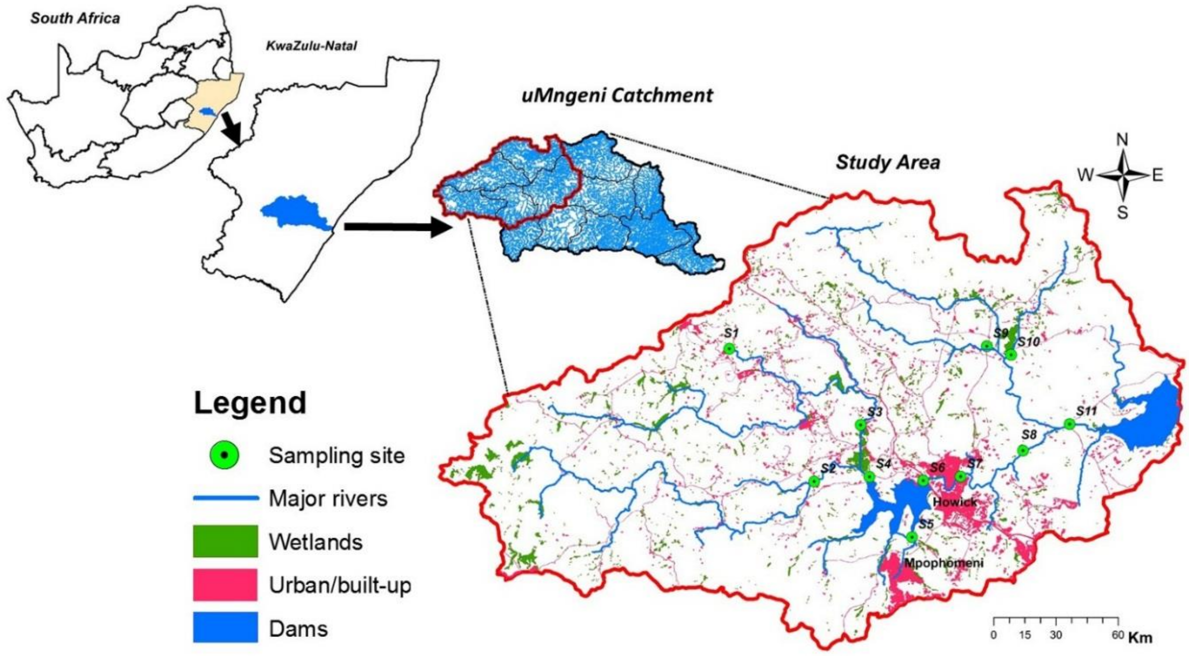

Figure 4.1 Location of the uMngeni catchment, the study area and the sampling sites within South Africa

Table 4.1 Water quality monitoring stations and data duration

No	Site ID	Site name	Latitude	Longitude	Data duration
1	S1	Outflow of the Mooi River transfer scheme	-29.389	30.032	(Mar-95/Oct-01)
2	S2	uMngeni at Petrus Stroom	-29.492	30.108	(Jul-88/Jun-15)
3	S3	Lions River at the weir U2H007	-29.443	30.149	(Jan-88/Jun-15)
4	S4	uMngeni inlet to Midmar Dam	-29.488	30.156	(Jan-88/Jun-15)
5	S5	Mthinzima inflow to the Midmar Dam	-29.540	30.193	(Jan-88/Jun-15)
6	S6	Outflow of the Midmar Dam	-29.491	30.203	(Jan-88/Jun-15)
7	S7	uMngeni at Howick	-29.488	30.235	(Jul-88/May-15)
8	S8	uMngeni upstream Karkloof Confluence	-29.465	30.289	(Jan-88/Aug-01)
9	S9	Karkloof River at Shafton	-29.375	30.258	(Jul-88/Sep-01)
10	S10	Karkloof upstream uMngeni River	-29.382	30.279	(Jan-88/Dec-04)
11	S11	uMngeni at Morton Drift	-29.442	30.235	(Jan-88/Jun-15)

4.3.2 Water quality data acquisition

A long-term water quality dataset was obtained from UW. Water quality parameters included in this assessment, among others, are electrical conductivity (EC), pH, temperature, turbidity, soluble reactive phosphorus (SRP), total phosphorus (TP), ammonium (NH_4-N), nitrate (NO_3-

N), total suspended solids (TSS) and *Escherichia coli* (*E. coli)*. The data set is made of samples collected following a monitoring frequency, which varied between monthly and weekly for the period 1988-2015. Water samples were immediately transported in a cooler box to UW laboratory for chemical analyses, according to international standards in their ISO9001 accredited laboratories. Heavy metals were not included in our data analysis because they do not influence eutrophication (Graham, 2004) and they are currently not considered an important issue of water pollution in the upper reaches of the catchment (Lin *et al.*, 2012; Rangeti, 2014), as surface water quality is not linked to any significant industrial activity in the area (Manickum *et al.*, 2014).

4.3.3 Calculation of the CCME WQI

For this study, the application of CCME WQI involved three steps: (1) the definition of a list of water constituents characterizing water quality of the water body (2) establishment of water quality objectives to be met and (3) the calculation of water quality index (Lumb *et al.*, 2006; Boyacioglu, 2010; Terrado *et al.*, 2010).

The scope, frequency and amplitude are three factors considered in assessing the CCME WQI: **Scope (F_1):** represents the percentage of water quality parameters that failed to meet their guidelines at least once, relative to the number of variables measured (Equation 4.1)**. Frequency (F_2):** represents the number of times the objectives are not met (Equation 4.2)**. Amplitude (F_3):** represents the amount by which failed test values do not meet objectives (Equation 4.6). All the three factors are summed as vectors to obtain the CCME WQI for a particular set of samples for each sampling site (Equation 4.7).

$$F1 = \left(\frac{Number\ of\ failed\ variables}{Total\ number\ of\ variables}\right) x\ 100 \qquad (4.1)$$

$$F2 = \left(\frac{Number\ of\ failed\ tests}{Total\ number\ of\ tests}\right) x\ 100 \qquad (4.2)$$

When the test value must not exceed objective:

$$Excursion\ i = \left(\frac{Failed\ test\ i}{Objective\ j}\right) - 1 \qquad (4.3)$$

If the test value must not fall below the objective :

$$Excursion\ i = \left(\frac{Objective\ j}{Failed\ Test\ Value\ i}\right) - 1 \qquad (4.4)$$

Then the normalised sum of excursions (*nse*) is calculated as:

$$nse = \frac{\sum_{i=1}^{n} departure\ i}{number\ of\ tests} \tag{4.5}$$

$$F3 = \left(\frac{nse}{0.01nse + 0.01}\right) \tag{4.6}$$

$$CCME\ WQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right) \tag{4.7}$$

Where the value 1.732 has been used to scale the index from 0-100;

$$\sqrt{100^2 + 100^2 + 100^2} = \sqrt{30000} = 173.2$$

Further details on CCME WQI calculations are explained by different authors(CCME, 2001a, b; Khan *et al.*, 2005; Lumb *et al.*, 2006; Akkoyunlu and Akiner, 2012). The CCME WQI can be calculated manually, following Equation 4.7. However, for a large data set of water quality information an excel macro is available for download at the CCME web page (http://www.ccme.ca/en/resources/canadian_environmental_quality_guidelines/calculators.html). The WQI score ranges from 0 to 100, respectively for poor water quality to excellent water quality. The categorisation of a waterbody according to the CCME WQI is summarized in Table 4.2.

Table 4.2 Categorization of waterbodies following the CCME WQI (CCME, 2001a, b; Khan *et al.*, 2005; Hurley *et al.*, 2012)

Category	WQI range	Status of a waterbody
Excellent	95.0-100.0	water quality very is close to pristine or natural conditions with a virtual absence of impairment
Good	80.0-94.9	water quality is protected with only a minor degree of impairment
Fair	65.0-79.9	water quality is usually protected but occasionally impaired
Marginal	45.0-64.9	water quality is frequently threatened or impaired
Poor	0.0-44.9	water quality is almost always threatened or impaired

To assess the water quality score for the uMngeni River and its tributaries, data collected were tested for compliance with eutrophication and safe recreational benchmarks and /or standards for South Africa, World Health Organization (WHO) and Canadian Council of Ministers of Environment. The choice of water quality variables to be included in index calculations was based on parameters which are known to contribute to eutrophication of a waterbody, impairment of human health through contact during recreational water use (for example, *E. coli*) and the availability of the water quality monitoring database in the catchment. A four by four rule was applied whereby at least four water quality variables consistently measured at least four times per year for each site was a requirement to be included in index calculation (CCME, 2001a; UNEP-GEMS/Water, 2007; Carr and Rickwood, 2008). Overall WQIs were computed in respect to eutrophication and recreational water use standards for each site as Table 4.3 indicates. Application of the CCME WQI in the upper reaches of the uMngeni River catchment resulted in the calculation of two water quality sub-indices namely, a eutrophication water quality index (EWQI) and a recreational water quality index (RWQI).

4.3.4 Data processing and analysis

Umgeni Water implemented a consistent weekly water quality monitoring programme of uMngeni River and its tributaries from earlier 1987 to 2000. However, from 2001 up to 2015, irregularity in frequency of sampling was noted, varying from bi-weekly, monthly, quarterly to occasionally, no samples per annum. Data below the detection limit of the method were halved, following the approaches of Graham (2004). Missing data were replaced by -999 as indicated in the excel macro sheet guideline for CCME WQI calculation.

Table 4.3 Eutrophication and recreational water quality guidelines and standards used in index calculations

Parameter	Unit	Eutrophication threshold	Recreation threshold	Details	Reference
E. coli	CFU/100mL	NA	250	*E. coli* must not exceed target	(DWAF, 1996a; CCME, 1999; DEA, 2012)
EC	mS/m	50	NA	EC must not exceed target	(Srebotnjak *et al.*, 2012)
NH4-N	mgN/L	0.05	NA	NH_4^+ must not exceed target	(Srebotnjak *et al.*, 2012)
NO_3-N	mgN/L	0.5	10	NO_3^- must not exceed target	(DWAF, 1996a, b; Boyacioglu, 2006)
SRP	µgP/L	25	NA	SRP must not exceed target	(DWAF, 1996b)
pH	pH units	6.5-8.5	5-9	pH must fall within target range	(DWAF, 1996a; DEA, 2012; HC, 2012)
Temperature	°C	8-28	15-30	Temperature must fall within target range	(CCME, 1999; WHO, 2003; DEA, 2012)
TP	µgP/L	50	160	TP must not exceed target	(Boyacioglu, 2006)
TSS	mg/L	100	NA	TSS must not exceed target	(DWAF, 1996b)
Turbidity	NTU	5	50	Turbidity must not exceed target	(CCME, 1999; HC, 2012)

With NA: not applicable

In order to assess the influence of the sampling frequency on WQIs, the weekly water quality data (1988-2000) was arranged into three categories which are: (1) for a weekly sampling programme all four samples (48 samples per year) were included in the index computation, (2) for a bi-weekly sampling, the first and third week’s samples were included in index calculation (24 samples per year), and other two samples hidden; and (3) for a monthly sampling frequency, three out of four samples were excluded in the index calculation (12 samples per year). For each sampling frequency, an overall annual WQI was computed for each site (Table 4.3). A comparison of the three calculated indices following different sampling frequencies was carried out, using graphs and trend analysis. In addition, a sensitivity analysis of the WQIs was undertaken to check the effect of each input parameter on overall WQI after its removal from the index computation compared to the original index. In this exercise, the water quality data collected from 1988 to June 2015 have been included in index calculation irrespective of the monitoring frequency. Descriptive statistic tools of Sigma plot (Version 10.1, Systat Software, Inc. SigmaPlot, ink) were used to assess the variability of water quality in the catchment.

4.4 Results and Discussion

4.4.1 Effects of monitoring frequency on water quality index

An attempt to assess the effects of the sampling frequency on the WQI score for each sampling station was undertaken as presented in Figure 4.2 The EWQI score variation within sites was not uniform. For example, when implementing a monthly sampling strategy, two scores of "good" water in the catchment were noted at Sites S1 and S6. When implementing a fortnightly monitoring frequency one score event of water ranked as "good" was noted at site S6, while following a weekly sampling plan, no site was rated as "good" (Table 4.4). This elucidates the sensitivity of the EWQI to the number of samples included in the index calculation. Simultaneously, the number of sites which scored "fair" decreased through the bi-weekly to weekly monitoring frequency, coinciding with an increase in number of sampling sites rated "marginal" (Table 4.4). However, the WQI has provided almost similar water quality information for the monthly and fortnightly monitoring frequency. The EWQI of uMngeni River and its tributaries ranged from fair to marginal, predominantly marginal, following a weekly sampling frequency (Figure 4.2).

Generally, there was a decrease in the water quality score as a result of increasing monitoring frequency from monthly to weekly. This was noted in all monitored sites. This confirms the reliability of WQI calculated by implementing a high-frequency sampling programme (Terrado *et al.*, 2010; Bieroza and Heathwaite, 2015). These results are consistent with findings of CCME (2006), which indicated the sensitivity of the WQI on the number of measurements. However, it was found that use of long-term dataset in calculation of WQI can dampen the impacts of climate variability, hydrological factors and pollutant inputs, which are not captured by the WQI.

Table 4.4 Spatial occurrence of annual WQI scored as excellent, good, fair, marginal and poor in respect to monthly (M), fortnightly (F) and weekly (W) monitoring frequency, for the period 1988-2000

Site/Index score	**Excellent**			**Good**			**Fair**			**Marginal**			**Poor**		
Frequency	*M*	*F*	*W*	*M*	*F*	*W*	*M*	*F*	*W*	*M*	*F*	*W*	*M*	*F*	*W*
S1	0	0	0	1	0	0	5	5	1	0	1	5	0	0	0
S2	0	0	0	0	0	0	9	9	4	4	4	9	0	0	0
S3	0	0	0	0	0	0	6	6	1	7	7	12	0	0	0
S4	0	0	0	0	0	0	6	6	3	7	7	10	0	0	0
S5	0	0	0	0	0	0	0	0	0	0	0	0	13	13	13
S6	0	0	0	1	1	0	9	9	8	3	3	5	0	0	0
S7	0	0	0	0	0	0	2	2	0	10	10	13	1	1	0
S8	0	0	0	0	0	0	2	2	0	10	10	12	1	1	1
S9	0	0	0	0	0	0	0	0	0	12	12	10	1	1	3
S10	0	0	0	0	0	0	4	4	3	9	9	9	0	0	1
S11	0	0	0	0	0	0	5	5	3	7	7	9	1	1	1
Total	**0**	**0**	**0**	**2**	**1**	**0**	**48**	**48**	**23**	**69**	**70**	**94**	**17**	**17**	**19**

4.4.2 Temporal variation of WQIs (1987-2000)

Temporal trends are illustrated in Figure 4.2. They indicate a high variability of WQIs, with exception of the sites S5 and S6. The site S5 (Mthinzima Stream) had a poor water quality score irrespective of the monitoring frequency and water quality of this station declined from 1988 to 2000, which could be ascribed to dysfunctional sewage systems and increase of informal human settlements in Mpophomeni Township (GroundTruth, 2012; Dabrowski *et al.*, 2013). At site S6, water quality score increased slightly but remained in the range of “fair” to marginal with occurrence of good with an improvement from 1988 to 2000. In other sites, downstream of the Midmar Dam (S7, S8, S9, S10 and S11) WQIs were predominantly marginal (Figure 4.2). The trends analysis indicated an overall water quality deterioration within sites over time. These results indicated the deterioration of water quality from upstream to downstream in the catchment as confirmed by other research studies (Graham, 2004; GroundTruth, 2012; Rangeti, 2014). The decline of water quality at site S7 was not surprising as this site may reflect major effluent discharges from Howick and Hilton urban areas and influence of the poorly functioning Howick Wastewater Treatment Works (WwTWs) (Taylor *et al.*, 2016). Furthermore, other point sources of pollution such as St Annes, Midlands and Cedara are possible sources of water deterioration at Sites S8 and S11 (Hudson *et al.*, 1993).

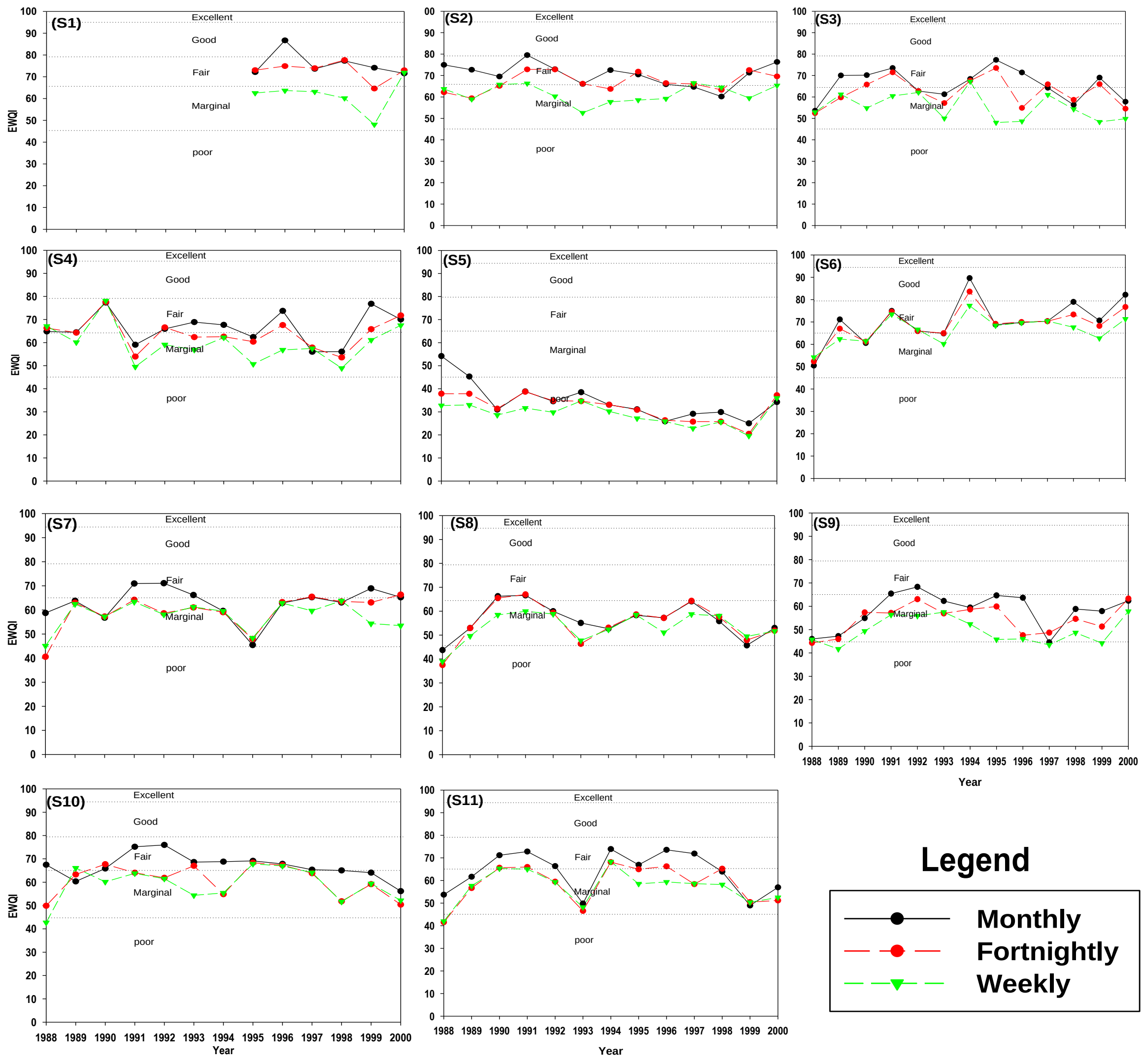

Figure 4.2 Temporal trends of EWQI in the catchment, using data collected between 1988 and 2000, following different sampling frequencies. Where Si is the sampling station.

4.4.3 Temporal and spatial variability of WQIs (1988-2015)

The period 2000-2015 showed decreasing sampling frequency, hence the analysis is compromised. In general, there was a temporally variable pattern in the WQIs from 1988 to 2015. A decrease in water quality monitoring frequency has occurred in all 11 sites across the catchment, ranging from weekly (48-55 samples per year) in pre-2000 period to monthly monitoring frequency (12 samples per year) after 2000 (Figures 4.3 and 4.4). Lack of water quality monitoring data for sites S1 (for the period before 1995 and after 2001), S7 (for 2002-

2009), S8, S9 and S10 (after 2002 upward) hindered the index calculations for these periods (Figures 4.3 and 4.4). EWQI varied between fair to marginal at 10 sites with the station S5 classified as “poor” from 1988 to 2015 (index was below 45 for 22 years out of 25). RWQI followed the same trends (fair to marginal) with exceptions at sites S5 and S2, which scored as poor. The consistent temporal pattern of poor water quality at S5 reflects the impacts of dysfunctional manholes and sewers discharging to the Mthinzima stream, as well as poor waste management from Mpophomeni Township (GroundTruth, 2012; Ngubane, 2016; Namugize *et al.*, submitted).

The poor RWQI score noted at site S2 could be ascribed to *E. coli* levels, which were high, exceeding the target of 250 CFU/100 mL and the index was very sensitive to this parameter at this site. Occurrence of “good” water quality score at the outflow of the Midmar Dam (S6) highlighted the pollutant sequestration by the dam reservoir (Maavara *et al.*, 2015). These results also show an increase of WQIs with a decline of the monitoring frequency. This relationship is consistent for the sites S2, S3, S4 and S6, upstream of the Midmar Dam (Figure 4.3). However, the opposite trend was noted at site S11, indicating the high level of pollution occurring between the Midmar and Albert Falls Dams, ascribed to effluent discharges from WwTWs and other point sources of pollution in that portion of the catchment (Hudson *et al.*, 1993; DWAF, 2008; Taylor *et al.*, 2016)(Figure 4.4). However, lack of the water quality data at Sites S7, S8, S9 and S10 for the period after 2002 was a major challenge.

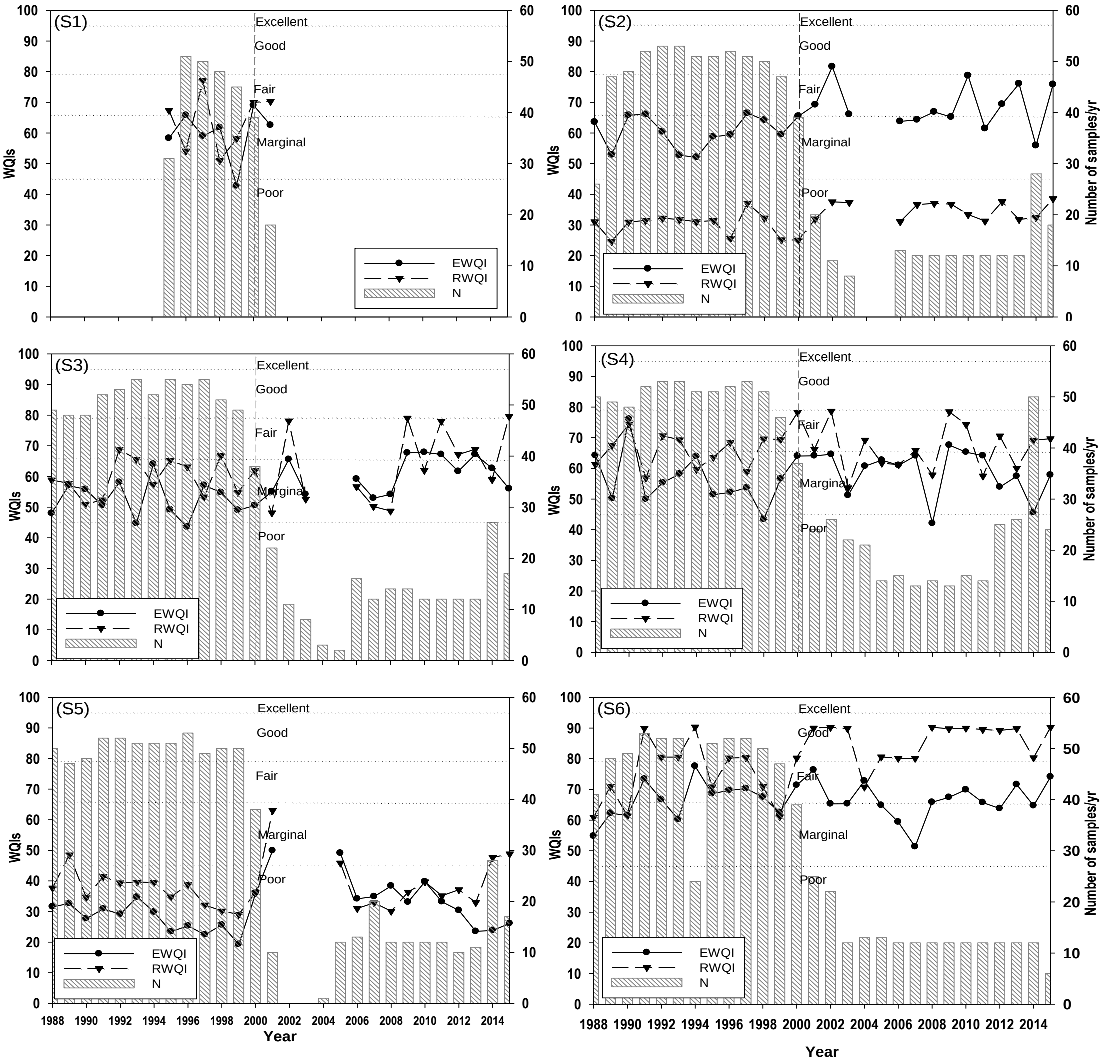

Figure 4.3 Variation of EWQI, RWQI and the number of water samples taken per year (N) for each station, upstream of the Midmar Dam using the data collected from 1988 to 2015

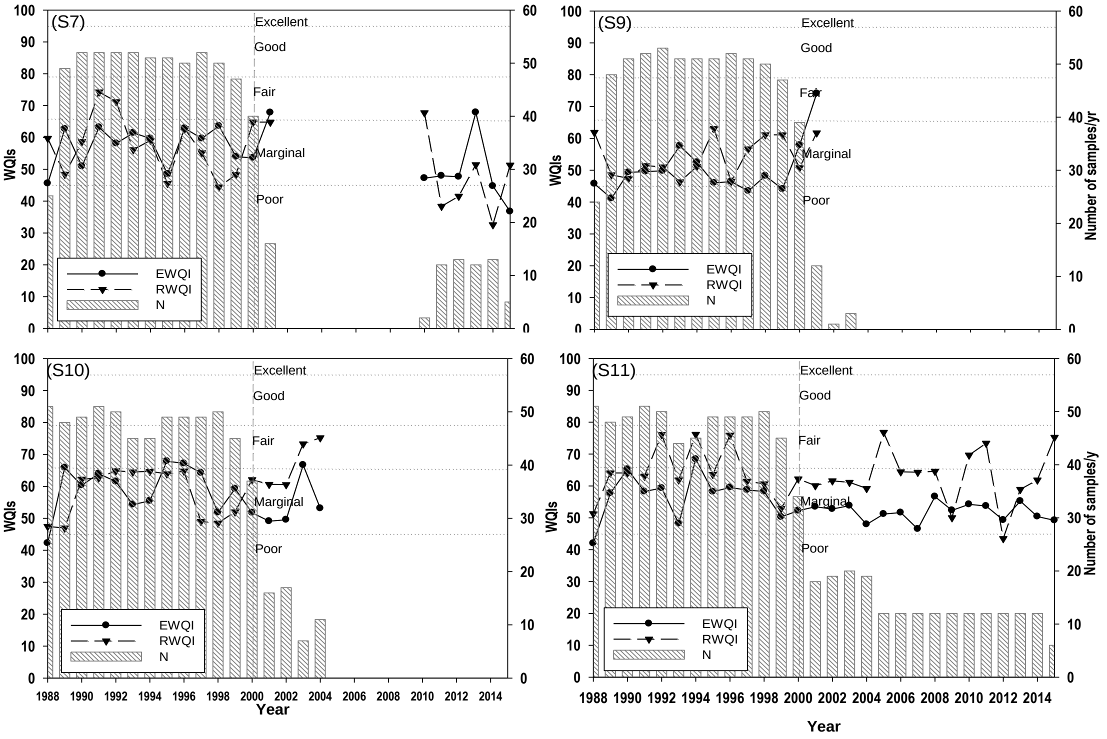

Figure 4.4 Variation of EWQI, RWQI and the number of water samples taken per year (N) for each station downstream of Midmar Dam using the data collected between 1988 and 2015

4.4.4 Sensitivity analysis of WQIs

A sensitivity analysis is defined as a study of the response of an output variable in respect to variations of input variables. This was undertaken to determine which water variable most influences the score of WQIs. The comparison was done by removing each water variable in turn from the calculation of WQI and the overall annual index and comparing results (Figures 4.5 and 4.6). In the RWQI data set, each individual parameter of nitrate, *E. coli*, temperature and turbidity has been removed and the index was computed. The output score was compared to the original index including all six parameters. Results have shown that the parameters with exceedance to the guidelines are the most influential to the output score. Thus, their removal has resulted in an increased WQI (CCME, 2006).

In this study, it was found that *E. coli* is the key parameter in influencing the RWQI in all sites. For example, the removal of *E. coli* in the index calculation at site S2 resulted in an overall index increase of 40 units per year. This resulted in an increase of the number of occurrence of index scored as "good", "fair" and "marginal" several times and across the catchment (Figure 4.5). This is in line with a previous study which highlighted *E. coli* as the major constituent affecting water quality in uMngeni Catchment (Graham, 2004; Lin *et al.*, 2012; Rangeti, 2014; Matongo *et al.*, 2015). Effects of turbidity and nitrate on an overall RWQI score was low and varied among the sites as their values were below the South Africa recreational standard limits (DWAF, 1996a). Therefore, their removal resulted in a drop in the index score. Temperature greatly influenced the RWQI at site S6 (outflow of Midmar Dam) as a result of variation of temperature between summer and winter days, water residence time within the reservoir and reservoir characteristics, making it an important parameter which catalyses biological and chemical transformations taking place in water (Effendi *et al.*, 2015). However, influence of this parameter was also noted at sites S4 and S11.

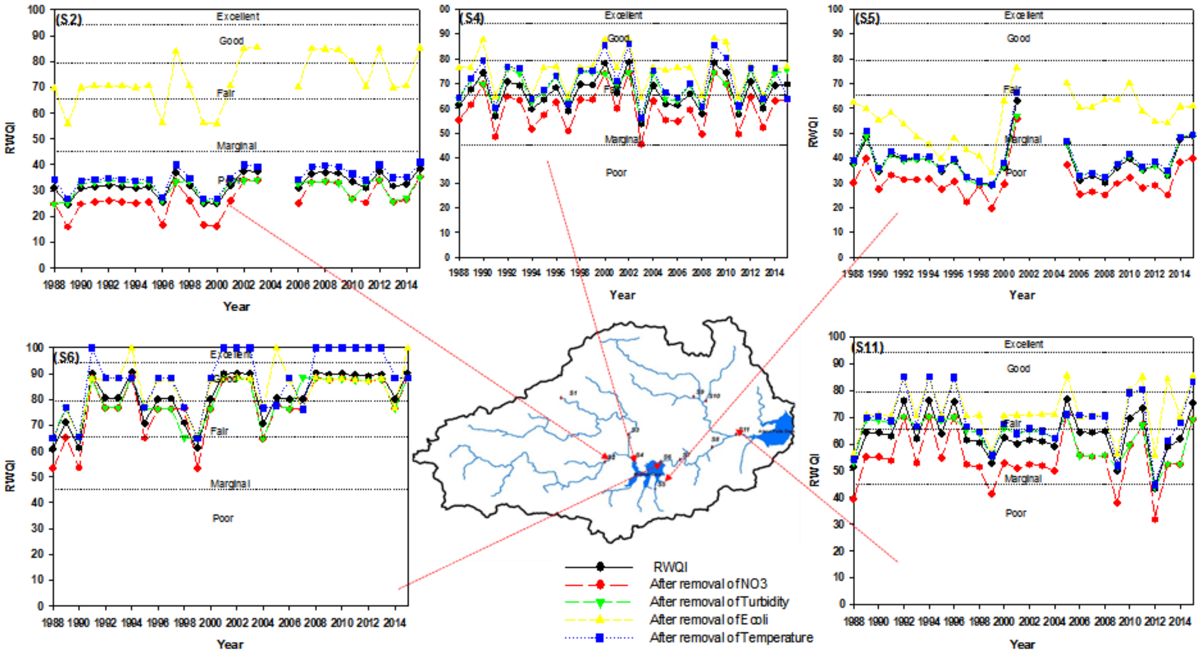

Figure 4.5 Sensitivity analysis of annual RWQI at key selected sampling sites: (S2) uMngeni at Petrus Stroom, (S4) uMngeni River inflow of the Midmar Dam, (S5) Mthinzima outlet to the Midmar Dam, (S6) uMngeni outflow of the Midmar Dam and (S11) uMngeni River at Morton Drift (between 1988 and 2015)

A sensitivity analysis of EWQI was assessed by the individual removal of EC, NO_3, NH_4, TP and turbidity in calculation of an overall index. EWQI is largely affected by the turbidity of water as removal of this parameter led to an increased frequency of EWQI, which shifted from “marginal” to “fair” score at the sites presented at Figure 4.6. The high turbidity of water characterises many South African rivers, as it is linked to naturally occurring soil types (CSIR, 2010). The removal of NO_3, NH_4 and TP resulted in an increase of the index score, but the score of the WQI remained in the range of “marginal” and “fair”. For example, in the ten sites out of eleven sites, the removal of turbidity in index computation results in an increased index. However, the contribution of turbidity to EWQI was weak at site S5, which had most of the parameters exceeding their objectives. The removal of each of the other variables (temperature, EC and TSS) led to a decrease of EWQI. Because for these variables, few records failed to meet the targets. These results highlighted the relevance of the number of water variables in the final index score (Rickwood and Carr, 2009).

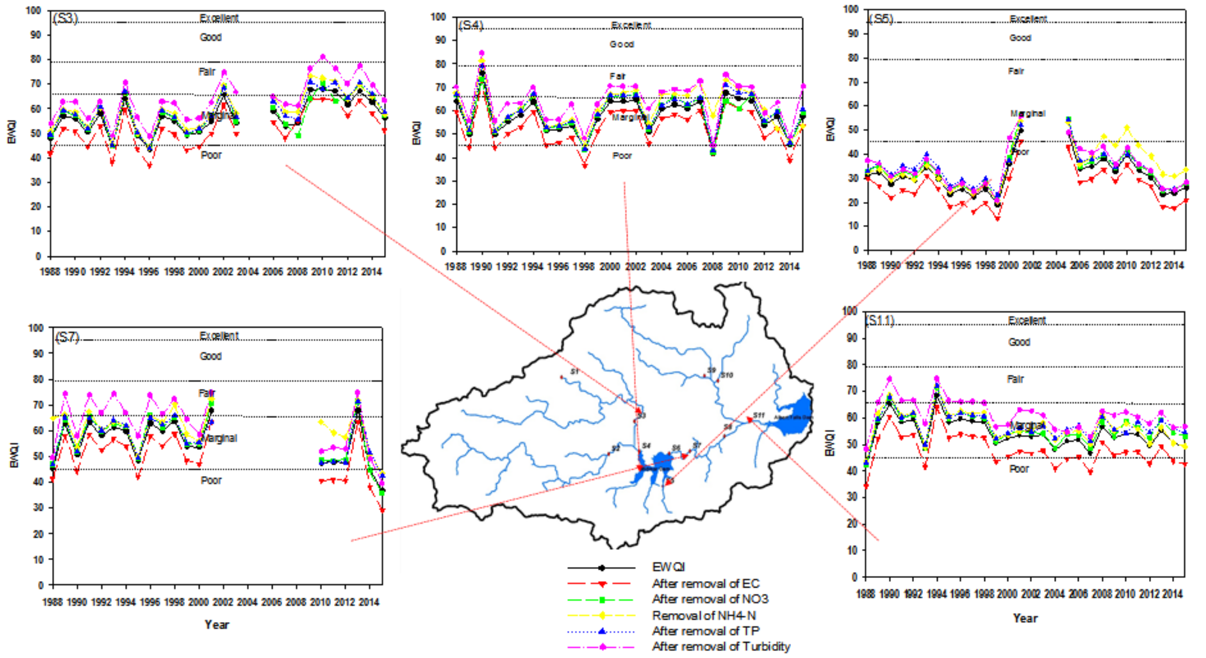

Figure 4.6 Sensitivity analysis of EWQI after removal of EC, NO3-N, NH4+, TP and turbidity concentrations in index computation in five selected sampling sites for water quality data collected from 1988 to 2015

In summary, the selection of water parameters, water quality standards/guidelines and occurrence of exceedance of the objective are the key factors which determine the sensitivity of WQI. This has provided useful information on the determination of the variables lowering WQI scores for both the recreational and eutrophication WQIs. The Canadian WQI system has advantages of application in data scarce areas, as four measurements are sufficient to calculate an annual index. However, the existing monitoring programme in the catchment could not change to fit the requirements of this index (CCME, 2006). The seasonal variation of WQI can also be calculated, using this index, but this was not part of this study, due to the poor quality of the available long-term dataset (28 years).

4.5 Conclusion and Recommendations

The aim of this study was to assess the effect of water quality monitoring frequency on water pollution reporting in the upper reaches of uMngeni Catchment, using a 28-year water quality dataset collected by UW from 1988-2015. Recreational and eutrophication indices of uMngeni River and its tributaries were developed based on the CCME WQI system to assess water quality deterioration in the area. A general decline of the monitoring frequency resulted in higher values of WQI than would be otherwise attained. In the catchment, water quality ranged between “marginal” and “fair” apart from the Mthinzima Stream draining Mpophomeni Township, with “poor” score. Across the catchment, water quality deteriorates in space (from upstream to downstream) and fluctuated over time (from 1988 to 2015) within the sites. However, lack of water monitoring data at sites (S7, S8, S9 and S10) downstream of Midmar Dam for the period after 2000 was a major challenge. This implies that water quality is poorer than reported.

A sensitivity analysis of WQIs showed that *E. coli* and turbidity were the key parameters affecting the recreational and eutrophication WQIs in the catchment. It was indicated that over 90% of monitored stations have *E. coli* levels exceeding the limits for human contact of water (≤250CFU/100mL). These results are consistent with other research studies carried out in this catchment, which indicated the bacteriological pollution putting serious public health risks in contact with uMngeni River waters and high turbidity of water of South African rivers (Kienzle *et al.*, 1997; Naicker, 2010; Lin *et al.*, 2012).

As no single water parameter, can characterize the status of the quality of a water body, these results highlight a need for continuous and long-term water quality monitoring programmes in the catchment. In addition, the WQIs are supporting tools to summarise large water quality datasets and provide information understandable by scientists, water suppliers, planners, policy makers and the public. However, information provided by using of WQIs is inconclusive without hydro-morphological and biological data and, as shown in this study, may be compromised by declining monitoring frequency. Moreover, reporting of WQIs outputs must be supported by scientific, traditional and local knowledge. Thus, WQIs should not substitute other methods of water quality data interpretation.

Given the importance of frequent samplings to adequately reflect water quality, the study recommends that a combination of event-based and spot sampling programmes could provide more conclusive information on the current range and status of water quality in the catchment. Event-based samplers should be installed on the major tributaries of the uMngeni River (Lions and Karkloof) and at the point of uMngeni inflows to the large dams. Continuation of the weekly sampling frequency, which includes the sites downstream of the Midmar Dam could provide clarification on the sources of a declining quality of water at site S11. Lack of key water quality variables indicative of organic pollution, such as dissolved oxygen and biochemical oxygen demand, in Umgeni Water's data base hindered the use of other water indices such as the NSFWQI, UWQI, OWQI and the FWQI. Furthermore, a comparative study of UW inhouse WQI which was not accessible during this study and the CCME WQI could confirm the reliability of WQIs used.

4.6 References

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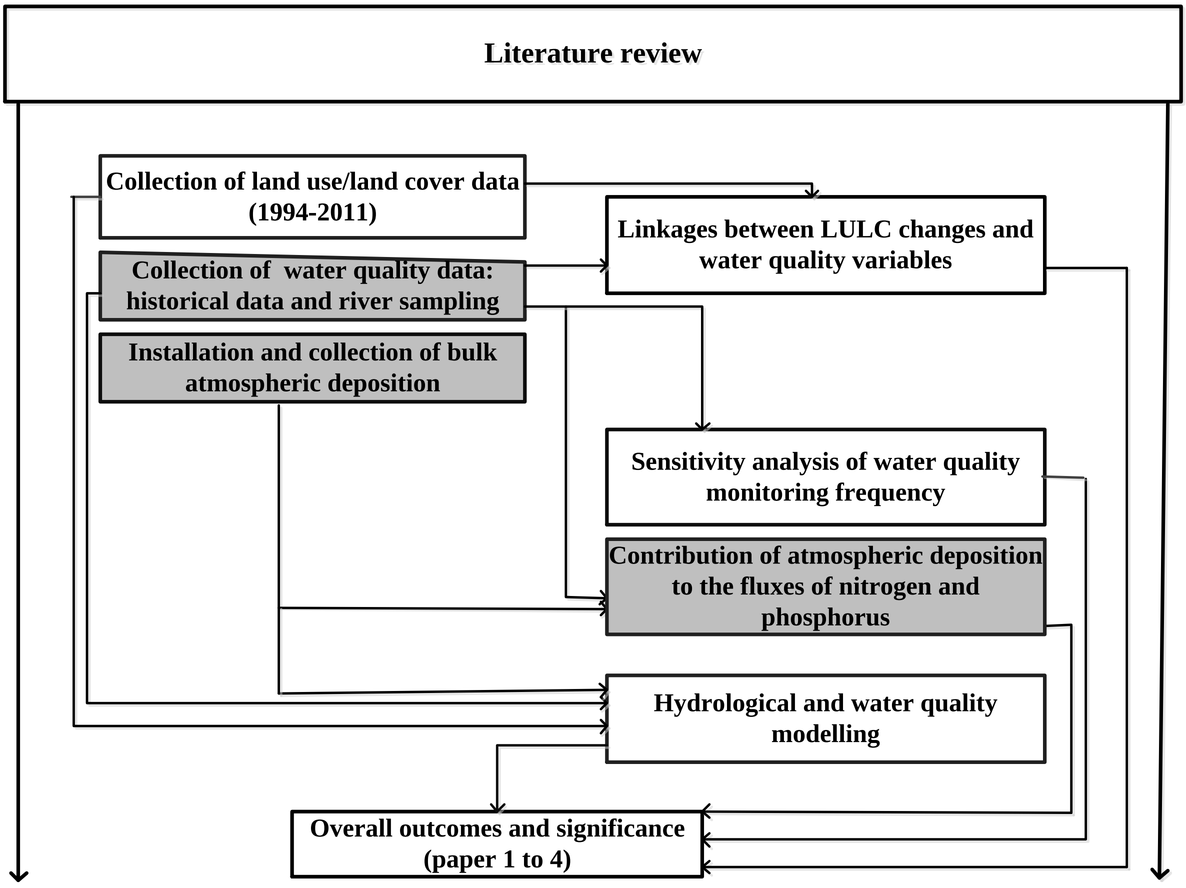
Preface to Chapter 5

The atmosphere and catchment link human activities and the hydrological cycle. LULC changes can alter the hydrological cycle and the chemical composition of the atmosphere (Chapter 3). Several studies on water quality monitoring of the uMngeni River and its tributaries were conducted using grab sampling of rivers (Chapters 3 and 4), but increased levels of nitrogen and phosphorus in water of the Midmar Dam may be under-estimated if the contribution of precipitation is ignored (Chapter 5). The most recent atmospheric deposition studies in the catchment were conducted three decades ago and since then the catchment has lost over 17% of its natural vegetation (Chapter 3). This chapter evaluates the contribution of bulk atmospheric deposition to loading of nitrogen and phosphorus into the Midmar Dam compared to river inflows.



CHAPTER 5: BULK ATMOSPHERIC DEPOSITION OF NITROGEN AND PHOSPHORUS IN THE MIDMAR DAM CATCHMENT, KWAZULU-NATAL, SOUTH AFRICA

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5.1 Abstract

Current research on water quality in the uMngeni Catchment has indicated a continuous decline throughout the catchment since records began and has raised the possibility of the eutrophication of the Midmar Dam in the near future. Typically, the mechanisms of groundwater and surface water pollution are the focus of the investigation. However, there is limited information on the relative contribution of bulk atmospheric deposition to the external nutrient inputs to Midmar Dam. A two-year study, involving fortnightly river sampling and the addition of bulk atmospheric collection of phosphorus and nitrogen, was carried out at 14 river sampling points and four atmospheric collection stations. Results showed that the concentrations of NO_3-N, NH_4-N and TP are higher in the bulk deposition than in the surface inflows, indicating the potential of a substantial contribution of atmospheric deposition to the nutrients entering the dam. Moreover, bulk atmospheric deposition was the largest source of NH_4-N load to the Midmar Dam, while TP and NO_3 come mainly from surface inflows. A slight increase in the atmospheric deposition rate of nitrogen and phosphorus over the study period was noted in the catchment, coinciding with a decline of riverine nutrient inputs to the dam, which can be ascribed to the severe drought experienced by the region during the period of this study.

Key words: *Bulk atmospheric deposition; eutrophication; nutrient specific flux; reactive nitrogen; water quality deterioration*

5.2 Introduction

The biogeochemical cycle of nitrogen is mainly controlled by atmospheric reactions, as well as geological and biological processes, before it is modified by anthropogenic activities (Canfield *et al.,* 2010; Lassaletta *et al.,* 2013). Atmospheric deposition and runoff directly link people to rivers, estuaries and oceans through the nitrogen cycle (Galloway *et al.,* 2004). The development of industry and new agricultural techniques has resulted in the increased use of fertilizers and the subsequent release of reactive nitrogen, causing acidification, the eutrophication of freshwater and estuaries, the emission of nitrous oxide into the atmosphere and related human health problems (Galloway *et al.,* 2003, 2008; Canfield *et al.,* 2010). It is particularly notable that the quantity of reactive nitrogen (Nr) production greatly exceeds the rate of its removal from the environment through the denitrification process (Galloway *et al*., 1995, 2003). Reactive nitrogen (Nr) is understood to include all forms of nitrogen (ammonia, ammonium, inorganic oxidized forms: NOx, HNO_3, N_2O, NO_3, urea, amines, proteins and nucleic acids), but excluding N_2 (Galloway *et al.*, 2003; Liang *et al.*, 2015).

Historically, from 1860 to 2000, dramatic increases in the atmospheric deposition of nitrogen have been noted in the northern hemisphere (Vitousek *et al.*, 1997; Galloway *et al.*, 2003), in contrast to the southern hemisphere, where human-linked nitrogen supply activities are less prevalent (Galloway, 1998). The highest atmospheric deposition of nitrogen in the world, i.e. 40-90 $kgN.ha^{-1}.yr^{-1}$, occurred in the Netherlands in 1996, the most densely populated country in Europe (Vitousek *et al.*, 1997). Vitousek *et al.* (1997) noted that this figure is much higher than the average nitrogen deposition rate of 0.1-0.7 $kgN.ha^{-1}.yr^{-1}$ in the southern hemisphere.

Mobile forms of nitrogen play a major role in the control of species diversity (Baron *et al.*, 2014), as well as their dynamics and functioning in terrestrial and aquatic ecosystems (Vitousek *et al.*, 1997; Galloway *et al.*, 2003). For example, Vitousek *et al.* (1997) and Baron *et al.* (2014) reported that increases of nitrogen deposition result in species reduction in a natural environment. Consequently, a critical nitrogen load of 5-10 $kgN.ha^{-1}.yr^{-1}$ has been used to prevent species reduction (Erisman *et al.,* 2013).

In 2003, it was reported that the atmosphere and agroecosystems receive 15% and 75%, respectively, of human-produced nitrogen, while industrial processes use approximately 10% (Galloway *et al.*, 2003). The two sources of nitrogen differ between regions, for example, human activities dominate in Northern America, Asia, Europe and the former Social Soviet Union, while the biological nitrogen fixation process is dominant in Africa and Latin America (Galloway *et al*., 2004). In the absence of anthropogenic activities, biological fixation is the main source of reactive N (Galloway *et al*., 1995). Nitrogen footprint calculation has been applied in many countries, including the Netherlands and the USA (Leach *et al.*, 2012), UK (Stevens *et al*., 2014), Japan (Hideaki *et al.*, 2014), China (Gu *et al.*, 2013) and Tanzania (Hutton *et al.*, 2017), to highlight the issue. These studies are aimed at informing the population on the effects of food consumption on nitrogen discharge to the environment, but there is still limited information on the African continent.

5.2.1 Atmospheric deposition as a source of nutrients

Direct atmospheric deposition as bulk is an important source of nitrogen and phosphorus in rivers and estuaries (Galloway *et al*., 2003). Deposition is affected by a number of factors, such as vegetation, land management practices, topography, climate and location (McDowell and Sharpley, 2009). However, the accumulation of Nr in rivers and associated wetlands is small, compared to its removal by denitrification. The denitrification process in rivers depends on river hydro-morphology, river size, riparian vegetation and water residence time. The rate of Nr removal from small to large river reaches ranges from 30 to 70% (Galloway *et al*., 2003).

In contrast to nitrogen, phosphorus is a non-renewable resource that is unevenly distributed across the globe, with over 90% of the planet's phosphorus reserves found in China, USA, Morocco, Western Sahara and Russia (Cordell *et al*., 2009; Ott and Rechberger, 2012). It has a short residence time of three days in the continental atmosphere, which makes it easily available in precipitation (Mahowald *et al*., 2008). The phosphorus concentration in the atmosphere is small (Graham and Duce, 1979) and its deposition differs, as it does not exist in a stable gaseous phase in the earth's atmosphere (Mahowald *et al*., 2008). As a result, few published papers have included the atmospheric component of phosphorus in the biogeochemical cycle (Graham and Duce, 1979). Globally, it is estimated that atmospheric deposition contributes up to 10% of dissolved phosphorus to the oceans, while 90% comes from river flow (Graham and Duce, 1979). In sub-Saharan Africa, 75% of the agricultural land has insufficient soil nutrients and an increase in phosphate fertilisers utilisation is ongoing in many countries to boost crop yield and to feed the 30% undernourished population (Cordell *et al*., 2009).

5.2.2 Atmospheric deposition investigations in Africa

While a large data set of information on rainfall chemistry is available for northern hemisphere countries (Europe, Canada and the USA), limited information is available for most African countries (Bootsma *et al*., 1999; Josipovic *et al*., 2011; Erisman *et al*., 2013). Atmospheric deposition has been reported to account for 55% of the phosphorus input to Lake Victoria (the largest world's tropical lake shared by Tanzania, Uganda and Kenya) (Prepas and Charette, 2004; Tamatamah *et al*., 2005). In Lake Kivu, surface inflows and atmospheric nutrient inputs to the lake were equal (Muvundja *et al*., 2009), while in Lake Tanganyika, 83% of dissolved inorganic nitrogen (DIN) and 63% of total dissolved phosphate (TDP) came from wet deposition (Langenberg *et al*., 2003). Several studies showed that the DIN (NH_4^+-N and NO_3^--N) are dominant in wet deposition, while phosphorus dominates in dry deposition (Muvundja *et al*., 2009; Markaki *et al*., 2010; He *et al*., 2011; Yu *et al*., 2014; Liang *et al*., 2015). However, in Lake Malawi, both the DIN and phosphorus were low in wet deposition samples (Bootsma *et al*., 1999).

Investigations into the atmospheric deposition of phosphorus and nitrogen in South Africa and in the uMngeni Catchment in particular, have been carried out previously (Hemens *et al*., 1977; Breen, 1983). In 1976, Hemens *et al*. (1977) estimated a deposition rate of 9.85 $kgTN.ha^{-1}. yr^{-1}$ and 0.348 $kgTP.ha^{-1}. yr^{-1}$, while Breen (1983) found 7.88 $kgTN.ha^{-1}.yr^{-1}$ and 0.374 $kgTP.ha^{-1}.yr^{-1}$ in the Midmar Dam catchment. Phosphorus and nitrogen loads in the Roodeplaat Dam catchment, north-east of Pretoria City, were lower in surface inflows than in bulk deposition, due to the high retention rate of nutrients in the catchment (Bosman and Kempster, 1985). A bulk deposition rate of 0.81 $kg.ha^{-1}.yr^{-1}$ of phosphorus was estimated at Pela, Western Cape Province (Brown *et al*., 1984). At Skukuza, in the Kruger National Park, Mpumalanga Province, a wet deposition rate of 2.8 $kgN.ha^{-1}.yr^{-1}$ was calculated (Mphepya *et al*., 2006). Average concentrations of ammonium and nitrate of 0.45 $mg.L^{-1}$ and 1.38 $mg.L^{-1}$, respectively, were measured in precipitation samples collected in rural and industrial sites of Mpumalanga Province (Mphepya *et al*., 2004). Mphepya *et al*. (2004) and Nyaga *et al*. (2013) stated that the specific fluxes of 4.8 $kg.ha^{-1}.yr^{-1}$ for TN and 0.16 $kg.ha.year^{-1}$ for TP, measured in bulk atmospheric deposition in the West Coast National Park in the Western Cape, were ascribed to urban expansion, agricultural activities and phosphate mining. Nonetheless, South

Africa is among the few countries in Africa with atmospheric deposition monitoring stations and is home to three of the ten IFAD atmospheric networks (The French contribution to the International Global Atmospheric Chemistry/Deposition of Biogeochemically Important Trace Species (IGAC/DEBITS)) program for Africa, located at Louis Trichardt, Amersfoort and Cape Point (Laouali *et al*., 2012), respectively.

These findings indicate that the atmospheric deposition of nitrogen is of great importance (Fenn *et al*., 2009; He *et al*., 2011; Pan *et al*., 2012; Yu *et al*., 2014; Liang *et al*., 2015). However, there is limited information on the atmospheric deposition of nutrients for the Midmar Catchment, with only a few studies in the catchment having been carried out, i.e. in 1976 and 1982 (Hemens *et al*., 1977; Breen, 1983). Thus, our goal was to assess the contribution of bulk atmospheric deposition to nitrogen and phosphorus fluxes in the Midmar Dam Catchment, when compared to the inputs from rivers. Our specific aims were:

(1) to assess the seasonal and spatial variation of dissolved inorganic nitrogen (nitrate and ammonium nitrogen) and phosphorus (total phosphorus and soluble reactive phosphorus) concentrations in precipitation and major rivers, feeding Midmar Dam,

(2) to provide estimates of external phosphorus and nitrogen fluxes and loads in the Midmar Dam catchment area; and

(3) to improve the level of understanding of other possible sources of increased nutrient levels in the Midmar Dam.

5.3 Material and Methods

5.3.1 Direct methods of atmospheric deposition collection

A number of methods for monitoring atmospheric deposition have been developed worldwide, as discussed in Fenn *et al.* (2009). However, only three of the most commonly-used direct methods are briefly presented here, one of which was selected because of its simplicity, its low cost of maintenance, and the deployment of instruments.

Dry/wet deposition: This consists of a dual automated sampler of dust and precipitation in two separate buckets. The event based collection of rainfall samples applies, while the dry deposition samples are collected after one week, two weeks or one month (Yu *et al*., 2014). This method has been extensively used (He *et al*., 2011; Izquierdo and Avila, 2012; Yu *et al*., 2014; Liang *et al*., 2015). However, this collector requires an electricity supply, which is not available in most of the remote areas of developing countries.

Wet-only deposition: The collection device is designed with a sensor, which opens the lid when rainfall occurs and closes again after the event (Staelens *et al*., 2005). An alternative manual wet-only collector, which needs a permanent operator is also used (Bosman and Kempster, 1985).

Bulk deposition collection: With this method, a combined sample of dry fallout and precipitation is collected in one container. The samples are collected following a weekly, bi-weekly or monthly interval (Hemens *et al.*, 1977; Markaki *et al*., 2010). This method is cheap, compared to the others, particularly in remote areas without electrical power (Cape *et al*., 2009; Izquierdo and Avila, 2012). However, its limitations are related to sample contamination by insects, the collection of local materials (Lovett, 1994), bird perching and defecation and the biological degradation of the sample (Fenn *et al*., 2009; Izquierdo and Avila, 2012). In some instances, biocides are used in sample preservation, though they are not generally recommended (Galloway and Likens, 1978). The combination of the two or more methods in atmospheric deposition monitoring was found to be relevant in the literature, owing to the reduction of uncertainties associated with each of the above-mentioned methods (Fenn *et al*., 2009; Izquierdo and Avila, 2012). The underestimation or overestimation of nutrient fluxes, using the bulk deposition (Lovett, 1994), dry and wet deposition methods alone were noted (Staelens *et al*., 2005; Anderson and Downing, 2006). Given the above considerations and the reality of the monitoring situation in Midmar, a bulk deposition approach was adopted.

5.3.2 Study area and sampling sites

This study took place in the Midmar Dam catchment, which is in the upper reaches of uMngeni catchment. The Midmar Dam catchment is situated between longitudes 29°78′ and 30°24′ East and latitudes 29°30′ and 29°63′ South, in the KwaZulu-Natal Province, South Africa (Figure 5.1). The topography of the area includes the Karkloof Mountain Range and the eastern extremities of the KwaZulu-Natal Midlands. Its geology consists of dolerite intrusion into the sandstone of the Vryheid formation, shale and sandstone of the Volksrust formation and shale, silt stone and sand stones of the Estcourt formation. Dystrophic soils, with sandy clay loam to clay and mesotrophic sandy clay loam to clay are the dominant soil textures (Land Type Survey Staff, 2001). Major land use and land cover types in 2011 were natural vegetation, cultivation and forestry plantations, which occupied 48%, 21% and 17%, respectively, while other land use types represent less than 15% of the catchment (EKZNW, 2013), see Figure 5.2. The annual rainfall across the catchment is highly variable, ranging between 600 mm to 1500 mm per annum, falling predominantly in January-March. The catchment is characterised by high evaporation which varies between 1567 and 1737 mm per annum. The average annual temperature ranges from 12 to 20°C. Predominant wind direction is south-easterly in summer and south-south easterly in the winter months, with occasional strong north-north-west winds associated with passing cold fronts in the dry winter months (PWS, 2016). A detailed description of the catchment is provided in Namugize *et al.* (submitted).

The population of the Midmar Catchment is predominantly rural, with pastoral activities, including sheep and dairy cattle, being practised in the Mpendle and Lions Rivers' sub-catchments. Economic activities are centred along the axis of the highway and railway line between Nottingham Road to Pietermaritzburg.

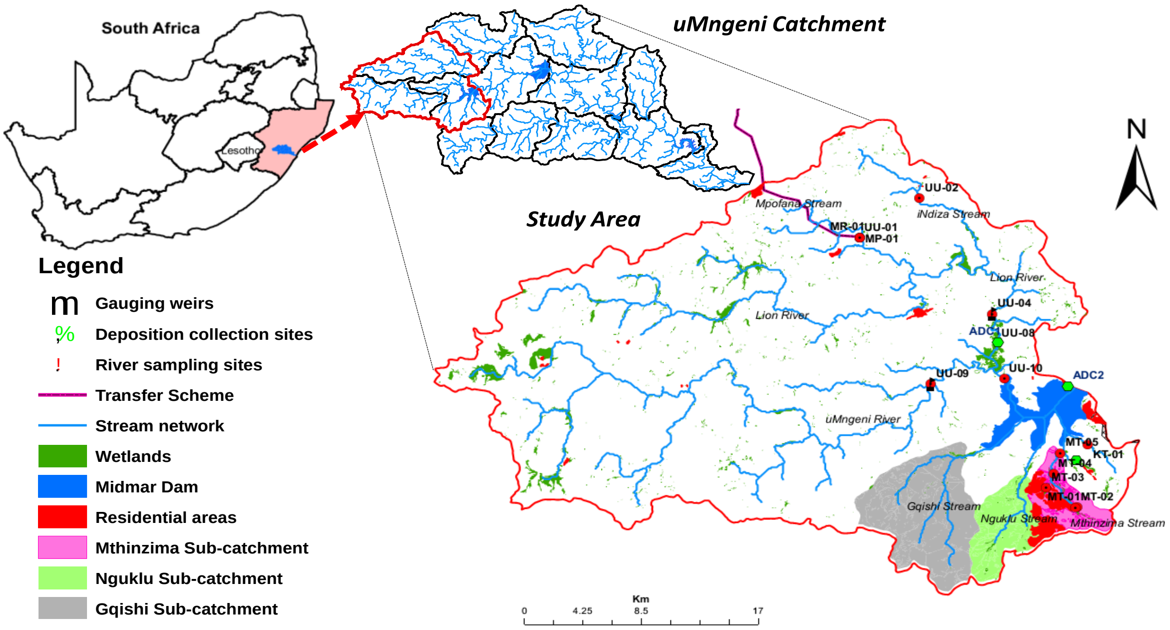

Figure 5.1 Location of the bulk deposition collectors and the river sampling sites along the uMngeni River and its tributaries, contributing to water quality of the Midmar Dam

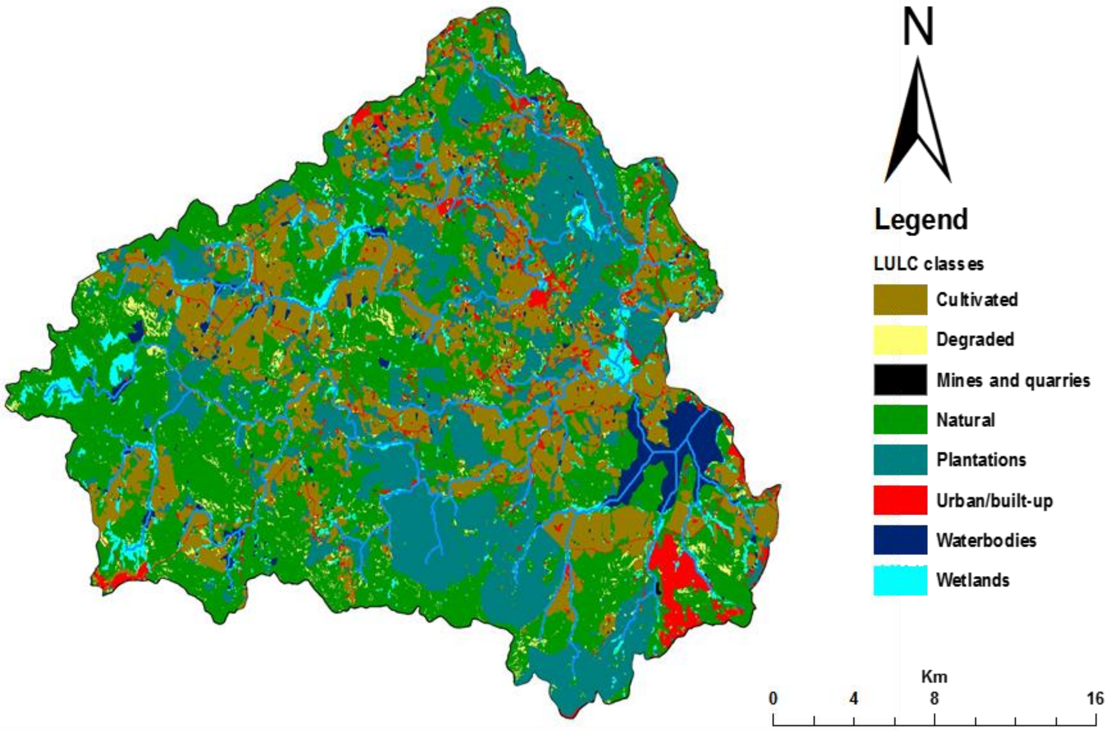

Figure 5.2 Distribution of land use and land cover classes in the Midmar Dam Catchment for 2011 (EKZNW, 2013)

5.3.3 Bulk deposition sampling

In this study, four locally-manufactured bulk atmospheric collectors, which consisted of a funnel (surface area = 452 cm^2) mounted at a height of 1.5 meters above the ground, and which were connected to a 20 litre polyethylene jerry-can, using a polyethylene pipe. To minimize sample contamination, the top of the funnel was covered with a polyester mesh (Figure 5.3). This follows the approach of Markaki *et al*. (2010), Izquierdo and Avila (2012) and Nyaga *et al*. (2013).

The equipment was placed on a flat area that had no obstacles, that was distant from foliage and residential houses, and that was kept open to the atmosphere, in order to collect the bulk deposition samples. Three Atmospheric Deposition Collectors (ADC) were installed in the catchment *viz.* ADC1 at the Lions River wetland, ADC2 at the Midmar Dam weather station (the same site used by Breen (1983) and Hemens *et al.* (1977)) and ADC3 in the Midmar Nature Reserve (south of Mpophomeni Township) (Figure 5.1). A further site, ADC4, was installed at the weather station of the School of Agriculture, Earth and

Environmental Sciences in Pietermaritzburg, approximately 25-30 km from Midmar Dam, as a control site. Rain water samples were collected in polyethylene bottles that had been pre-cleaned and rinsed with distilled water, from November 2014 to October 2016 on a bi-weekly basis. This coincided with the start of the rainfall season in the area, except in ADC4, where the sample was collected immediately after each storm event. ADC2 and ACD4 are located at the Midmar Dam wall and in the urban area of Pietermaritzburg, respectively. The other two sites (ADC1 and ADC3) are in sub-basins characterized by grassland and forest plantations. Several factors guided the selection of the three collection sites in the Midmar area, i.e. the accessibility of the site, the security of equipment, minimal disturbance by human activities, the distance from the road infrastructure, and the availability of a rain gauge in the surrounding area. Sample preservatives were not used, to avoid their interference with the laboratory analytical methods (Galloway and Likens, 1978). When collected, samples were immediately placed in a cooler box, before being transported to the Umgeni Water laboratory for chemical analyses within 24 hours. During sample collection, any samples contaminated by bird defaecation or insects were rejected. After each sample collection, the mesh, the funnel and the jerry-can were cleaned three times with the distilled water in preparation for the next sample collection.

Figure 5.3 Device for the bulk atmospheric collector of nitrogen and phosphorus

5.3.4 River sampling

Grab sampling was carried out, following a bi-weekly sampling frequency (between June 2014 to May 2016), at 14 sampling points along the uMngeni River and its tributaries upstream of the Midmar Dam (the Mooi-uMngeni River transfer scheme, the Indiza Stream, the Lions River and the Mpofana River), as well as the Amhlanga Stream, which is the tributary of the Mthinzima and Khayalisha Streams flowing to the Midmar Dam (Ngubane, 2016). Seven of the fourteen sampling stations are already monitored by Umgeni Water (UW), a public water supplier entity in the catchment (Figure 5.1 and Table 5.1).

Table 5.1 Sampling sites along the uMngeni River, its tributaries and other streams contributing to water quality of the Midmar Dam

No	Site ID	Site description	Type of site	Northing	Easting
1	MP-01	Mpofana Stream upstream of the transfer scheme*	stream	-29.3890	30.0619
2	MR-01	Mooi River transfer scheme at the outlet pipe	pipe	-29.3890	30.0618
3	UU-01	Mpofana Stream downstream of the outlet pipe*	river	-29.3891	30.0618
4	UU-02	iNdiza Stream tributary of Lions River*	stream	-29.3613	30.1011

5	UU-04	Lions River at the weir	river	-29.4427	30.1487
6	UU-08	Lions River outlet in uMngeni*	river	-29.4628	30.1518
7	UU-09	uMngeni River at Petroos Stroom	river	-29.0918	30.1083
8	UU-10	uMngeni inflow to Midmar Dam	river	-29.4878	30.1562
9	MT-01	Mthinzima before crossing Mpophomeni Township *	stream	-29.5801	30.2039
10	MT-02	Mthinzima tributary in Mpophomeni wetland*	stream	-29.2691	30.1925
11	MT-03	aMhlanga Stream tributary of Mthinzima*	stream	-29.5546	30.1884
12	MT-04	Mthinzima tributary under the bridge	stream	-29.5645	30.1835
13	MT-05	Mthinzima river influent in the Midmar Dam	stream	-29.5402	30.1932
14	KT-01	Khayalisha influent to Midmar Dam*	stream	-29.5426	30.2106

*Sites were only monitored during this study, while others are included in the routine monthly water quality monitoring plan implemented by the UW

5.3.5 Analytical procedures

pH, electrical conductivity and temperature were measured on site, using a hand-held Combo pH/EC meter (HI 98129, Hanna Instruments Woonsocket RI USA), total suspended solids (TSS) and turbidity, using a HACH portable meter (HACH 1401072). The two instruments were calibrated regularly, before taking measurements. The above mentioned *in situ* water variables were not measured in bulk atmospheric deposition samples, due their small quantity.

The nutrient content of the bulk deposition and river samples were taken on the same day to the Umgeni Water and were analysed according to international standards in the UW ISO9001 accredited laboratories. A sub-sample of rainwater and a river sample were filtered through 0.45 µm filter paper for NH_4^+-N, NO_3^--N and SRP analysis, while an unfiltered sub-sample was digested for TP analysis. Analytical methods for nutrients analysis are presented in Table 5.2.

Table 5.2. Summary of analytical methods for nutrients analysis (APHA, 1999)

Parameter	**Method**	**Test procedure**	**MDL***
Ammonium nitrogen	Colorimetric	Reaction of water sample with hypochlorite ions to form monochloramine, reaction of monochlomine with salicylate ions (pH= 12.8) and formation of a green-coloured complex measured at a wavelength of 660 nm	0.10 mgN/L
Nitrate nitrogen	Ion Chromatography	Induced Coupled Plasma with a conductivity detector (ICP-CD)	0.10 mgN/L

Soluble Reactive Phosphorus (SRP)	Colorimetric	Reaction of orthophosphate ions with antimony potassium tartrate under acidic conditions to form a complex which is reduced by ascorbic acid and formation of a phosphor-molybdenum blue compound which is measured at a wavelength of 880mm	0.005 mgP/L
Total Phosphorus (TP)	Colorimetric	Digestion of unfiltered sample by persulphate acid in an autoclave for one hour at 121°C (to convert condensable and organic forms into orthophosphate, then, follow the ascorbic method as for SRP	0.015 mgP/L

*Minimum detection limit of the method

5.3.6 Data acquisition and processing

Nutrient specific fluxes in the bulk deposition (N_f, $mg.m^{-2}$. $month^{-1}$) were computed as a product of the average monthly concentration (C_m, µg. L^{-1}) with cumulative monthly precipitation (P_m, mm. $month^{-1}$), following the approach of several authors (Anderson and Downing, 2006; He *et al*., 2011; Zhu *et al*., 2015) (Equation 5.1). An annual nutrient specific flux from the atmosphere was obtained by summing the monthly specific fluxes for each site.

$$\mathrm{N_f = 10^{-3} x C_m x P_m} \qquad (5.1)$$

The annual atmospheric loading of nutrients to the Midmar Dam surface was calculated as a product of the average annual nutrient specific flux measured at Site ADC2, located at Midmar wall and the dam surface area (dam area of 1793.15 ha) (DWS, 2016), as presented in Equation (5.2).

$$\mathrm{N_{Load} = N_f \, x \, A} \qquad (5.2)$$

Where N_{Load} = annual nutrient loads to the Midmar Dam surface (kg) and A= Midmar Dam surface area (ha).

As the bulk atmospheric samples were collected over a period of two years, the annual nutrient specific fluxes were calculated for the period from November 2014 to October 2015 and November 2015 to October 2016.

In assessing the spatial and temporal variability of the concentration of nutrients throughout the river sampling sites, water quality data were grouped into two seasons, namely, the low rainfall months, i.e. the dry season (from April to September) and the high rainfall months, the wet season (from October to March). Descriptive statistic methods were used to calculate the seasonal mean, as well as the maximum, minimum and standard deviations for each sampling site. Dissolved Inorganic Nitrogen (DIN) was calculated as the sum of NH_4-N and NO_3-N. In estimating the dominant form of phosphorus, we assumed that the total phosphorus equals SRP + Particulate Phosphorus. Therefore, the ratio SRP/TP has been used.

River nutrient loads were computed as a product of the cumulative monthly streamflow and average monthly concentration of the chemical determinant for the two-year study period. The annual load was then a sum of the monthly loads. Due to a lack of stream flow data at site UU-10 (the inflow of Midmar Dam), the overall nutrient flux to the Midmar Dam was assumed to be the product of the sum of stream flows at two upstream sites (UU-04 and UU-09), with the mean monthly nutrient concentration measured at site UU-10 (the inflow of the Midmar Dam). The Lions and uMngeni Rivers are the major flows to the Midmar Dam, having functional gauging weirs and they provide over 70% of the total runoff entering the Midmar Dam (Breen, 1983). The remainder of runoff originates from the Gqishi, Nguklu and Mthinzima Streams, the gauging weirs of which have been abandoned (Ngubane, 2016). Streamflow data were acquired from the web page of the Department of Water and Sanitation (www.dwa.gov.za/Hydrology/hymain.aspx). Rainfall records from the two standard rain gauges were provided by Umgeni Water and the Agro-meteorology Instrumentation Mast system data of the School of Agriculture, Earth and Environmental Sciences.

5.4 Results and Discussion

5.4.1 Nutrient content in bulk atmospheric deposition

Nitrates are the dominant form of DIN in the bulk deposition of nitrogen in the three stations (ADC1, ADC2 and ADC3), with concentrations ranging between 0.62±0.41 at ADC1 and 0.84±0.72 mgNL at ADC3 (Table 5.3). However, at Site ADC4, the NH4 was dominant in the precipitation samples (0.76±1.38 $mg.L^{-1}$). The ammonium content of rainfall fluctuated between 0.34±0.28 at ADC2 and 0.76±1.38 $mg.L^{-1}$ at ADC4. These values of NO_3 and NH_4 are comparable to the findings of Bosman and Kempester (1985) in the Roodeplaat Dam area, South Africa. However, the range of arithmetic means values of NH_4+ and NO_3- at the three sites of the Midmar Dam Catchment (ADC1, ADC2 and ADC3) presented in Table 5.3 are high, in comparison to 0.295 $mgN.L^{-1}$ of NH_4^+-N and 0.259 $mgN.L^{-1}$ of NO_3 found at the Vryheid long-term precipitation chemistry monitoring site, located in a coal mining area of the KwaZulu-Natal Province, South Africa (Josipovic *et al*., 2011).

Moreover, in atmospheric studies, the ratios of NH4/NO_3 have been used to identify the source of reactive nitrogen. When the ratio is greater than 1, agricultural activities are the major source, whereas the ratio lower than 1 indicates that Nr is mainly emitted from industrial activities (He *et al*., 2011; Zhu *et al*. 2015). In this study's area, the ratio of NH4/NO3 ranged between 0.6 and 0.7 at Sites ADC1, ADC2 and ADC3, whereas it was approximately 1.4 at Site ADC4. These results showed that the levels of DIN in Midmar Catchment are largely related to industrial activities, while they were influenced by agricultural activities at ADC4. However, this lower ratio NH_3/NO_3 in the Midmar Sites, as well as the significant variations in the concentrations of inorganic nitrogen and phosphorus in the bulk atmospheric samples (high standard deviations) may be ascribed to: (1) volatilisation or microbial assimilation in open atmospheric collectors, (2) possible traffic congestion, (3) movement of air masses from other regions; and (4) interval of sample collection (Fenn *et al*., 2009, Nyaga *et al*., 2013).

The average values of SRP ranged between 9.4 and 15.1 µgP.L^{-1} at the sites surrounding the Midmar Dam with the highest value of 18.2 µgP.L^{-1} at Site ADC4, in the urban area of Pietermaritzburg. As it was for SRP, the highest average TP of 83.3±72.8 µgP.L^{-1} was noted at Site ADC4 and the lowest values were noted at Sites ADC1, ADC2 and ADC3. An attempt was made to estimate the dominant form of phosphorus in the bulk precipitation samples. Results showed a small ratio SRP/TP (around 80% in particulate phosphorus) in bulk deposition, which indicates that most phosphorus is in organic form, which is not easily available to the plants. These results are consistent with the results of Brown *et al.* (1984) in South Africa and Anderson and Downing (2006) in USA.

Table 5.3 Average nutrient concentrations in atmospheric deposition samples collected, from November 2014 to October 2016, where SD is the standard deviation and n: number of observations

	NH_4-N (mgN.L-1)		**NO_3-N (mgN.L^{-1})**		**SRP (µgP.L^{-1})**		**TP (µgP.L^{-1})**	
Stations	*Mean±SD*	*n*	*Mean±SD*	*n*	*Mean±SD*	*N*	*Mean±SD*	*n*
ADC1	0.36±0.29	33	0.62±0.41	31	9.4±18.5	31	53.1±34.5	29
ADC2	0.34±0.28	25	0.73±0.45	24	14.4±24.6	23	52.7±51.2	24
ADC3	0.38±0.31	27	0.84±0.72	25	15.1±41.2	25	52.5±24.6	25
ADC4	0.76±1.38	25	0.63±0.38	23	18.2±24.2	24	83.3±72.8	23

An assessment of the seasonal variation of DIN concentrations of bulk deposition indicated peak NH_4^+-N during the high precipitation months from November to March, which was consistent with other findings in the literature (Yu *et al*., 2014). One possible conclusion that can be drawn from this is that high temperature speeds up NH_4^+-N volatilisation and it is possible that fertilizer application in summer increases the release of NH_4^+-N into the atmosphere (Yu *et al*., 2014). Peak NH_4^+-N deposition can also be attributed to biomass burning, emissions from animal excrements and agricultural activities in the catchment (He *et al*., 2011; Yu *et al*., 2014). A temporal variation of dominant forms of nitrogen between NO_3^--N and NH_4^+-N was noted in all the sites, with an overall greater concentration of nitrate, in comparison to ammonium in the bulk precipitation samples. However, this difference was not significant, as NH_4^+-N accounted for over 31% of DIN concentration in all sites (see Table 5.3 and Appendix 5.A). Substantial levels of NH_4 in bulk deposition are also attributed to its high solubility in rainwater, as reported in other studies (Mphepya *et al*., 2006; Pan *et al*., 2012).

5.4.2 Water quality of rivers

The pH of water along the catchment is slightly alkaline, ranging between 7.2 ±0.4 and 7.6 ± 0.6, which has been established in other research studies in the catchment (Manickum *et al*., 2014; Namugize *et al*., submitted). Higher variability in water temperature throughout a year ranged between 15.8 ± 4.3 and 21.7 ± 4.5 at Sites UU-02 and MT-03, respectively. The lowest water temperatures of 7.6°C and 7.9°C at Sites UU-01 and UU-02 and the highest temperature of 31.4°C at MT-04 and KT-01 were recorded.

The electrical conductivity (EC) of water ranged between 11.8 ± 15.1 mS/m and 19.7 ± 20.8 mS/m in ten of the fourteen sites and there were high levels of 59.6 mS/m, 56.1 mS/m and 46.9.4 mS/m at Sites MT-04, MT-03 and MT-05, respectively (Appendix 5.B). Low EC indicates the low salinity of water in the catchment (Graham, 2004). In all sites, with the exception of Sites UU-02 and UU-09, the turbidity was higher, exceeding 10 mS/m. The high turbidity of water is characteristic of silt and clay soil types, which are dominant in the catchments of many South Africa rivers (CSIR, 2010). TSS was also high in the sites located in Mpophomeni sub-catchment, because of human disturbance and stray livestock. However, Sites UU-02 and UU-09 had TSS values less than 100 $mg.L^{-1}$, contrary to sites along the Mthinzima, aMhlanga and Khayalisha Streams. Along the Mthinzima Streams there was an increase of EC, turbidity and TSS from MT-01 to MT-03 and a sharp decline from MT-03 to MT-05, at the inflow of the Mthinzima Stream to the Midmar Dam (Appendix 5.B).

The NH_4^+-N and NO_3-N contents of water are still low across the catchment, except for the Mthinzima and Amhlanga Streams in Mpophomeni (MT-2, MT-03, MT-04 and MT-05) and at Site UU-08 on the Lions River, before flowing into the uMngeni River (Appendix 5.C). This is in comparison to the South African guidelines for the protection of aquatic ecosystem and eutrophication, developed at the Department of Water Affairs and Forestry i.e. 0.5 mg /L of inorganic nitrogen (DWAF, 1996). These results provide more clarification on the impact of dysfunctional sewer systems and the illegal dumping of waste in the Mpophomeni sub-catchment (GroundTruth, 2012; Namugize *et al*., submitted; Ngubane, 2016). The seasonality affects the two forms of nitrogen in water differently: the ammonium content of water is high in the dry season, while the relationship of nitrate is inconsistent and fluctuates among the sampling sites (Figure 5.4).

The water quality of rivers in the two dry seasons monitored behaved differently for SRP, i.e. the highest concentrations occurred in the 2014 dry season, while the lowest were noted in the 2015 dry season (Figure 5.4). This could be a consequence of the severe drought experienced in the catchment, from 2015-2016, which could have changed the hydrological processes and water quality dynamics (UNEP-GEMS/Water, 2008; Biazin and Sterk, 2013).

The spatial variation of water quality showed that the Mpofana River (MP-01) has the highest content of TP (54.5±50.7 $\mu gP.L^{-1}$) and this decreases after mixing with MR-01 (the Mooi-Lions River transfer scheme) at UU-01. Downstream, the Indiza tributary (UU-03) provides considerable levels of TP (45.6±47.3 $\mu gP.L^{-1}$), as illustrated by an increase at Site UU-04 (at the Lions River weir). The high concentrations of ammonium noted at outflow of Lions River wetlands (UU-08) may be ascribed to the hydro-morphological properties of the river in the wetland, owing to the anaerobic reduction of nitrate to ammonium in the alkaline pH conditions of the water (pH= 7.4±0.5) (Choe *et al*., 2004). However, in this Lions River wetland, the water content of TP reduces from upstream to downstream. These results highlight the important role of wetlands in pollutant retention (Mitsch and Gosselink, 2000; Bristow *et al*., 2010; Ndlovu, 2015). High levels of nitrate come from the uMngeni River at Petrus Stroom (UU-09), while TP, SRP and NH_4^+-N originate largely from the Lions River.

However, the Mthinzima Stream is a major source of pollution to Midmar Dam, as indicated by the largest levels of nutrients at site MT-05 (Figure 5.4). In the Mthinzima sub-catchment, stream water chemistry is good at headwaters (MT-01), declines in the middle reaches and then improves (MT-05) as it passes through the wetland, which highlights its role in the retention of pollutants, as mentioned above (Figure 5.4). However, concentrations of all forms of phosphorus and nitrogen entering the Midmar Dam at MT-05 are still higher than the eutrophication and recreational standards. The Amhlanga Stream (MT-03), a tributary of Mthinzima carries sewerage spilling from dysfunctional manholes in the Mpophomeni Township and is a major concern (Ngubane, 2016). The concentrations of NH_4 and NO_3 at Site KT-01 are below the eutrophication threshold limit (DWAF, 1996), but there are large levels of total phosphorus (75.1±57.3 $\mu gP.L^{-1}$). Water quality data collected at this site (KT-01) can serve as background information for the new government low cost housing project that is expected to be implemented in the Khayalisha area. The high variability of river water chemistry, which is shown by the high standard deviations within the sites, indicated that water quality in the catchment was relatively unstable.

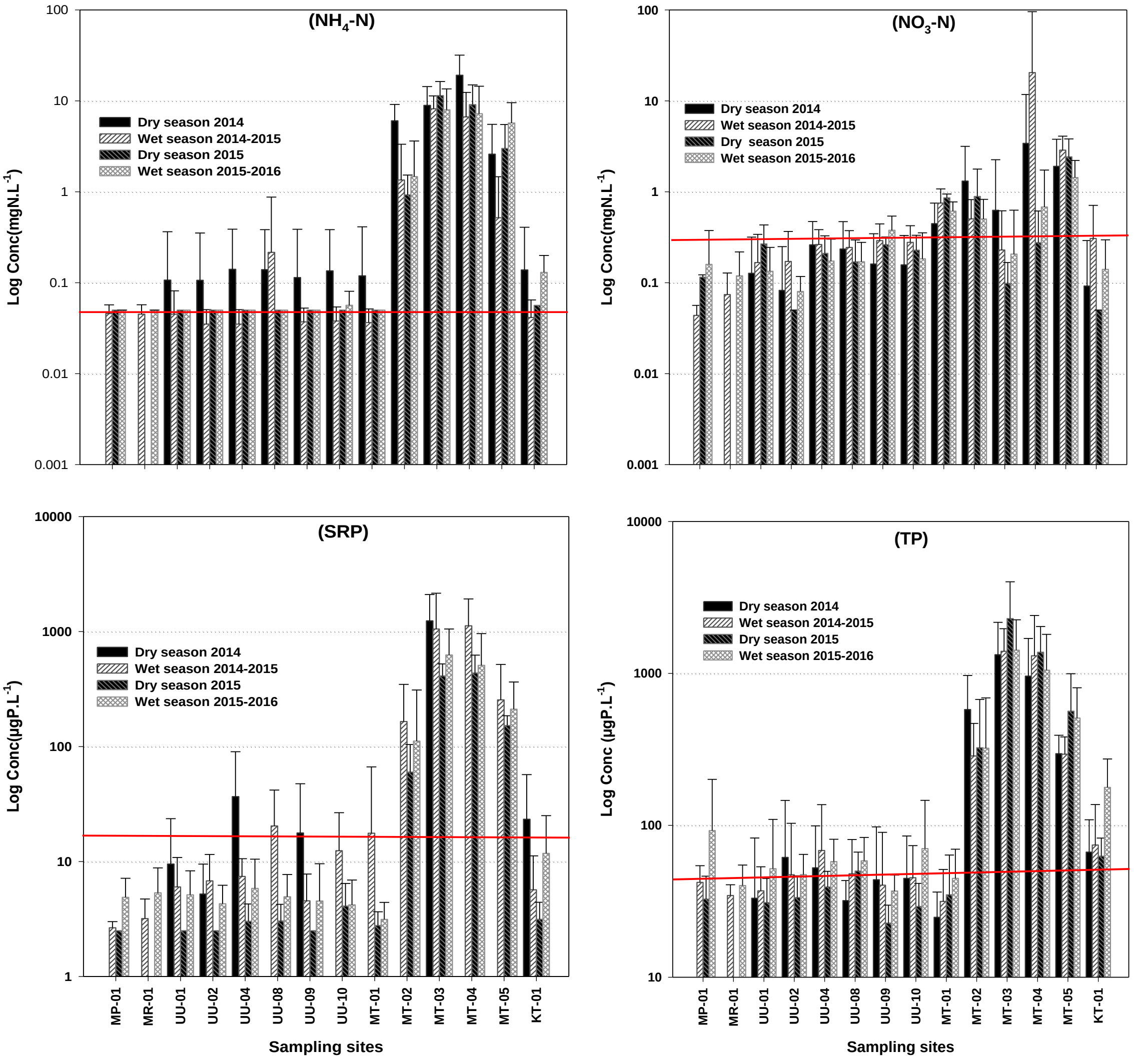

Figure 5.4 Seasonal variation of nutrient concentrations in the upper uMngeni River and its tributaries (at log scale). The red line indicates the reference to eutrophication target of the Department of Water Affairs and Forest (DWAF)

Apart from the river sampling sites located in the Mpophomeni Township (MT-01 to MT-05 and KT-01), the concentrations of NH_4, NO_3 and TP of bulk precipitation were higher than those in the runoff (Appendix 5.A, Table 5.3, Figures 5.4 and 5.5). The most probable sources of the high levels of phosphorus and nitrogen in bulk deposition could be: (1) the common practice of biomass burning during the winter months; and (2) atmospheric dust deposition from agricultural practices. The low levels of phosphorus and DIN in river samples could be ascribed to the low risk of soil erosion and the phosphorus-retention properties of the soil in the catchment (Breen, 1983). Overall, these results highlight the important contribution of atmospheric deposition to the high levels of nitrogen and phosphorus of the large dams of the uMngeni Catchment.

5.4.3 Specific nutrient fluxes in bulk atmospheric deposition

The measured precipitation at the two standard rain gauges that were used during this research (2014-2016) was 793 mm per annum and 828 mm per annum at Midmar Dam and 712 mm per annum and 560 mm per annum at Pietermaritzburg. Higher rainfall occurs between November and March and lower precipitation is in May or June. The months with high rainfall events coincided with abrupt increases in ammonium and nitrate fluxes (Figure 5.5). Specific fluxes of ammonium varied between the stations and were 2.6 kgN.ha^{-1}.yr^{-1}, 2.7 kgN.ha^{-1}.yr^{-1}, 4.3 kgN.ha^{-1}.yr^{-1} and 5.2 kgN.ha^{-1}.yr^{-1} at ADC2, ADC3, ADC1 and ADC4, respectively. The corresponding annual DIN (NH_4 +NO_3) fluxes of 8.1 kgN.ha^{-1}.yr^{-1}, 8.0 kgN.ha^{-1}.yr^{-1}, 8.8 kgN.ha^{-1}.yr^{-1} and 10.4 kgN.ha^{-1}.yr^{-1} were also recorded. These DIN fluxes are greater with respect to other monitored sites in South Africa, for example, those located in the West Coast National Park (4.8 kg.ha^{-1}.yr^{-1}) (Nyaga *et al*., 2013) and as those measured at the Kruger National Park (2.8.kg.ha^{-1}.yr^{-1}) (Mphepya *et al*., 2006). However, the DIN fluxes of this study (8.0-10.4 kg.ha^{-1}.yr^{-1}) are smaller than the value of 7-14 kgN.ha^{-1}.yr^{-1} measured in the urban area around the Cape Town Metropolitan (Wilson *et al*., 2009). The high flux of DIN (10.4 kgNha^{-1}.yr^{-1}) at Site ADC4, could be attributed to industrial and traffic emissions in the urban area of Pietermaritzburg.

The flux of NH_4^+-N was high at Site ADC4, as the samples were collected after each rainfall event to minimize ammonium volatilization (Figure 5.5). Moreover, the high deposition of NH_4-N at ADC4 can also be attributed to agricultural activities in greenhouses in the proximity of the site. The higher values of NO_3 -N at the other three stations (ADC1, ADC2 and ADC3) could be a result of biological degradation processes in the continuously open samplers between collection times (Galloway and Likens, 1978), the presence of a dense population of wild animals (Site ADC3) and the bush burning (ADC1), which are known to be important sources of inorganic nitrogen . However, the difference between rural and urban areas was not significant in this study, suggesting that both rural and urban areas emit substantial amounts of nitrogen into the atmosphere, was also identified in China (Du and Liu, 2014). The results of this are consistent with the findings in Connecticut, USA (Nadim *et al*., 2001). It was noted that maximum fluxes of NO_3 and NH_4 occur during the summer, the period of much rainfall in the region (Figure 5.5). Sites ADC1 and ADC4 have recorded the highest fluxes of DIN (8.8kgNha^{-1}.yr^{-1} and 10.4 8 kgNha^{-1}.yr^{-1}), while the highest flux of TP (0.83 kgP.ha^{-1}.yr^{-1}) was recorded at Site ADC1. These levels of nitrogen at Site ADC4 can be attributed to the location of the site in the urban area of Pietermaritzburg, which is deemed to be the largest source of N emission and subsequent deposition during precipitation (Figures 5.5 and 5.6).

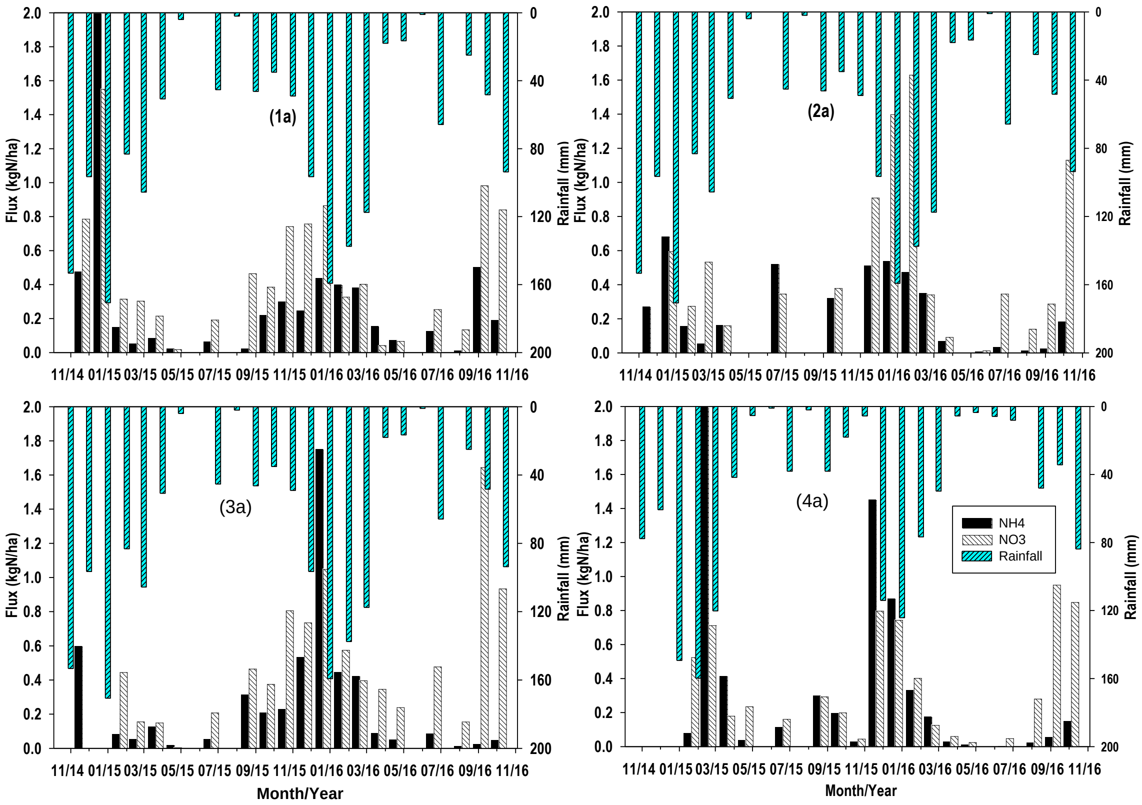

Figure 5.5 Monthly rainfall (P_m, mm. month^{-1}) and monthly specific flux (N_f, kg.ha^{-1}.month^{-1}) of NH_4^+-N and NO_3^-N in the catchment, from November 2014 to October 2016: (1a) at the Lions River wetland (ADC1), (2a) at Midmar Dam (ADC2), (3a) at Midmar Dam Nature Reserve (ADC3) and (4a) at Pietermaritzburg (ADC4)

Annual TP fluxes of 0.475 kgP.ha^{-1}, 0.484 kgP.ha^{-1}, 0.437 kgP.ha^{-1} and 0.437 kgP.ha^{-1} were found at Sites ADC1, ADC2, ADC3 and ADC4, respectively. High monthly fluxes were recorded during high storm event months. These results on phosphorus loads are smaller, compared to 0.8 kgTP.ha^{-1}.yr^{-1} reported at the Pella Site to the north of Cape Town, South Africa (Brown *et al*., 1984), but they are higher, compared to the findings of Hemens *et al*.

(1977) and Breen (1983), at the same site of in the catchment. Our estimates of the phosphorus deposition rate in the Midmar Dam are within the suggested global terrestrial ranges between 0.07 and 1.7 kgP.ha^{-1}.yr^{-1} by Newman, (1995). However, Nyaga *et al*. (2013) reported a phosphorus specific flux of 0.16 kgTP.ha^{-1}. yr^{-1} at the West Coast National Park of South Africa, which is almost three times lower than the findings of this study in the Midmar Dam Catchment (0.483 kgP.ha^{-1}. yr^{-1}). The current TP specific flux estimate (0.484 kgP.ha^{-1}), from 20 observations at ADC2 shows an increase of 30%, in comparison to the value of 0.374 kgTP.ha^{-1}.yr^{-1} reported in 1983 at the same site (Breen, 1983) (Figure 5.6).

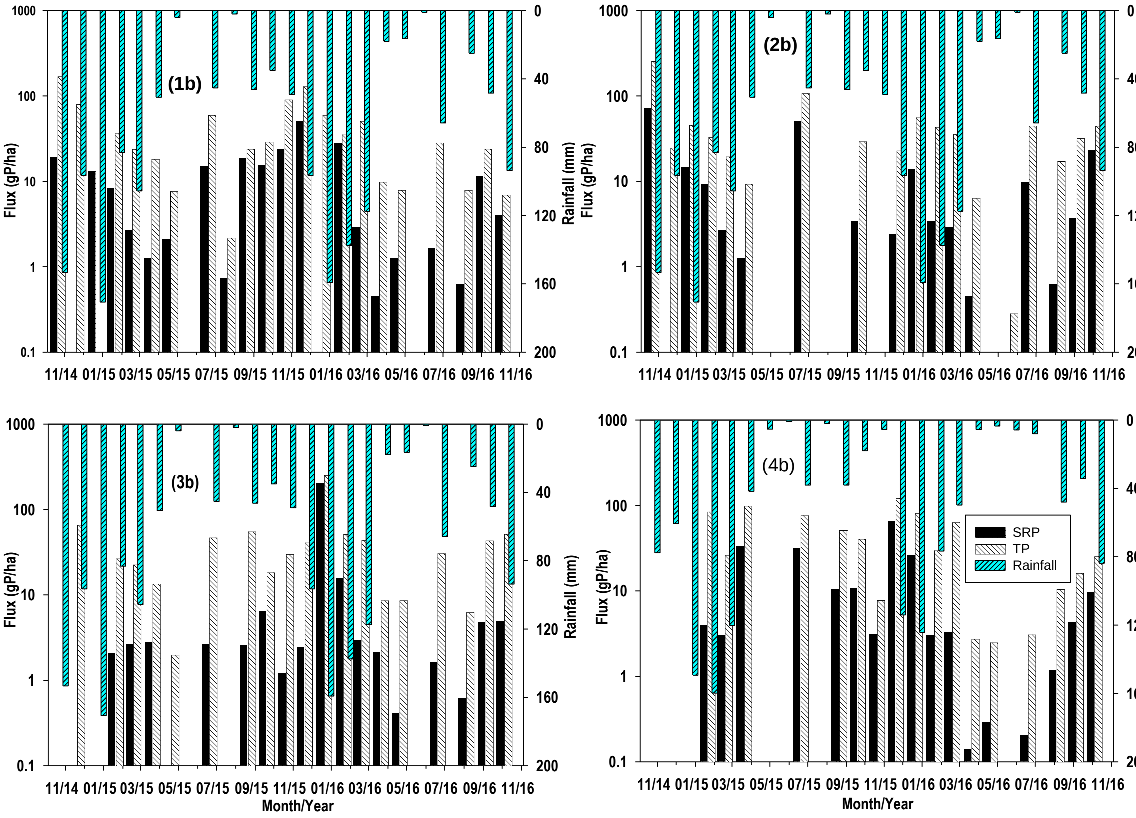

Figure 5.6 Log scale monthly phosphorus fluxes (Nf, g.ha^{-1}.month^{-1}) and monthly rainfall (P_m, mm.month^{-1}) of atmospheric deposition of TP and SRP, from November 2014 to October 2016: (1b) at the Lions River wetland site (ADC1), (2b) at the Midmar Dam Site (ADC2), (3b) at the Midmar Nature Reserve (ADC3) and (4b) at Pietermaritzburg (ADC4)

The site located at Midmar Dam (ADC2) was found to have the largest specific flux of TP (0.484 kgTP.ha^{-1}. yr^{-1}) followed by Site ADC1 near the Lions River wetland. The two other sites (ADC2 and ADC3) were characterized by the same value of TP, with a specific flux of 0.437 kgTP.ha^{-1}.yr^{-1}, despite being located in two different localities (Figure 5.6). The DIN deposition rates of this study are lower than the results found in some other South African localities (Brown *et al*., 1984; Nyaga *et al*., 2013), the East African Great Lakes Region (Tamatamah *et al*., 2005), China (Zhang *et al*., 2011) and the USA (Anderson and Downing, 2006). In contrast, the DIN deposition rates in the catchment are in the same range as other polluted countries, such as the USA (Du *et al*., 2014) and China (Pan *et al*., 2012; Zhang *et al*., 2012; Liang *et al*., 2015).

An assessment of the seasonal variability of nutrient fluxes showed that high levels of NO_3 and NH_4 in bulk deposition were noted during the high rainfall months. This supports the hypothesis that high rainfall events result in increased rates of atmospheric deposition of nutrients (Anderson and Downing, 2006). However, some peak fluxes were noted for TP in dry months, which supports the reality that fine particle matter is a source of atmospheric phosphorus (Mahowald *et al*., 2008).

5.4.4 Nutrient loads from river flows

The highest loads were noted in the period between December and March (summer), which are high rainfall months in the catchment, and the lowest loads occurred during the winter. These results indicate that runoff is a driving factor of nutrient loading in the catchment, as the farm-dams are filled up during rainfall periods, with subsequent release of high levels of nutrients in rivers (Ngubane, 2016). Moreover, phosphorus is mainly discharged from the point sources of pollution and during soil erosion, since its binding properties with the soil in the area are strong (Breen, 1983). The nitrate load from river flow is almost five times higher than the ammonium load. SRP represents less than 25% of the total phosphorus entering the dam (Figure 5.7). This indicates the predominance of particulate phosphorus, which is not easily bioavailable for algal blooms, as reported by Breen (1983). However, river nitrogen load estimates are much lower than the values reported by Hemens *et al*. (1977) and slightly greater than findings of Breen (1983) in the same catchment. This could be attributed to the fact that the period of this investigation was the driest season in KwaZulu-Natal since 1900, as a result of *El Nino* weather pattern (Macharia and Hudson, 2015). The Lions River was the largest contributor of pollutants to the Midmar Dam, as it provides 70% of TP, 58% of NH_4-N, 56% of NO_3-N and 66% of SRP. Under drought conditions, approximately 58% of the uMngeni streamflow entering the Midmar Dam comes from the Lions River via the inter-basin transfer scheme from the Mooi River (Table 5.4**).**

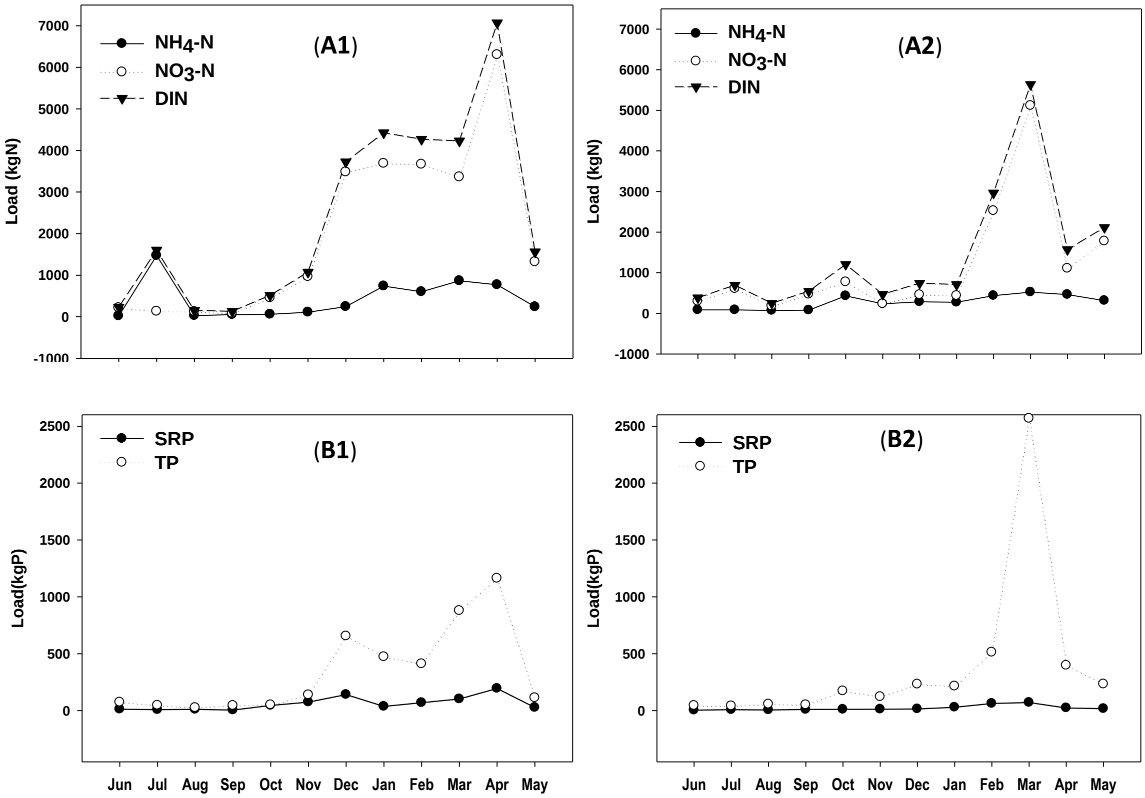

Figure 5.7 Monthly riverine DIN and phosphorus loads (kg) to the Midmar Dam through the two major tributaries (Lions and uMngeni Rivers) for the period June 2014 to May 2015 (A1 and B1) and for the period June 2015 to May 2016 (A2 and B2) (combination of the Lions River and Petrus Stroom)

5.4.5 Total nutrient loading to the Midmar Dam

During the two consecutive years of this study, the bulk deposition of DIN to the Midmar Dam area varied between 12480 kg and 17119 kgN per annum. Ammonium nitrogen contributed to ~31% and 49%, respectively of the total DIN loads during drought and normal conditions. The bulk deposition loads of TP estimated in this study ranged between 856 and 816 kgTP.yr^{-1} in the Midmar Dam catchment, which are higher than those of previous studies (Hemens *et al.*, 1977; Breen, 1983). Moreover, the dominance of particulate phosphorus in bulk deposition and in the surface waters of the Midmar Dam Catchment (over 72% of TP) noted in this study, has been also reported in other research (Breen, 1983; Ngubane, 2016).

Bulk deposition is a significant source of nutrients to the Midmar Dam. It provided approximately 16%, 58% and 33% of TP, NH_4 and NO_3, respectively, of the total external load, over the study period (Table 5.4). Relatively lower atmospheric deposition loads of SRP and TP, compared to nitrates, were also reported in other case studies in the world, for example, at Lake Tahoe in the USA (Jassby *et al*., 1994, the Mediterranean Sea (Markaki *et al*., 2010), the Lake Tanganyika (Langenberg *et al*., 2003) and Lake Kivu (Muvundja *et al*., 2009).

Bulk atmospheric deposition was an important source of ammonium loading to the Midmar Dam (over 54% of ammonium load), consistent with studies in other lakes (Bosman and Kempster, 1985; Jassby *et al*., 1994; Muvundja *et al*., 2009; Yu *et al*., 2014). This can be ascribed to the high solubility of ammonium in rainwater (Anderson and Downing, 2006), ammonium emissions from local agricultural and livestock farming activities and biomass burning in the catchment (Mphepya *et al*., 2004; Mphepya *et al*., 2006; Shen *et al*., 2014).
Higher bulk atmospheric deposition of phosphorus can be ascribed to a noted rapid conversion of the natural vegetation to cultivation, forest plantations, urban/built-up and other land use types in the catchment (Jewitt, 2012; Mauck and Warburton, 2013; Jewitt *et al*., 2015; Namugize *et al*., submitted). Moreover, a high evapotranspiration rate that is characteristic of semi-arid climate (Prepas and Charette, 2004), as well as the expansion of agricultural activities (Ngubane, 2016) result in an increase of nutrient emissions to the atmosphere.

The volume of surface inflows (Lions + uMngeni Rivers) that enter the Midmar Dam declined by 31% over a period of two years (June 2014-May 2015 and June 2015-May 2016). The corresponding volume of rainfall that falls across the Midmar Dam surface area has decreased by 25% (Table 5.4). This resulted in a decline in the load of DIN and a slight increase of TP entering the Midmar Dam via rivers. However, a contrasting effect was identified in bulk deposition, where NO_3 increased in drought conditions (Table 5.4). Other studies (Hemens *et al*., 1977; Breen, 1983; Ngubane, 2016) have reported a high variability in the surface loads of DIN to the Midmar Dam, but TP surface loads have been stable for many years.

Table 5.4 Annual external nutrient load to the Midmar Dam

Source	Period	Flow/Rainfall $Mm^3.yr^{-1}$	SRP $kgP.yr^{-1}$	TP $kgP.yr^{-1}$	NH_4^+-N $kgN.yr^{-1}$	NO_3^--N $kgN.yr^{-1}$	DIN $kgN.yr^{-1}$
Lions + uMgeni Rivers inputs to the dam	2014-2015	90	727	4072	5196	23791	28987
	2015-2016	62	269	4645	3281	13986	17267
Bulk atmospheric deposition at Midmar Dam surface	2014-2015	14	220	857	6186	6294	12480
	2015-2016	11	270	816	5332	11787	17119

This study elucidated that, for the period June 2014 to May 2016, surface inflow of nutrients to the Midmar Dam varied between 4072 and 4645 kg. yr^{-1} for TP and 28987 to 17267 kg. yr^{-1} for DIN (Table 5.4). Nutrient loads have been affected differently by the drought in the region, e.g. the DIN and SRP loadings for June 2015 to May 2016 declined, while the loads of TP increased. These load estimates of DIN for the period June 2014 to May 2015 are slightly higher than the values reported by Breen (1983) for the period 1979-1982 (they ranged between 8820 and 27544 kg. a^{-1}). However, our DIN loads fall in the range of loads calculated by Ngubane (2016) for the period 2009-2013, which showed a high variability (ranged between 10.1 and 29,0 tons per annum of DIN). The river inputs of NH_4-N have almost tripled in comparison to 1801 $kgN.yr^{-1}$ reported for the season 1981-1982 (Breen, 1983). However, possible under-estimation of total surface load of IN and TP that enter the Midmar by this study, due to a non-inclusion of the other small tributaries of the Midmar Dam. For example, the Mthinzima catchment alone was reported to contribute significant loads of DIN and TP, as a result of raw sewage discharging in the stream and cattle grazing in the downstream wetlands (Ngubane, 2016).

It is important to note that river sampling and the collection of the bulk atmospheric deposition were carried out during severe drought conditions, which may lead to under-estimation of nutrient loads from both sources (river and atmospheric deposition) to the Midmar Dam, compared to normal conditions. In addition, this study did not calculate nutrient loads emanating from other small inflows to Midmar Dam, due to the lack of streamflow (the Mthinzima and Khayalisha Streams) and water quality data (the Nguklu and Gqishi Streams). Moreover, it has been reported that the bulk atmospheric deposition of N and P can provide approximately 90% of total atmospheric deposition (wet + dry deposition) to water sources (Izquierdo and Avila, 2012).

5.5 Conclusion and Recommendations

A comparison of the bulk deposition of nitrogen and phosphorus and riverine water quality in the upper reaches of the uMngeni Catchment above the Midmar Dam allowed for a better understanding of nutrient loads and major sources of water quality deterioration in the catchment.

High concentrations and loads of nutrients in bulk atmospheric deposition and river flows were noted during summer months i.e. the period of high rainfall in the catchment, indicating that rainfall and the resulting runoff are the driving factors of water quality variability in the catchment. Substantial concentrations of ammonium, nitrate and TP in bulk atmospheric deposition samples were noted, which exceeded their levels in the major tributaries of Midmar Dam (the Lions and uMngeni Rivers), which suggest a high retention of nutrients in the catchment.

The spatial variability of the concentrations of nutrients in surface inflows and rainfall in the catchment, was noted. However, in comparison to the previous studies in the Midmar Dam catchment, this study shows high atmospheric deposition rates of DIN and TP. The surface inputs of DIN to the Midmar Dam are affected by changes in-stream flows, while those of TP are almost stable. Moreover, results indicated that bulk atmospheric deposition is the largest source of ammonium nitrogen to Midmar Dam, while nitrate and phosphorus were supplied mainly by river flow, as reported in other research (Langenberg *et al*., 2003; Muvundja *et al*., 2009). Furthermore, the organic fraction of phosphorus was the dominant species of phosphorus in runoff and bulk deposition, which represented approximately 80% of the TP. Thus, these results highlight the relative contribution of bulk atmospheric deposition to the eutrophication of Midmar and Albert Falls Dam under drought conditions.

Due to the high variability of rainfall patterns during the period of this study, coinciding with the subsequent changes in concentration and load of nutrients in bulk deposition and river samples, a continuation of bulk atmospheric deposition collection and river sampling in the Midmar Dam Catchment is suggested. However, a combination of bulk deposition collection method with automatic wet-only or dry deposition collectors, could provide more accurate and conclusive information.

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5.7 Appendices

Appendix 5.A

Monthly concentration of nutrients in atmospheric deposition samples collected from November 2014 to October 2016

Sampling Date	NH4-N(mgN/L)				NO3(mgN/L)				SRP(ugP/L)				TP (ugP/L)			
	ADC1	**ADC2**	**ADC3**	**ADC4**	**ADC1**	**ADC2**	**ADC3**	**ADC4**	**ADC1**	**ADC2**	**ADC3**	**ADC4**	**ADC1**	**ADC2**	**ADC3**	**ADC4**
2014-11-18	0.76	0.25	nd	nd	0.74	1.40	nd	nd	12.4	47.2	nd	nd	111.5	167.5	nd	nd
2014-12-02	0.57	nd	nd	nd	0.82	nd	nd	nd	nd	nd	nd	nd	23.6	nd	nd	nd
2014-12-17	0.43	0.28	0.62	nd	nd	nd	nd	nd	nd	nd	nd	nd	143.8	25.9	69.0	nd
2015-01-27	nd	0.40	nd	nd	nd	0.35	nd	nd	nd	8.5	nd	nd	nd	27.0	nd	nd
2015-02-10	0.21	0.23	0.15	nd	0.27	0.17	0.40	nd	2.5	4.5	2.5	nd	29.1	20.4	24.7	nd
2015-02-24	0.15	0.15	0.05	0.05	0.50	0.50	0.68	0.33	17.7	17.7	2.5	2.5	59.2	59.2	39.9	53.3
2015-03-10	0.05	0.05	0.05	0.12	0.26	0.31	0.15	0.29	2.5	2.5	2.5	2.5	17.1	7.5	21.6	21.9
2015-03-24	0.05	0.05	nd	7.04	0.32	0.71	nd	0.90	2.5	2.5	nd	nd	28.5	29.7	nd	nd
2015-04-07	0.28	nd	0.20	nd	0.26	nd	0.26	nd	2.5	nd	5.6	nd	19.6	nd	26.9	nd
2015-04-21	0.05	0.32	0.30	0.15	0.60	0.32	0.34	0.23	2.5	2.5	nd	2.5	53.1	18.6	nd	25.7
2015-05-05	0.49	nd	nd	nd	0.53	nd	nd	nd	103.0	nd	nd	nd	nd	nd	nd	nd
2015-05-20	0.75	nd	0.47	nd	0.53	nd	0.17	nd	2.5	nd	2.5	nd	51.6	nd	50.2	nd
2015-07-28	0.14	1.15	0.12	0.30	0.43	0.77	0.47	0.43	2.5	111.5	5.8	82.4	133.0	239.0	104.1	202.2
2015-08-11	0.11	nd	nd	nd	0.22	nd	nd	nd	16.2	nd	nd	nd	110.0	nd	nd	nd
2015-09-08	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
2015-09-22	0.05	nd	0.68	0.53	1.01	nd	1.01	0.68	5.7	nd	5.6	13.8	52.3	nd	120.0	102.4
2015-10-06	nd	nd	nd	1.21	nd	nd	nd	nd	nd	nd	nd	42.9	nd	nd	nd	215.0
2015-10-20	0.63	0.92	0.60	0.98	1.11	1.09	1.08	1.12	15.4	9.7	18.6	76.0	83.9	84.6	52.6	239.0
2015-11-03	0.89	nd	0.51	0.42	nd	nd	1.28	0.05	21.6	nd	2.5	62.7	nd	nd	70.0	164.5
2015-11-17	0.33	nd	0.43	0.63	1.52	nd	2.02	1.66	6.6	nd	2.5	2.5	nd	nd	52.8	38.9
2015-12-01	nd	nd	0.41	2.00	nd	nd	0.69	0.75	nd	nd	2.5	nd	nd	nd	40.4	nd
2015-12-15	0.41	0.53	0.70	1.00	0.77	0.95	0.84	0.75	2.5	2.5	2.5	30.5	81.7	24.0	45.1	83.5
2016-01-12	0.42	nd	1.36	0.84	0.67	nd	0.75	0.69	2.5	nd	207.0	33.0	55.3	nd	nd	88.3
2016-01-26	0.13	0.34	0.84	0.37	0.42	0.88	0.57	0.39	2.5	8.7	51.2	4.7	20.5	36.0	73.3	24.8
2016-02-09	0.24	0.26	0.39	0.44	0.05	1.81	0.34	0.29	2.5	2.5	9.6	2.5	20.7	35.8	25.2	20.1
2016-02-23	0.34	0.43	0.26	0.49	0.43	0.57	0.50	0.72	2.5	2.5	12.9	4.0	31.0	27.8	50.0	50.2
2016-03-08	0.42	0.55	0.57	0.39	0.35	0.47	0.46	0.35	2.5	2.5	2.5	2.5	42.3	24.0	41.2	33.9
2016-03-23	0.23	0.05	0.15	0.32	0.34	0.12	0.22	0.17	2.5	2.5	2.5	10.9	45.1	37.1	33.6	222.6
2016-04-05	0.86	0.36	0.50	0.53	0.52	0.36	0.82	0.55	2.5	2.5	12.0	2.5	55.3	43.9	48.1	49.6
2016-04-18	nd	0.41	nd	nd	nd	0.53	nd	nd	nd	2.5	nd	nd	nd	27.9	nd	nd
2016-05-03	0.05	nd	0.56	0.42	0.25	nd	1.94	1.13	12.8	nd	2.5	14.1	38.5	nd	45.7	105.0
2016-05-17	0.85	nd	0.05	0.25	0.59	nd	0.99	0.40	2.5	nd	2.5	2.5	58.2	nd	59.6	36.1
2016-06-02	nd	0.80	nd	nd	nd	1.57	nd	nd	nd	3.9	nd	nd	nd	28.6	nd	nd
2016-06-14	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
2016-07-25	0.19	0.05	0.13	0.05	0.39	0.53	0.73	0.62	2.5	14.9	2.5	2.5	43.4	68.7	46.9	38.2
2016-08-23	0.05	0.05	0.05	0.05	0.55	0.57	0.63	0.59	2.5	2.5	2.5	2.5	31.9	69.4	25.2	22.0
2016-09-21	1.04	0.05	0.05	0.16	2.04	0.60	3.41	2.78	23.7	7.7	10.0	12.7	50.2	66.7	90.1	47.5
2016-10-04	0.22	0.16	0.05	0.05	0.80	1.13	1.00	1.00	6.1	13.0	5.2	10.3	46.9	45.0	55.4	30.5
2016-10-25	0.19	0.23	nd	0.31	1.00	1.29	nd	1.03	2.5	36.7	nd	12.8	7.5	51.2	nd	nd
2016-11-01	0.44	0.40	nd	nd	0.90	0.54	nd	nd	2.5	35.0	nd	nd	40.7	130	nd	nd

With nd: not determined because of the lack of sample, the grey colour indicates the discarded sample due to sample contamination

Appendix 5.B

Physical chemical parameters in the catchment, where M stands for average, SD: standard deviation, Min: minimum, Max: maximum and N: number of samples

	EC (mS/m)			**pH**			**Temperature (°C)**			**TSS (mg.L^{-1})**			**Turbidity (NTU)**		
Site	Ave±SD	Min-Max	N	Ave±SD	(Min-Max)	N	Ave±SD	(Min-Max)	N	Ave±SD	(Min-Max)	N	Ave±SD	(Min-Max)	N
MP-01	19.7±28.0	(1.9-121.0)	26	7.5±0.5	(6.4-8.9)	24	18.4±3.4	(12.0-25.0)	26	149.0±120.5	(13.0-519.0)	23	18.0±10.9	(0.9-38.6)	18
MR-01	15.6±22.4	(0.5-71.0)	23	7.5±0.6	(6.2-8.6)	22	19.5±3.0	(12.9-23.8)	23	132.3±115.6	(40.0-570.0)	20	11.1±13.1	(0.8-56.4)	17
UU-01	12.4±15.1	(1.2-72.0)	52	7.4±0.5	(6.2-9.0)	52	16.6±4.5	(7.6-23.7)	50	106.8±97.9	(1.0-528.0)	48	14.5±21.7	(0.4-116.0)	29
UU-02	14.0±21.9	(0.0-101.0)	52	7.3±0.4	(6.3-8.1)	51	15.8±4.3	(7.9-24.5)	49	91.0±60.5	(2.0-343.0)	47	9.8±8.8	(0.1-42.7)	29
UU-04	12.5±14.5	(2.2-70.0)	52	7.3±0.5	(6.2-8.2)	51	17.5±4.5	(8.8-25.1)	50	105.2±75.6	(2.0-408.0)	47	22.8±33.1	(0.1-190.0)	32
UU-08	12.5±14.8	(2.2-71.0)	52	7.4±0.5	(6.4-8.8)	50	18.2±4.4	(9.8-27.1)	50	115.1±65.4	(2.0-290.0)	47	20.3±15.0	(0.3-55.2)	33
UU-09	11.8±17.7	(2.2-84.0)	52	7.5±0.5	(6.5-9.0)	51	17.6±4.8	(9.5-26.7)	50	87.9±54.9	(2.0-196.0)	47	9.3±8.9	(0.1-37.8)	33
UU-10	11.8±15.1	(2.3-72.0)	51	7.5±0.6	(6.4-9.9)	51	18.5±4.5	(10.0-28.0)	50	103.5±57.2	(2.0-191.0)	47	14.7±14.1	(0.1-72.0)	33
MT-01	15.1±22.7	(2.0-106.0)	51	7.6±0.6	(6.5-9.5)	50	19.3±4.8	(10.3-27.8)	50	110.8±77.9	(2.0-462.0)	47	16.6±10.1	(2.0-34.2)	33
MT-02	26.3±33.2	(2.1-162.0)	51	7.3±0.5	(5.9-8.8)	50	20.5±4.9	(10.2-29.1)	50	192.0±133.5	(2.0-559.0)	48	51.2±38.0	(1.1-176.0)	33
MT-03	56.1±73.8	(2.1-359.0)	51	7.2±0.4	(6.4-8.3)	49	21.7±4.5	(10.6-29.8)	50	290.6±236.9	(5.0-1081.0)	48	67.1±50.7	(3.1-250.0)	32
MT-04	59.6±80.0	(2.1-383.0)	51	7.6±0.4	(6.7-8.6)	49	21.6±4.9	(10.5-31.4)	50	347.6±1014.5	(9.0-7076.0)	47	112.3±338.6	(11.0-1886.0)	31
MT-05	46.9±73.2	(2.1-383.0)	51	7.3±0.4	(6.5-8.4)	49	19.3±4.8	(9.5-29.1)	50	160.7±115.9	(8.4-463.0)	47	36.1±18.8	(4.2-77.4)	30
KT-01	18.0±4.8	(2.2-25.8)	35	7.5±0.6	(6.7-9.5)	35	19.8±5.1	(11.1-31.4)	34	127.2±131.1	(5.0-707.0)	33	36.3±14.8	(13.1-61.0)	20

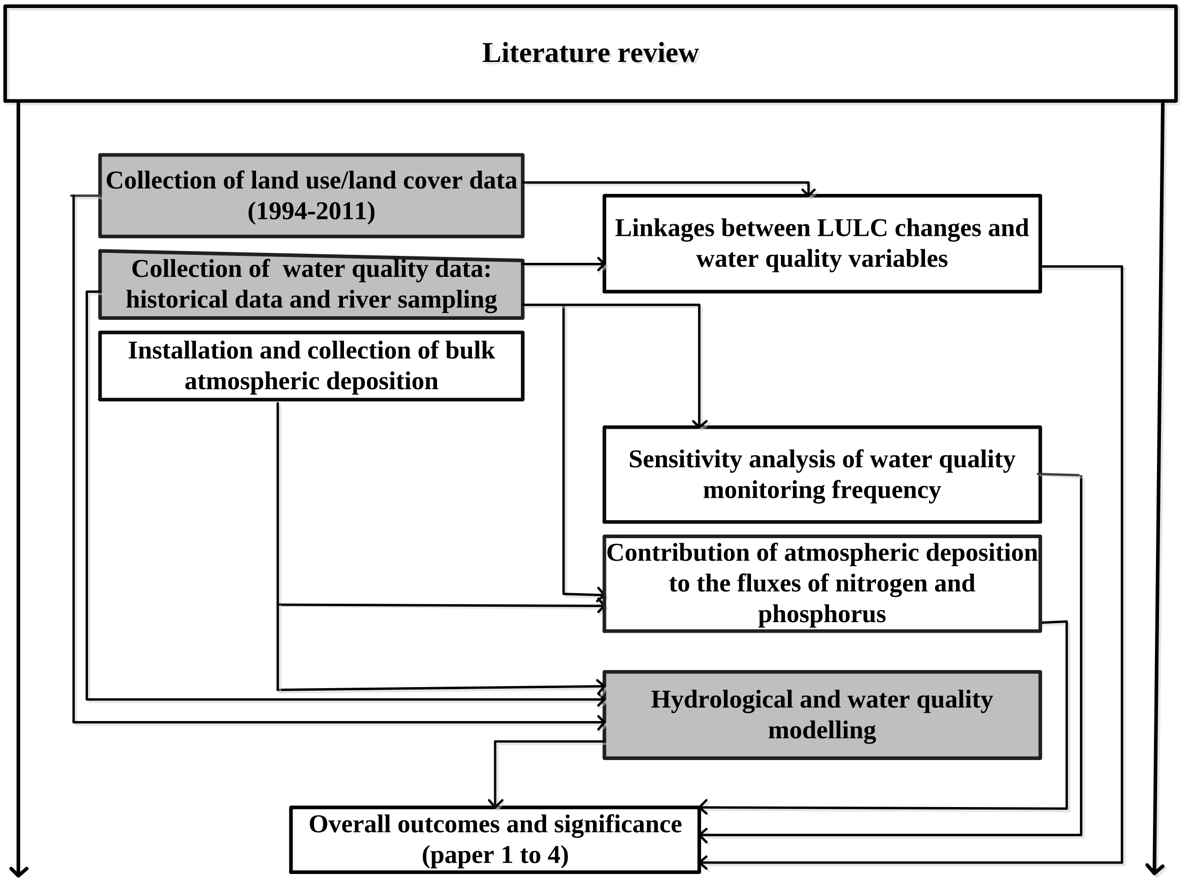
Appendix 5.C

Descriptive statistics of nutrient concentrations in river samples collected from June 2014 to May 2016, where M stands for average, SD: standard deviation, Min: minimum, Max: maximum and N: number of samples

Nutrient	**NH$_4$-N**			**NO$_3$-N**			**SRP**			**TP**		
Unit	**mgNL^{-1}**			**mgNL^{-1}**			**µgP.L^{-1}**			**µgP.L^{-1}**		
Site ID	M±SD	Min-Max	N	M±SD	Min-Max	N	M±SD	Min-Max	N	M±SD	MinMax	N
MP-01	0.06±0.06	0.02-0.31	26	0.13±0.15	0.03–0.80	25	4.4±2.5	2.5–9.9	26	63.2±77.4	17.1–390.0	26
MR-01	0.08±0.07	0.02-0.28	23	0.11±0.08	0.05–0.32	22	4.4±2.7	2.5–11.4	23	36.3±12.5	18.3–57.2	23
UU-01	0.07±0.11	0.00-0.74	52	0.17±0.16	0.01–0.63	52	5.4±6.3	0.0–42.1	52	39.5±36.7	7.5–239.0	50
UU-02	0.06±0.10	0.01-0.71	52	0.10±0.13	0.01–0.62	51	4.7±3.4	0.0–20.8	53	45.0±41.8	7.5–232.0	50
UU-04	0.06±0.10	0.01-0.74	52	0.21±0.14	0.05–0.69	52	11.4±24.2	0.0–169.2	53	53.9±42.6	21.0–292.0	50
UU-08	0.11±0.35	0.01-2.50	52	0.21±0.15	0.05–0.81	52	18.8±36.7	1.6–195.6	53	48.0±24.9	1.3–141.0	50
UU-09	0.06±0.11	0.01-0.79	52	0.27±0.16	0.04–0.78	52	6.6±13.2	2.1–96.1	53	34.0±32.6	7.5–206.0	50
UU-10	0.06±0.10	0.01-0.73	52	0.22±0.15	0.03–0.64	52	17.9±38.9	2.5–173.5	53	47.1±46.8	15.0–259.0	50
MT-01	0.06±0.11	0.00-0.84	52	0.70±0.28	0.08–1.66	52	13.4±30.3	1.5–172.6	53	34.0±22.9	7.5–107.0	50
MT-02	2.28±2.68	0.05-13.37	52	0.75±0.92	0.03–4.99	51	208.3±413.0	6.0–2345.4	53	362.1400.1	53.5–1991.0	44
MT-03	9.78±6.00	0.02-29.90	51	0.25±0.73	0.00–4.94	51	896.4±756.0	40.7–4023.5	52	1630.1±1086.7	179.0–6520.0	49
MT-04	11.11±9.06	0.05-45.99	50	6.35±39.04	0.00–281.30	52	841.0±618.1	57.0–2326.2	51	1235.6±795.8	7.9–3878.0	43
MT-05	3.36±3.33	0.02-11.80	50	2.31±1.44	0.05–6.03	51	254.7±415.6	71.0–2878.7	52	409.9±278.0	151.0–1699.0	49
KT-01	0.07±0.13	0.01-0.80	36	0.17±0.29	0.00–1.24	36	9.7±17.8	0.0–79.8	35	78.2±59.2	16.3–278.0	34

Preface to Chapter 6

Understanding the dynamic nature of water quality in a catchment and the drivers of water quality deterioration of a waterbody cannot be achieved using only physical collection of water samples and subsequent laboratory analyses of pollutants (Chapters 3 and 4), due to limits in sampling programmes. A combination of these methods with the hydrologic and water quality modelling systems has been found to be useful, despite uncertainties associated with the model structure, input data and the modeller (Chapters 2 and 6). In this chapter a physically-based hydrological and nutrients model i.e. the Hydrological Predictions for the Environment (HYPE) was tested, calibrated and validated in the upper uMngeni Catchment to simulate streamflow, nitrogen and phosphorus.



CHAPTER 6: ASSESSMENT OF THE HYPE MODEL FOR SIMULATIONS OF WATER AND NUTRIENTS IN THE UPPER UMNGENI RIVER CATCHMENT IN SOUTH AFRICA

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6.1 Abstract

Most studies considering water quality pollution in the upper reaches of the uMngeni Catchment have relied on the physical grab sampling of water and the subsequent laboratory analysis of chemical determinants**.** However, this provides limited spatial and temporal information. Thus, the objectives of this study are to assess the capability of the Hydrological Predictions for the Environment (HYPE) model in simulating streamflow, dissolved inorganic nitrogen (DIN) and total phosphorus (TP), in the fast developing uMngeni Catchment in KwaZulu-Natal province, South Africa. The model was set up and calibrated, following a stepwise approach and then validated. Results indicated that the simulation of discharge is most sensitive to the parameters related to evapotranspiration and the water-holding capacity of the soil, while DIN and TP are affected by plant uptake and initial pools of nutrients. DIN is also affected by denitrification. Runoff was captured well during the calibration (1989-1995) and validation periods (1961-1999), with a Nash-Sutcliffe efficiency (NSE) greater than 0.0 in eight of the nine stations and a Pearson's correlation coefficient (r) of > 0.5 at all the sites. High streamflow events were represented well, low streamflows were over-simulated. Water balance was over-predicted in the downstream sub-catchments, with an absolute percentage of bias (PBIAS) of > 25%. The transport and dynamics of DIN and TP vary differently and they are driven by hydrological and biochemical processes. The concentration of TP follows the pattern of the streamflow, whereas DIN shows an inconsistent variation. The values of DIN decrease from upstream to downstream, while the TP values increase from the headwaters to the outlet of the catchment. Agricultural activities were found to be the largest source of DIN, while the TP is mainly ascribed to the point sources of pollution.

Key words: *denitrification; HYPE model; nutrients; uMngeni Catchment; water quality model*

6.2 Introduction

A key aspect of the global water quality challenge arises from the eutrophication of fresh, marine and coastal waters, and it is ascribed to the world's rising population, a change in the demographics and land use/land cover patterns, water consumption, urbanisation and climate change effects (Falkenmark, 1990; UNEP-GEMS/Water, 2008; Zimmerman *et al.*, 2008). Globally, the agricultural sector was reported to use approximately 70% of the used freshwater in 2000 and this rate was over 85% in the developing countries of Asia and Africa (UN-Habitat, 2003; FAO, 2004). The deterioration of water quality is a worldwide concern and is highly accentuated in developing countries, due to a growing demand for water and limited funding-sources for water research, treatment and restoration (Prepas and Charette, 2004).

Runoff from agriculture, as well as human and industrial waste, are known to be the largest sources of the increased concentrations of nitrogen and phosphorus in surface and groundwater (UNEP, 2010). To better understand the factors affecting water quality decline in waterbodies, the primary nutrients responsible for eutrophication, investigations on the interactions between the hydrological cycle, soil types, climatic conditions and land use activities are of the utmost importance (Tong and Chen, 2002). This cannot be achieved by following the routine water quality monitoring programmes, or relying on grab and/or continuous river sampling. Therefore, process-based hydrological and water quality models with varying levels of complexity, have been used to provide useful information on catchment responses in terms of nutrient loading, owing to land use activities, soil type, crop management and climatic conditions (Thirel *et al.*, 2015).

Depending on the size and location of the basin, the accessibility to the sampling sites, the cost and time of physical collection and the analysis of samples, water quality models can be integrated into monitoring plans, or be used alone (Loucks and Van Beek, 2005). However, high uncertainties in model simulations are recognised (Loucks and Van-Beek, 2005; Moriasi *et al.*, 2007; Dayyani *et al.*, 2010). A number of hydrological models, such as the ACRU-NPS agro-hydrological modelling system (Campbell *et al.*, 2001; Smithers and Schulze, 2004), the Soil and Water Assessment Tool (SWAT) and its extensions (Arnold *et al.*, 1998; Gassman *et al.*, 2007; Arnold *et al.*, 2011), the Better Assessment Science Integrating point source and Non-point Source of pollution (BASINS) (Di Luzio *et al.*, 2002), the HBV-NP model (Andersson *et al.*, 2005) and the Hydrological Predictions for the Environment (HYPE) (Lindström *et al.*, 2010) have been developed.

Research studies in uMngeni Catchment in South Africa have reported on the nutrient, sediment and bacteriological pollution of the river and its impoundments (Hemens *et al.*, 1977; Breen, 1983; Graham, 2004; Quayle *et al.*, 2010; Van-Ginkel, 2011; GroundTruth, 2012; Lin *et al.*, 2012; Gakuba *et al.*, 2015; Matongo *et al.*, 2015; Ngubane, 2016), which were ascribed to rapid urbanisation, increases of informal settlements with poor sanitation, the expansion of agricultural lands, livestock farming, bulk atmospheric deposition, dysfunctional sewage networks and the use of phosphorus detergents. The concentrations of total nitrogen and total phosphorus that exceed the recommended South African eutrophication threshold limits of 0.6 mg and 0.055 mg/l, respectively, were noted in the rivers and impoundments of the upper reaches of the uMngeni Catchment (DWAF, 2002). As a result, the occurrence of cyanobacterial algae and increased levels of Chlorophyll-a have been reported in the Midmar and Albert Falls Dams (Matthews, 2014; Matthews and Bernard, 2015).

A locally-developed rainfall-runoff model, ACRU has previously been applied in the uMngeni Catchment, to simulate the flow of water, sediment, *Escherichia coli* and phosphorus (Kienzle *et al.*, 1997) and its sub-model, ACRU-NPS in the Mkabela sub-catchment (41 km^2), to simulate nitrate, phosphorus and sediments (Kollongei and Lorentz, 2015). In addition, the pollution loading estimator (PLOAD) was used in the simulation of the total phosphorus export-coefficient at quaternary catchment level (Dabrowski *et al.*, 2013). The continental assessment of the ACRU-NPS model is part of another study. The focus here is to apply a readily available "off the shelf" model and to test its applicability in this setting. Thus, following the bilateral collaboration in water resources management between the

Department of Water and Sanitation of South Africa and the Ministry of Environment and Energy of Sweden, the successful application of the HYPE model in simulating the transport and dynamics of water, nitrogen and phosphorus in catchments of different scales (Strömqvist *et al.*, 2012; Jiang *et al.*, 2014; Jomaa *et al.*, 2016); and the lack of in-stream processes in ACRU-NPS. This study sought to test the capabilities of the HYPE model. Focus is on simulation of nutrients in a fast-developing catchment, where the human conversion of natural vegetation to other land uses is substantial and where the increasing nutrient content of water is an issue. This catchment has also very different climatic and physiographic conditions to Sweden. Therefore, the overall aim of this study was to test HYPE in the upper reaches of the uMngeni Catchment, an area which is typical of rapidly developing catchments of southern Africa. This involved: (i) the simulation of streamflow and the concentration of dissolved inorganic nitrogen (DIN equates $NH_4 + NO_3$) and total phosphorus; and (ii) providing insight into sources of the increased concentrations of DIN and TP and their spatial distribution in the catchment.

6.3 Methodology

6.3.1 Study area

The case study catchment in the upper reaches of the uMngeni Catchment cover a surface area of 1653 km^2 (29.78° and 30.42° longitude East and 29.23° and 29.63° latitude South), in the KwaZulu-Natal province, South Africa (Figure 6.1). The mean annual precipitation in the catchment ranges between 400 and 1000 mm per annum, with most of the rains falling in summer months (October to April) and the occurrence of occasional rains in winter. The mean annual temperature in the catchment ranges between 12°C and 14°C, with the minimum temperature during winter months of June and July and the maximum temperature during December-February. The potential evaporation measured at the A-pan in the area, ranges between 1600 mm and 1800 mm per annum (UW, 2016).

Based on the topography, soil type, land use, altitude, water management, inter-transfer, water sampling and the gauging sites, the uMngeni Catchment has been demarcated into 13 sub-catchments, known as the Water Management Units (WMUs) by the Department of Water Affairs and Forestry (Warburton, 2012). The flow of the major river draining the catchment from the Drakensberg Mountains to the Indian Ocean, the uMngeni River is regulated by four large dams, from upstream to downstream viz. the Midmar, Albert Falls, Nagle and Inanda. These dams are the sources of drinking water for over five million inhabitants of the catchment, as well as for agriculture water use (Kienzle *et al.*, 1997; Hay, 2017). The Lions and Karkloof Rivers are the major tributaries of the uMngeni River, upstream of the Midmar and Albert Falls Dams, respectively. Over 300 farm dams are scattered through the catchment. The Msunduzi River passes through Pietermaritzburg, the major city of KwaZulu-Natal Province, and joins the uMngeni River downstream of the Nagle Dam. The catchment has lost over 15% of its natural vegetation over the past two decades, due to rapid urbanization and the expansion of agricultural lands and forest plantations (Jewitt, 2012; Mauck and Warburton, 2013; Jewitt *et al.*, 2015a; Namugize *et al.*, submitted).

In 2004, water demands began to exceed the supply in the catchment, water transfer schemes were constructed from Mooi River to the uMngeni River and others are planned for the future (DWAF, 2008; UW, 2013, 2016). This involved the construction of the Mearns Weir and Spring Grove Dams and the transfer pipelines which outfall into Mpofana River, the tributary of Lions River upstream of the Midmar Dam. It was expected that by 2016, the two transfer schemes could supply approximately 4.5 m^3/s on continuous basis (UW, 2016). The water quality of the Upper uMngeni River and large dams has been monitored by Umgeni Water (UW) since its establishment in 1974. Recent data have showed a deterioration of water quality in the upper reaches of the uMngeni catchment, as indicated by an increase in the concentrations of phosphorus, nitrogen and *Escherichia coli (E.coli)*. This was attributed to growth of informal settlements in the Mphophomeni Township, expansion of agricultural activities, effluent discharges from wastewater treatment and runoff from urban areas of Howick and Hilton (DWAF, 2008; Taylor *et al.*, 2016). In addition, water of the Spring Grove Dam and Mearns Weir (in Mooi River Catchment), the sources of water which is transferred to Midmar Dam, contains high concentrations of nutrients and *E.coli* counts which could affect the receiving Mpofana River (DWAF, 2008). UW is also the supplier of the bulk water to municipalities to support different users (the population, agriculture and industry). Previous analyses have highlighted the Midmar and Albert Falls Catchments, which are part of the focus of this study, as important sources of water supply of the whole uMngeni Catchment system (Jewitt *et al.*, 2015b).

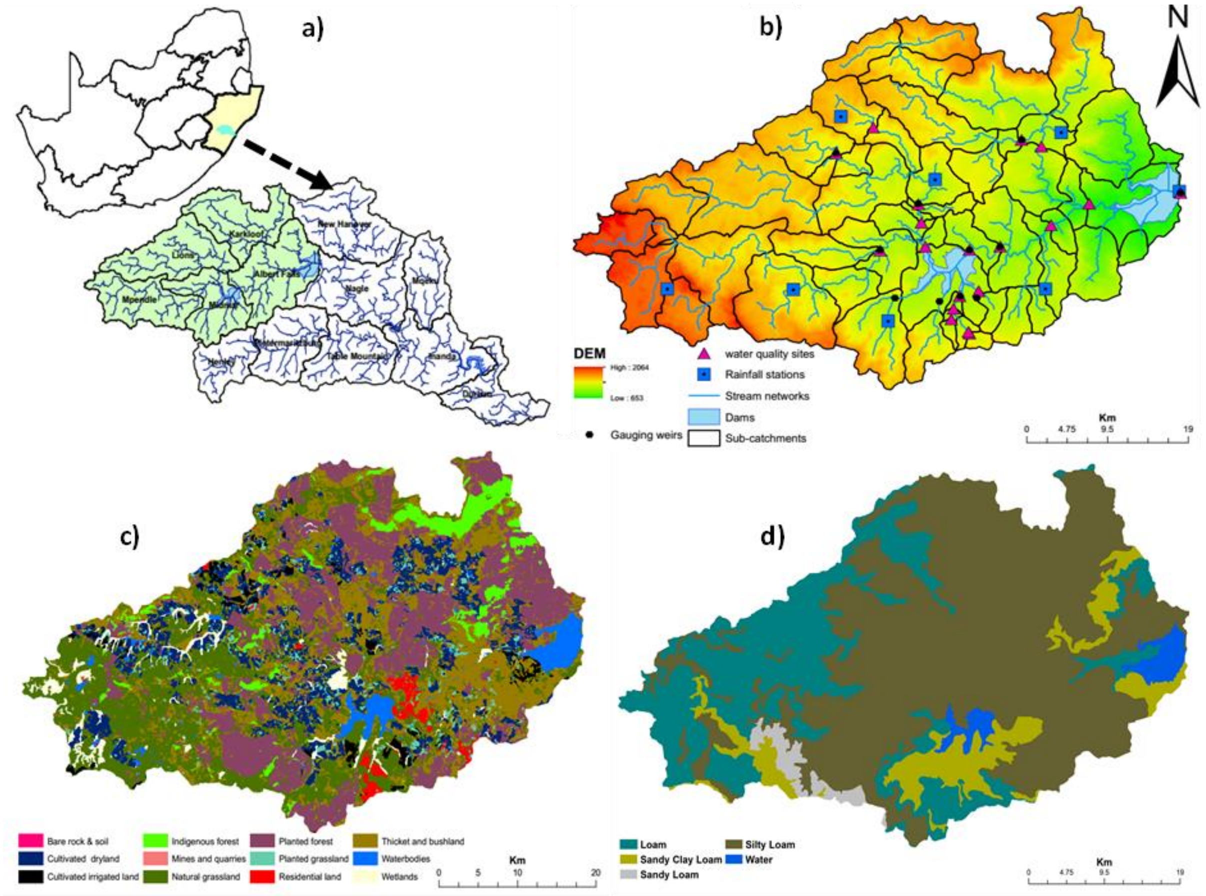

Figure 6.1 The location of the study area in the uMngeni Catchment, KwaZulu-Natal province, South Africa (a), a digital elevation model (DEM) with 53 sub-catchments, water monitoring sites, stream flow gauges and rainfall stations (b), a land use and land cover map for 2000 (c) and the soil type (d)

6.3.2 Description of the HYPE model

The HYPE model is a physically-based, semi-distributed water quantity and water quality model, developed by the Swedish Meteorological and Hydrological Institute (SMHI**).** The first version was developed during the period 2005-2007, but the development of the model is still ongoing and the model source code is open**.** The model simulates at a daily time-step the transport and turnover of water and nutrients in the soil, river and lakes and has been primarily applied in large catchments, with areas ranging between 0.35 million km^2 and 8.8 million km^2 (Lindström *et al.*, 2010; Strömqvist *et al.*, 2012; Arheimer *et al.*, 2015; Hundecha *et al.*, 2016). However, the model also works well at small scales (for example, a catchment of 99.5 km^2) (Jiang *et al.*, 2014; Andersson *et al.*, 2015; Pers *et al.*, 2016). The model's establishment was based on previous Swedish models, HBV and HBV-NP (Lindström *et al.*, 2010; Yin *et al.*, 2016). HYPE was developed to assist in overcoming the problem of eutrophication, which was a major issue of water quality in Sweden (Strömqvist *et al.*, 2012). In the model, the catchment is divided to sub-catchments, which, in turn, are divided into classes, based on a combination of soil texture and land cover types (SLC). These SLCs are referred as hydrological response units, which are the smallest units of hydrological calculations in the model (Lindström *et al.*, 2010; Strömqvist *et al.*, 2012).

Above the ground, the model simulates snow, evapotranspiration, glaciers, rivers, lakes and routing. In the sub-catchments, air temperature is calculated using the average elevation, while precipitation is assumed to be uniform over each sub-catchment. In the HYPE model, potential evaporation is calculated from the air temperature and occurs when the air temperature is greater than a threshold temperature. It is assumed that evaporation from the soil decreases with depth and occurs in the two upper layers. The modeller can select one of six available methods of calculating potential evaporation in HYPE model, depending on the availability of input data. Within the soil, water content is computed for each of a maximum of three layers. The location of the ground water table is calculated from the degree of soil saturation above field capacity in the different soil layers. Internal and outlet lakes and local and main rivers are defined in the model. Internal and outlet Lakes are taken as Soil and Land use Classes (SLCs). The length of the local river in each sub-catchment may be given as an input to the model or is by default calculated as the square root of the sub-catchment land area.

The delay in the river was determined as the length of the river (rivlen) and the water maximum velocity (rivvel). Soil runoff from the different soil layers depends on water content above field capacity and recession coefficients. Overland flow may occur if the top soil layer is over-saturated or if the infiltration capacity is exceeded. All local runoff waters from the SLC classes in a sub-catchment enter the local river from where it is routed directly to the main river or partially through an internal lake. The main river receives water from the local rivers in addition to flow from upstream sub-catchments. Water from the main river may pass an outlet lake before being discharged to the downstream sub-catchment (Lindstrom et al., 2010). Lakes are assumed to be completely mixed and for each lake a rating curve, area and depth are defined. Different reservoir regulation routines are also available. Water withdrawal for irrigation is considered as an important factor in water management and may be handled by the model.

Daily volumes and concentrations of nutrients from wastewater treatments plants, industries and inter-basin water transfer are considered as positive point sources, while water abstraction from lakes are defined as negative point sources. The water discharges from the rural households which are not connected to the municipal wastewater works are added to the internal river and to the deepest soil layers for each sub-catchment. Atmospheric deposition is recognised as an important source of nitrogen and phosphorus to land and lake classes. Wet deposition of nitrogen and phosphorus are added in the form of their respective concentrations of rainfall. Dry deposition of inorganic nitrogen is defined for each sub-catchment and are assumed to be land type dependent. Dry deposition of soluble phosphorus is given as a land use dependent parameter. In the HYPE model the simulated processes that affect the nutrients in surface waters are denitrification, mineralisation, primary production and sedimentation. It is also assumed that there is an exchange between particulate phosphorus in the water column and in sediments in the river. The width and the depth of a watercourse are important for the in-stream transformation of nutrients. These are calculated from a number of empirical equations. The bottom area of watercourse is calculated as the width times the length. The temperature of a water course is calculated by weighting the previous day water temperature and the air temperature.

The major biological and chemical transformation of nitrogen and phosphorus in land, streams and lakes, namely, immobilisation, absorption/desorption, plant uptake, primary production, mineralisation, denitrification, sedimentation and resuspension, are taken into account.

The model simulates nitrogen (inorganic (IN) and organic (ON)) and phosphorus (particulate (PP) and soluble reactive phosphorus (SRP)), and total nitrogen (TN) and total phosphorus (TP) are calculated as the sum of their respective fractions. In addition, organic carbon and conservative tracers, such as chloride and ^{18}O, can also be modelled (Lindström *et al.*, 2010; Jiang and Rode, 2012; Pers *et al.*, 2016). A schematic illustration of the processes and routing of water and nutrients (N and P) in the HYPE model is shown in Figure 6.2. The major model parameters and algorithms are fully described in Lindström *et al*. (2010). Comprehensive documentation on model processes, source code and update versions are free for download at the webpage http://hypecode.smhi.se/.

The HYPE model has been applied in many catchments of the northern hemisphere in the simulation of water quantity and pollutants (nitrogen, phosphorus and organic carbon). Examples of this include the whole of Sweden (Strömqvist *et al.*, 2012; Arheimer *et al.*, 2015; Pers *et al.*, 2016), a European multi-basin study (Donnelly *et al.*, 2016; Hundecha *et al.*, 2016), simulation of nutrient losses in Germany (Jiang and Rode, 2012), the Baltic Sea (Donnelly *et al.*, 2011), the assessment of climate change effects on water resources in the whole of India (Pechlivanidis *et al.*, 2015) and in few studies on the African continent (Andersson *et al.*, 2014; Andersson *et al.*, 2015), but limited to West Africa.

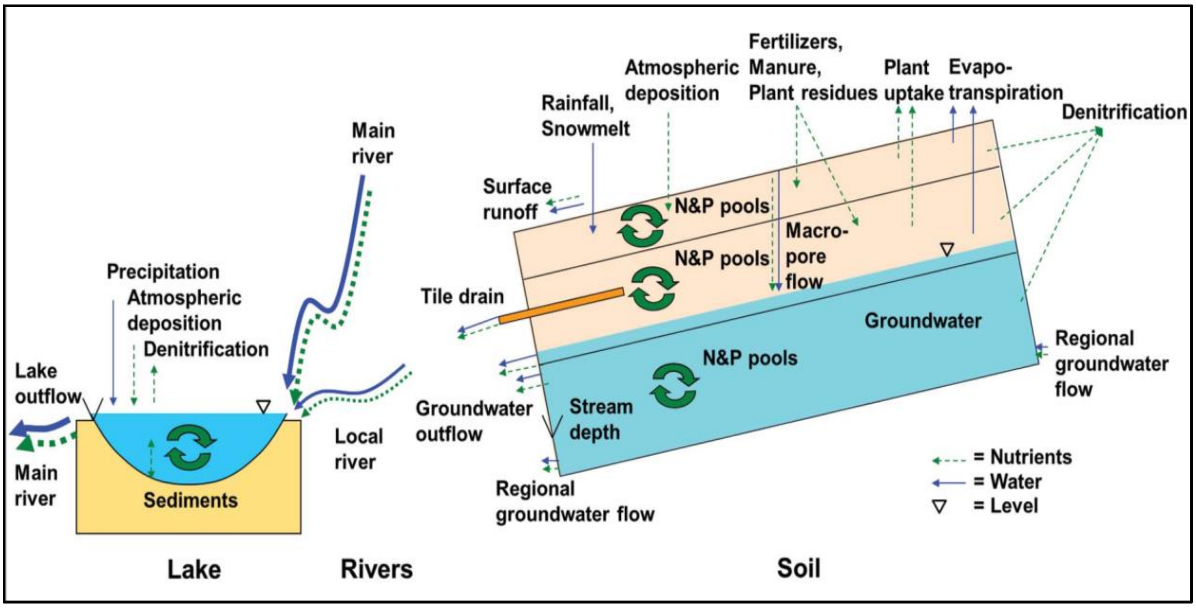

Figure 6.2 Schematic illustration of nutrient transport and turnover of nutrients within a sub-basin in the HYPE model (Strömqvist *et al.*, 2012)

6.3.3 Model set-up

The application of the HYPE model to the upper reaches of the uMngeni Catchment has involved the collection of input data from various sources. The mandatory data for the model included climate data (daily temperature and precipitation), land use types, soil type information, crop type, agricultural practices, dam data, water quality data and information on the point sources of pollution in the catchment.

The model was set up for the period 1950-1999, for which a complete dataset of temperature and precipitation is available. The 53 sub-catchments were delineated, based on the extraction of the 45 sub-catchments covering the study area. This mirrors the process for configuration of ACRU developed by Warburton *et al.* (2010) for water quality studies. The DEM was used to calculate the elevation-means, the elevation standard deviation, the slope-means and the slope standard deviation for each sub-catchment. Soil information has been disaggregated from the Land Type Map of South Africa, which resulted in five classes of soil texture, i.e. loam, sand clay loam, sand loam, silt loam and no texture, as shown on Figure 6.1d (Land Type Survey Staff, 1972-2006). The reclassification of the National Land Cover (NLC) 2000 dataset resulted in twelve land use classes that can affect water quality *viz*. indigenous forest, thicket/bushland, natural grassland, planted grassland, planted forest, bare rock/soil, cultivated dryland, cultivated irrigated land, residential, waterbody, mines/quarries and wetlands. Information on crop types was deduced from the NLC 2000 (Figure 6.1c).

The combination of soil types, land use and crop type information in ArcGIS 10.1 led to 68 SLCs, which have been reduced to 53 SLCs after aggregating the SLCs that have similar properties (Yin *et al.*, 2016). Each SLC is not coupled to any geographical location, but it represents a fraction of the sub-catchment area (Lindström *et al.*, 2010; Jiang *et al.*, 2014). The model sums the simulated flow of water and nutrients from each SLC within a sub-catchment and routes that and water from upstream sub-catchments to the sub-catchment outlet. The flow path of water and nutrients follows the flow direction between the sub-catchments and ends up at the catchment outlet (Jiang *et al.*, 2014). A sketch illustrating the direction of flow is presented in Figure 6.3.

Two soil layers extracted from the Land Type map of South Africa, their corresponding depths and the drain depth were defined (Land Type Survey Staff, 1972-2006). However, a third thick soil layer was added during the calibration of the model. In the HYPE model, evapotranspiration is assumed to occur from the top two upper soil layers, decreases with soil depth and is at potential rate if the water content of soil exceeds field capacity (fc) or a large proportion of field capacity (lp) (Lindström *et al.*, 2010). For this study, the potential evapotranspiration (PET) was calculated using the modified Jensen-Haise/McGuinness models (Oudin *et al.*, 2005) (Equation 1). This PET model is less data demanding, as it needs only air temperature and solar radiation, and provides better simulations of stream flows in comparison to the other PET models (Jensen and Haise, 1963; Oudin *et al.*, 2005).

$$\mathrm{PE} = \frac{R_e}{\lambda\rho}\left(\frac{T_a+K_2}{K_1}\right) \; if \; T_a + K_2 > 0 \qquad (6.1)$$

PE=0 otherwise

Where: PE is the rate of potential evapotranspiration (mm.day^{-1}), R_e = extra-terrestrial radiation (MJm^{-2}.day^{-1}) which depends on latitude and julian day, T_a = mean daily air temperature (°C) is a function of the Julian day for a given location, λ = latent heat flux (assumed equal to 2.45MJkg^{-1}) and ρ represents the density of water (kg.m^{-3}). The constants K_1(°C) and K_2 (°C) are the model fixed parameters which are fixed for each rainfall/runoff model.

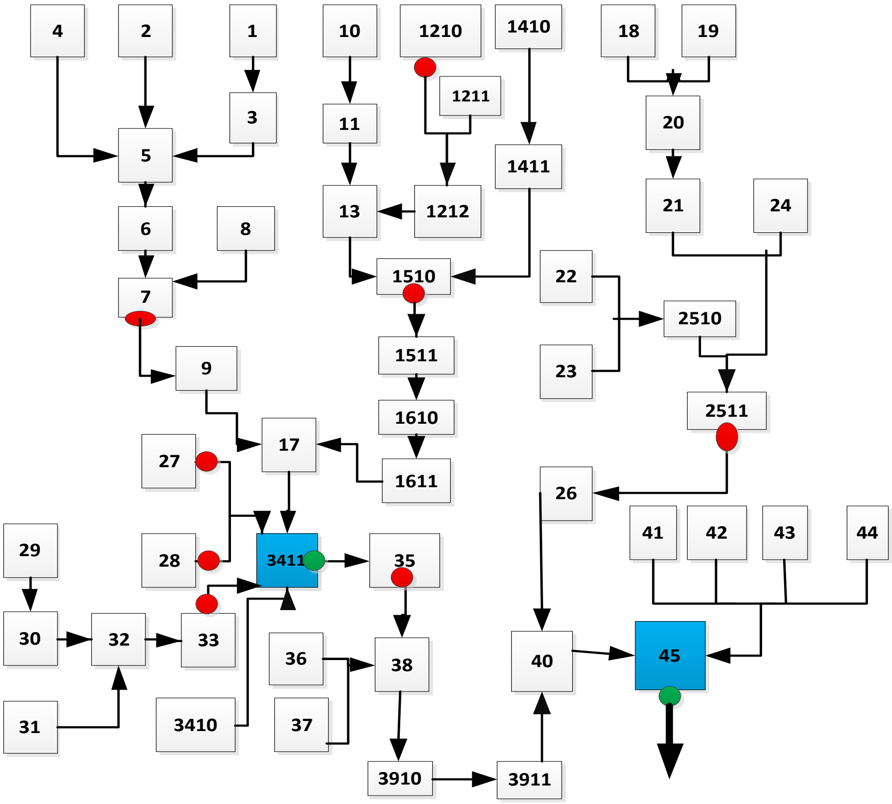

Figure 6.3 Direction of flow in the catchment, where a white square represents a sub-catchment, a blue square represents a reservoir sub-catchment, a red circle represents a gauging station and a green circle for an outflow from a dam

In estimating effluent generation from the households not connected to municipal wastewater plants for each sub-catchment, the ArcGIS tools have been used to overlay sub-catchments and administrative boundaries. An equal distribution of the population within a sub-catchment was assumed, and the fraction of the population per sub-catchment was calculated, using the 1996 population census data in four local municipalities covering the upper reaches of uMngeni Catchment namely, Impendle, uMngeni, Mooi-Mpofana and uMshwati (SSA, 2016). Domestic wastewater generation was estimated to be 150 litres per capita per day, which is the average domestic wastewater discharge established by the Department of Public Works (DPW) (DPW, 2012).

In the model set-up, rating curves of the two lakes (the Midmar and Albert Falls Dams) were defined in the lakeData file, while the average daily water abstraction and water transfer were added as negative and positive point sources, respectively, in the model file

PointSourceData. Information on the fraction of water withdrawn from groundwater for irrigation in each sub-catchment was set in the MgmtData file. Data on the amount of fertilisers and the timing was obtained from the literature and from the ACRU-NPS Model, as well as information on the soil water holding capacity and the number of soil layers and their corresponding thicknesses. Concentrations of nitrogen and phosphorus in the effluent discharge, rivers and daily streamflow data were acquired from the South African Department of Water and Sanitation (DWS) webpage and from UW. More details on the source of the model inputs are presented in Table 6.1.

Table 6.1 Sources and types of input data for the HYPE Model in the upper reaches of the uMngeni Catchment, where CWRR = Centre for Water Resources Research; DWS = Department of Water and Sanitation; and UW = Umgeni Water

	Data	**Data type**	**Source**
1	Climatological data	Daily precipitation	(Warburton, 2012)
		Daily air temperature	(Warburton, 2012)
2	Geographic data	Sub-basin area	(Warburton, 2012)
		Land use types	(NLC, 2000)
		Elevation/slope means	(Weepener *et al.*, 2011b)
		Hydrographical network, stream drainage depth, main river length	(Weepener *et al.*, 2011a)
3	Dam information	Depth, regulation rules, rating curve	DWS
4	Soil data	Soil layer depth and number of horizons, soil layer thickness, soil water holding capacity	(Land Type Survey Staff, 1972-2006; Schulze, 2007)
		soil nutrient content (initial nutrient storage)	Literature
		Soil texture	(Land Type SurveyStaff, 1972-2006; Schulze, 2007)
5	Water quality	Measured daily streamflow	DWS/UW
		weekly/monthly nutrient concentrations (dissolved inorganic nitrogen (DIN), soluble reactive phosphorus (SRP) and total phosphorus (TP))	Umgeni Water
6	Agricultural practices	Manure and inorganic fertilizer application, crop husbandry, timing and amount of fertilization, sowing and harvesting for the area	Literature
7	Water management	Sub-catchment fraction of irrigation Water withdrawn from the groundwater	(WARMS, 2014)
8	Other source of nutrients	Flow from rural household not connected to the municipal wastewater works	Literature
		Discharge and concentration of DIN, SRP and TP	UW, DWS
		Atmospheric deposition	Literature

6.3.4 Model calibration and evaluation

The HYPE model has over one hundred parameters. Most of them are either general, land use or soil-type dependent (Lindström *et al.*, 2010). Consequently, a step-wise manual calibration was carried out, starting with the parameters affecting the hydrological simulation and followed by the water quality calibration (Strömqvist *et al.*, 2012). The calibration involved an iterative adjustment of the model's input parameters, until the model outputs represented the hydrological behaviour of the catchment as far as possible, through verification against observed data. As the water quality component of the model has been largely used in the climatic and physiographic conditions of the northern hemisphere, many of the water quality variables were adjusted to the conditions of the study area.

From the nine gauging stations (Nodes 7, 27, 28, 1510, 2511, 33, 3411, 35 and 45), only three stations 2511 (DWS number U2H006), 1510 (DWS ID number U2H007) and 7 (DWS ID number U2H013) were selected for the calibration of both hydrology and nutrients (DIN and TP). These stations have a complete data set of daily discharges and weekly nutrient concentrations, they are located upstream of the two large impoundments of the study area, they are less influenced by urban development, they cover approximately 60% of the catchment surface and they have different land use and land cover types. The model was calibrated for the period 1989-1995 for both the streamflow and water quality. The streamflows and water quality were validated for the period 1961-1999 and 1995-1999, respectively, following the hydrological year, which starts on the 1st October and ends on 30th September. A number of parameters that affect the generation of runoff at the outlet of each sub-catchment, were manually adjusted.

The most important parameters that affected the simulation of runoff in the model are divided into two categories: those linked to land use, for example, the crop coefficient for potential evapotranspiration (Kc); those that are more general, like the factor for calculating the soil water limit for evapotranspiration (lp); and others related to the flow and retention of water in the soil viz. the runoff coefficient for the first and second soil layers (rrcs1 and rrcs2), the wilting point (wcwp), the effective porosity (wcep) and the field capacity (wcfc).

For water quality, the HYPE model simulates immobile and dissolved pools of nitrogen and phosphorus, which are influenced by the soil properties and external sources of nutrients.

In this study, the concentration of DIN was largely controlled by the initial values of the pools of humus (humusN) and the fast-organic nitrogen in the soil (fastN), as well as the amount of N in manure (mn1) and fertilisers (fn1) applied to the soil. The process of transformation of nitrogen in the soil and water, such as the crop uptake function of nitrogen (up1), the denitrification in local/main rivers (denitwl/denitwrm), in lakes (denitwrl) and in soil (denitrilu), influences the outputs of DIN. The outputs of TP also depend on the initial soil pools of phosphorus (humusP, partP, fastP), crop uptake function (up1), as well as the amount of P in fertilisers (fp1), in manure (mp1) and in decaying plants (resP). The soil type dependent factors namely, the phosphorus leaching factor (freuc), soil erodibility (soilerod) and soil resistence to erosion (soilcoh) also have slight effects on the output of P. An adjustment of the rate of sedimentation of particulate P in lakes (sedPP) and the sedimentation and resuspension of PP in the local watercourse also have minor effects.

The performance of the model was evaluated, using commonly-used statistics in hydrology, such as the Nash Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970), which compares the residual variance of the simulated and the measured data, the Pearson's correlation coefficient (r), which describes the degree of collinearity between the modelled and the measured data, and the percent bias (PBIAS) (Arnold *et al.*, 2012; Yin *et al.*, 2016), which represents the capability of the model to capture the water balance (Moriasi *et al.*, 2007; Yin *et al.*, 2016). The NSE ranges between $-\infty$ and 1, with a perfect fit when NSE = 1. An acceptable performance value of NSE between 0.0 and 1.0 was suggested for a daily time-step, whereas the NSE value < 0.0 indicates an unacceptable performance.

The optimal value of PBIAS is 0, whereas the positive and negative PBIAS values indicate the model over-estimation and under-estimation of the flow, respectively (Gupta *et al.*, 1999; Jomaa *et al.*, 2016). Moriasi *et al.* (2007) highlighted that, for a monthly time-step, the absolute PBIAS value $\leq$ 25% and NSE >0.5 for streamflow can be judged as satisfactory. The Pearson's correlation coefficient ranges between -1 and +1, depending on whether a negative or a positive relationship exists between the simulated and the observed values, while an r = 0 shows non-existent of relationship between the variables. Moreover, graphical visualisation techniques were also used on time-series data, to examine the capability of the model to represent the peak and the base flow events (Moriasi *et al.*, 2007; Crout *et al.*, 2008). These evaluation criteria were used in other applications of the HYPE model (Strömqvist *et al.*, 2012; Jomaa *et al.*, 2016; Yin *et al.*, 2016). Moreover, another evaluation criterion, comparing the average daily simulated and observed flows, was used. An acceptable simulation is achieved when the percentage difference between the observed and simulated daily streamflows is less than 15%. This criterion was used in former studies in the catchment (Warburton *et al.*, 2010). Lists of the most sensitive parameters used in the calibration as well as their physical meaning, are presented in Appendices 6.A, 6.B and 6.C.

The equations of NSE, r and PBIAS are described below:

$$\mathrm{NSE} = 1 - \frac{\sum_{n}(s-o)^2}{\sum_{n}(o-\bar{o})^2} \qquad (6.2)$$

$$\mathrm{PBIAS} = \frac{\sum_{n}(s-o) * 100}{\sum_{n} o} \qquad (6.3)$$

$$r = \frac{\sum_{i=1}^{n}(s-\bar{s}).(o-\overline{o})}{\sqrt{\sum_{i=1}^{n}(s-\bar{s})^2.\sum_{i=1}^{n}(o-\bar{o})^2}} \qquad (6.4)$$

Where (s) stands for simulated, (o) for observed, (s) for simulated, $\bar{o}$ for average observed value and ($\bar{s}$) for average simulated.

6.4 Results and discussion

6.4.1 Simulation of streamflows

During the calibration period (1989-1995), the HYPE model has satisfactorily simulated water flow at seven sub-catchments out of nine (NSE ≥ 0.0). The best model performances were noted at the outlets of sub-catchments 7, 28, 2511, 35 and 3411 (NSE~0.6), with unacceptable simulations at Site 33 (NSE <0.0). A linear relationship between simulated and observed values was noted (r ranging between 0.5 and 0.8) in all nine sites, during both the calibration and validation periods. In the validation period, NSE remained in the same range, with a slight improvement at Site 45 (NSE = 0.5) and with the exception of the Site 33 (NSE = -0.5). As suggested by Moriasi *et al*. (2007), the shorter time intervals, the poorer the model simulations. Thus, the simulation of streamflows at a monthly step provided acceptable simulation results (NSE > 0.5) at six out of the nine stations (Table 6.2).

The NSE value <0.0 for daily and monthly simulations at Site 33 suggests that observed streamflows are better predictors than simulated values, which indicates a generally poor performance of the model at this site. This poor performance at Site 33 may be attributed to possible errors in the observed streamflow and a short time-span of observed streamflows. The good simulations at outlet of sub-catchment (45) were achieved after adding manually the daily water release from Albert Falls Dam into the simulated streamflows. This resulted in good representation of the water balance in the model (PBIAS of -4.8 % for calibration and -7.7% for validation periods). Furthermore, these under-simulations of the water balance of the model in downstream sub-catchments (3411 and 35) during the validation period (Table 6.2) can also be ascribed to the simplified evapotranspiration processes in the HYPE model (Strömqvist *et al.*, 2012; Jiang *et al.*, 2014).

The values of PBIAS indicated a good performance of the model in four sub-catchments, for the validation period, with some improvement for a monthly time-step (PBIAS ≤ 25%). An over-simulation of streamflow was noted during the calibration period at the uMngeni at Petrus Stroom (7), at the outflow of the Midmar Dam (3411) and at the uMngeni in Howick (35), with good simulation at Node 45, where the absolute values of PBIAS were less than 25% (Table 6.2). During the validation period, there was alternation between the over-simulation of flows in some sub-catchments (1510) and under-simulation in the others (7, 2511, 3411and 35).

Table 6.2 Model performance statistics for streamflows during the calibration and validation periods, where (1) and (2) stand for daily and monthly time-steps, respectively

Sub-		**Calibration**			**Validation (1)**			**Validation (2)**		
Catchment	*ID*	*NSE*	*R*	*PBIAS*	*NSE*	*r*	*PBIAS*	*NSE*	*r*	*PBIAS*
Petrus Stroom	7	0.6	0.8	56.2	0.5	0.7	-29.8	0.7	0.9	-29.5
Lions River	1510	0.4	0.7	10.5	0.3	0.6	28.0	0.3	0.7	28.3
Karkloof Shafton	2511	0.6	0.8	-3.7	0.5	0.7	-29.8	0.7	0.9	-31.2
Gqishi	27	0.5	0.8	2.2	0.5	0.8	2.1	0.6	0.9	1.3
Nguklu	28	0.6	0.8	-5.9	0.6	0.8	-4.4	0.7	0.9	-4.1
Mthinzima	33	-0.5	0.5	8.6	-0.5	0.6	8.1	-1.6	0.8	9.1
Outflow Midmar	3411	0.6	0.8	65.8	0.5	0.7	-36.7	0.7	0.9	-36.4
uMngeni/Howick	35	0.6	0.8	85.0	0.4	0.6	-42.3	0.5	0.8	-40.8
Ouftflow Albert Falls	45	0.3	0.7	-4.8	0.5	0.8	-7.7	0.5	0.8	-12.2

The high flow events were captured well in some instances, while in the others, a model deviation was noted (Figure 6.4). A generalised over-simulation of base flow was identified in the three representative sub-catchments (Figure 6.4). The model has consistently predicted high streamflows in the summer months (December to February), which is the period when much of the rain falls in the catchment, and low streamflows in the winter months. Moreover, the non-inclusion of a large number of farm dams within the catchment could have increased the level of uncertainties in the model outputs (Venohr *et al.*, 2005). Inconsistencies in representing the low flow events that occurred between August and November were noted, with their over-simulation in some instances (for example, at Site 7 on 5/10/1992 and 20/09/1993, at Site 1510 on 20/09/93 and 22/10/1992, at Site 2511 on 18/09/1993 and 16/09/1995), as well as their under-simulation (for example, at Site 7 on 18/8/1990, at Site 1510 on 22/9/1991 and at Site 2511 on 10/09/1991). This has further implications on the simulation of nutrients. Non-representation of some peak flows in the HYPE model was reported by other studies, as a result of the low precision of the model in capturing flash flood events, which are caused by heavy and short-term rainfall events (Jiang *et al.*, 2014).

However, the high percentage of over-prediction of streamflows (30%) recorded at Petrus Stroom (7) during the calibration period, decreased to 12% during the validation period (Table 6.3). This is consistent with findings of Donnelly *et al.* (2016) who reported on the poor representation of daily hydrographs and extremes in mountainous regions. Otherwise, the HYPE model has provided acceptable simulations of streamflow in eight sub-catchments, as indicated by the statistics presented in Table 6.2. The modelled daily simulated streamflows exceeded the measured values by less than 15% for the validation period (1961-1999), which confirms the acceptability of our results at the three sites used for the calibration (Table 6.3). Our percentages of the over- or under-estimation of streamflows are comparable to the findings of Warburton *et al*. (2012), which are 7.9% at Site 7, 9.9% at Site 1510 and 13.05% at Site 2511 for average daily simulations (for the period 1987-1998). However, the HYPE Model provided better representations of high flow events than ACRU, despite its over-prediction of low flows. For this study, an over-simulation of low flows could be ascribed to the recession coefficients, which control the downward movement of water in the soil.

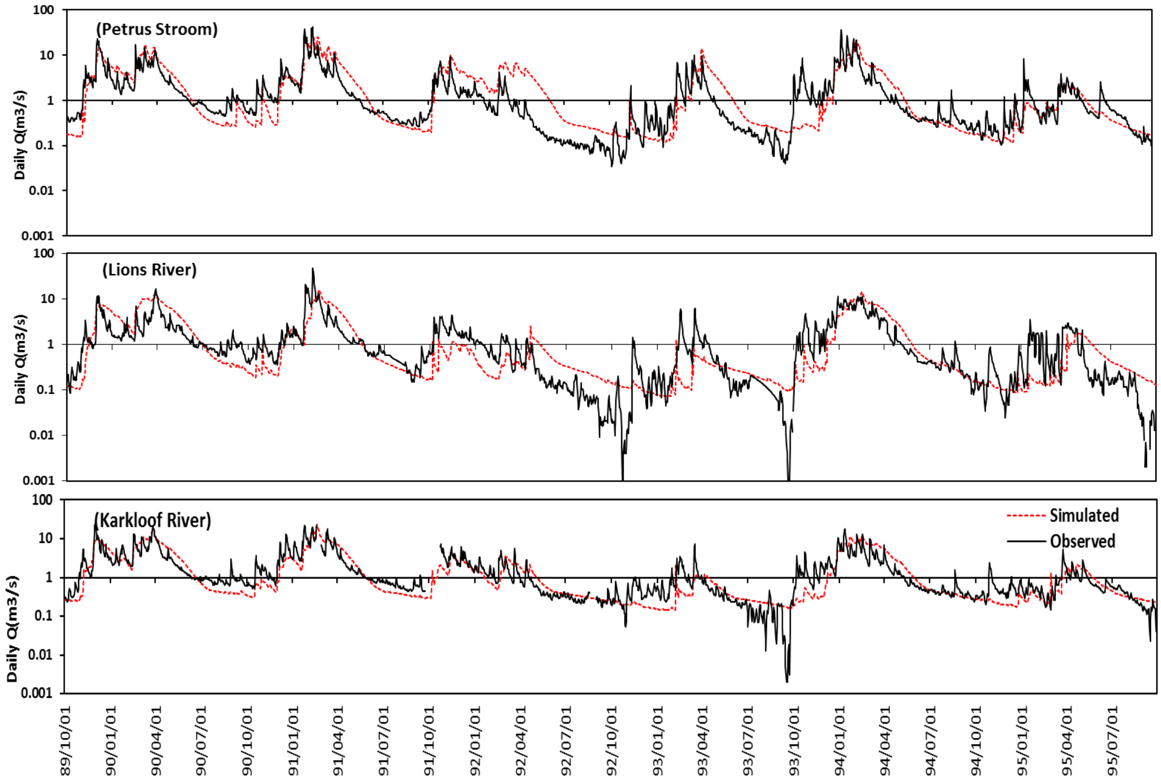

Figure 6.4 Comparison of daily simulated and observed streamflows at three sub-catchments (on log scale): Petrus Stroom (7), Lions River (1510) and Karkloof River (2511), during the calibration period (1989-1995)

When the model was run for a monthly time-step, many improvements were noted in the model's performance, where the NSE value for calibration and validation at four sub-catchments (7, 2511, 28 and 3411) was 0.7, as presented in Table 6.2. Furthermore, the graphic visualisation showed good fits between the monthly simulated and observed streamflows, and the high and low streamflow events are represented well (Figure 6.5). The severe drought in 1983 and the 1987 floods that occurred in the catchment were effectively captured by the model (see Figure 6.5).

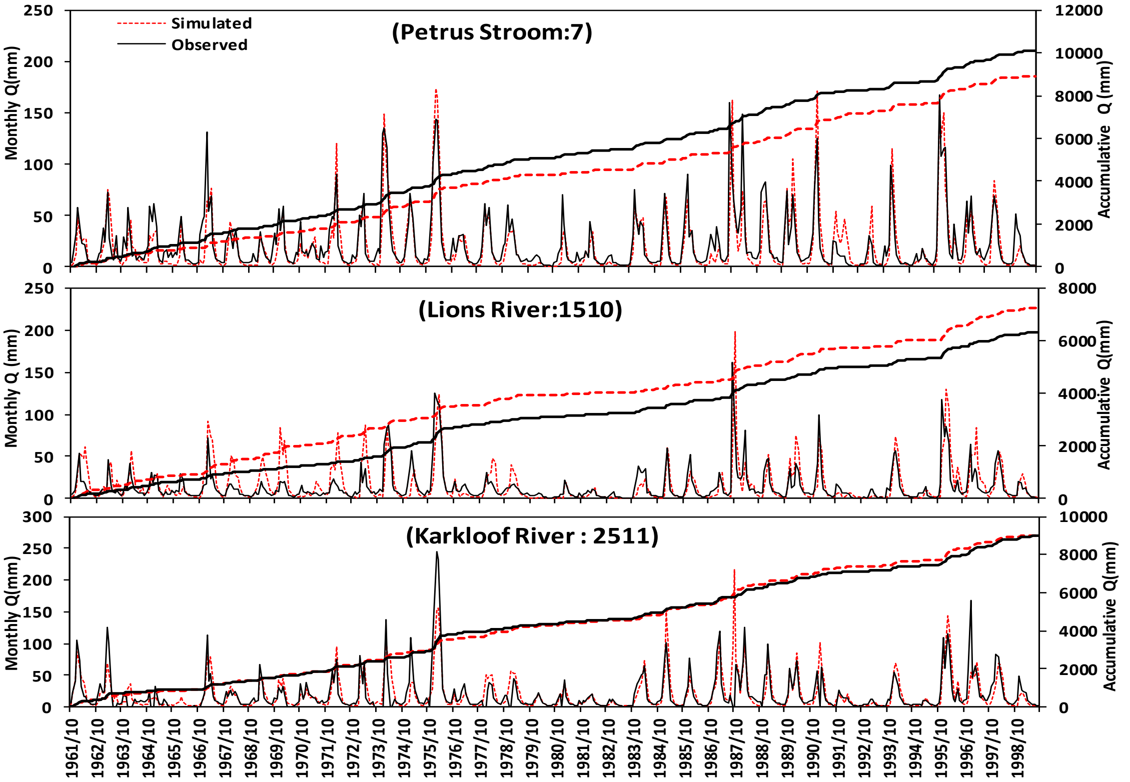

Figure 6.5 Comparison of monthly totals of daily simulated and observed streamflow during the validation period

Table 6.3 Summary of daily streamflow simulations during the calibration (1989-1995) and validation (1961-1999) periods at three sites, 7, 1510 and 2511, where c stands for the calibration period, v represents the validation period, sim for simulated and obs for observed

	Catchment ID (Km^2)		**7 (294.01)**		**1510 (356.21)**		**2511(334.29)**	
		Unit	Obs	Sim	Obs	Sim	Obs	Sim
c	Accumulative streamflow	Mm	1217.6	1579.3	788.2	843.8	1035.2	1054.5
	Average daily streamflow	mm/day	0.56	0.72	0.36	0.39	0.47	0.48
	Standard deviation	mm/day	1.03	1.13	0.67	0.65	0.73	0.74
	Pearson's coefficient		0.81		0.67		0.77	
	% of under/over-simulation	%	-29.71		-7.06		-1.87	
v	Accumulative streamflow	Mm	10180.1	8965.8	6357.7	7301.7	9390.2	8855.7
	Average daily streamflow	mm/day	0.73	0.65	0.46	0.53	0.68	0.64
	Standard deviation	mm/day	1.42	1.06	1.09	0.84	1.35	1.04
	Pearson's coefficient		0.70		0.59		0.62	
	% of under/over-simulation	%	11.93		-14.85		5.69	

6.4.2 Simulations of water quality

We have simulated TN, DIN, ON, PP, SRP and TP in the model. However, in the section below only the concentration of DIN and TP are presented, as no historical data on TN were available. Thus, TN was not calibrated. Moreover, in the model input data, the PP was calculated as the difference between TP and SRP and most of data points on SRP were below the detection limit of the analytical methods used at the UW laboratories (5ugP/L). In the evaluation of the daily simulations of water quality outputs, we have avoided using the NSE coefficient, since the errors are compared to the variance of the concentrations data, which were collected on a weekly sampling-frequency. The graphical visualisation techniques and the Pearson's correlation coefficient r were used in this case. This approach has also been followed in other applications of the HYPE Model (Strömqvist *et al.*, 2012).

A high variability in the concentrations of DIN in the simulations was noted, as presented at Figure 6.6. For example, some spikes in concentrations were identified during the period of low flows, while the others were noted during high flows events. This was noted at all three sites during the calibration and validation periods. The occurrence of large concentrations of DIN was noted during the winter months and in the first months of summer. These high values of DIN in winter could be ascribed to the possible release of nitrates from ammonium-nitrate fertilisers in the agricultural lands, with a substantial leaching of NO_3 into the water. Furthermore, the contribution of bush burning, a common practice in the area during the winter months, as well as the first rains falling at the beginning of summer, cannot be ignored, as they transport the accumulated nutrients into the landscape.

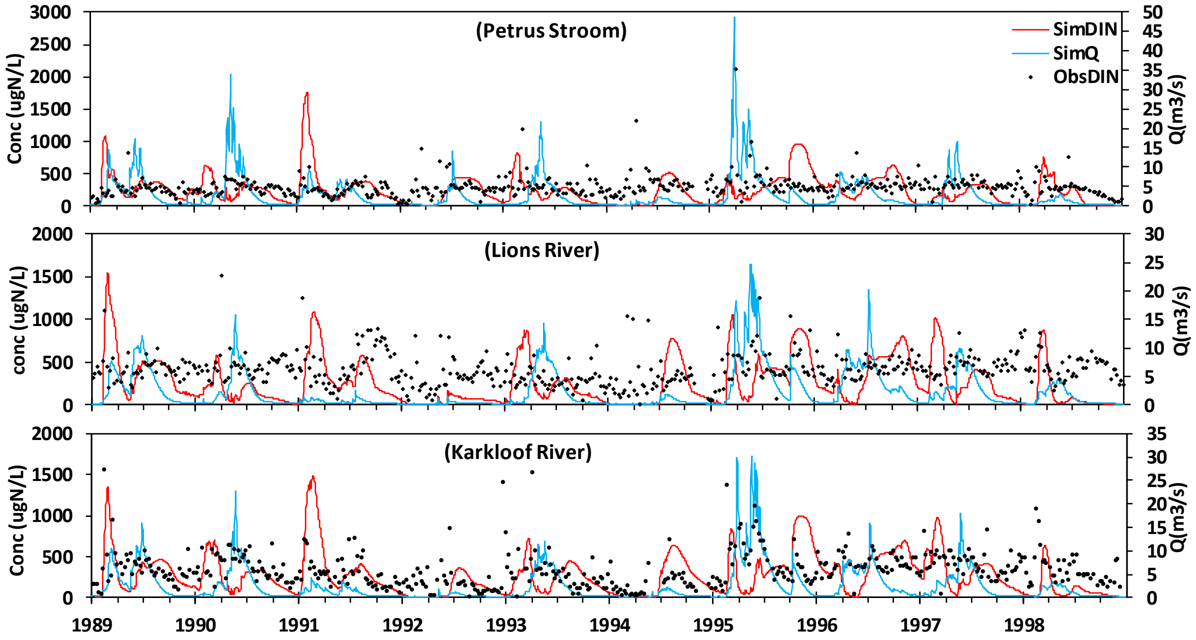

Figure 6.6 Comparison of model predictions of DIN with observed data, at Petrus Stroom (7), at Lions River (1510) and at Karkloof River (2511), for the calibration (1989-1995) and validation (1995-1999) periods. The red line represents the daily simulated concentrations (μg/L), the blue line represents the simulated daily stream flow and the dots represent the observed weekly concentrations (μg/L).

An under-simulation of DIN concentrations was found at the three sub-catchments in February 1991 and December 1995, when flood events occurred in the catchment, but runoff was captured well. The model seems to result in dilution of DIN during floods while observed data seems to show that the floods are mobilising the DIN. In general, in cases where high concentrations of DIN were measured in period of high peak flows, the model under-estimated these consistently across the three sub-catchments (Figure 6.6). Despite these mismatches between the simulated and observed DIN, an overall under-simulation of DIN was noted during the validation and calibration periods.

The daily concentration of TP followed the pattern of the simulated streamflows. This indicated that much of runoff in the catchment coincides with the high contents of TP in water during the period from December-March (Figure 6.7). Therefore, some peaks of the observed values greatly exceeded the simulated values, and vice versa. The possible reasons could be that: (1) water quality samples emanate from a grab sampling programme, which cannot capture all high flow events, (2) samples are usually collected in the morning, while much of the rain in the catchment falls in the afternoon (Ngubane, 2016), (3) the model itself provides average daily concentrations of nutrients, indicating that short high flow events are not captured well, which may result in the release of high levels of P and N from farm dams, (4) phosphorus release by the soil and in-stream erosion, since the soil-phosphorus cohesion properties in the catchment limit its release; and (5) a number of data points of the measured TP were below the detection limits (<15 µgP/L) of the analytical methods used at Umgeni Water's laboratories (for example, from May to October 1994 for Petrus Stroom and from April to September 1991 for the Karkloof River).

In comparison to DIN, the TP outputs were satisfactory, as the percentage of under-/over-simulation at Sites 7, 1510 and 2511 were -4%, -9% and +6%, respectively, for the period 1989-1999. However, under-simulation of DIN at Sites 7, 1510 and 2511 were 24%, 39% and 18%, respectively, which indicates the poor performance of the model for DIN.

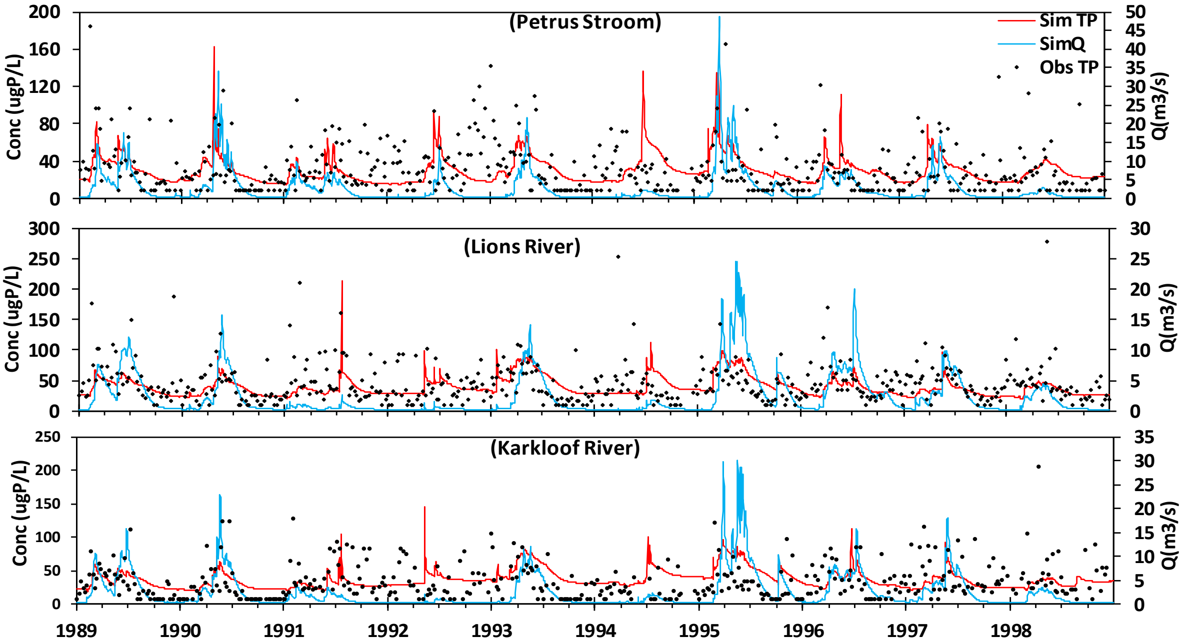

Figure 6.7 Comparison of model predictions of TP with observed data, at Petrus Stroom (7), Lions River (1510) and Karkloof River (2511), for the calibration (1989-1995) and validation (1995-1999) periods. The red line represents the daily simulated concentrations (µg/L), the blue line represents the simulated daily stream flows and the dots represent the observed weekly concentrations (µg/L).

6.4.3 Evaluation statistics of water quality

The performance of water quality simulations indicated that for TP, ten of the twelve sites have positive Pearson's correlation coefficients. The highest r of ~0.4 was noted at Site 33 (representing the Mthinzima outflow to the Midmar Dam). However, the strength of this linear relationship declines during the validation period, with a maximum value of 0.28 at Site 7. Simulated IN correlated well with the measured values, compared to TP, especially during the calibration period (r=0.55 at 1210). A generally poor performance of the model in the sub-catchments downstream of the Midmar Dam was identified (Table 6.4).

Table 6.4 Nutrient simulation performance indicated by a correlation coefficient (r) during the calibration and validation periods. ID represents the sub-catchment number; TP represents the total phosphorus and DIN represents dissolved inorganic nitrogen

Sub-catchment	***Sub-basin***	***Calibration (89-95)***		***Validation (95-99)***	
Name	*ID*	*TP*	*DIN*	*TP*	*DIN*
Petrus Stroom	7	0.171	0.048	0.287*	0.012
Mpofana	1210	-0.285	0.554*	0.127	-0.040
Lions River	1510	0.208	0.086	0.266*	0.125
Inflow Midmar	17	0.080	-0.005	-0.103	0.032
Karkloof 1**	2510	0.012	0.143	-0.004	0.189
Karkloof at Shafton	2511	0.236	0.235	-0.002	0.035
Mthinzima	33	0.382*	0.329*	0.144	0.357*
Outflow Midmar	3411	-0.037	0.258	-0.038	-0.059
uMngeni/Howick	35	0.101	-0.206	0.227	-0.068
uMgeni d/s Howick	3910	0.152	-0.083	0.003	0.003
uMgeni/Morton Drift	40	0.064	-0.320	0.120	-0.155
outflowAlbert Falls	45	0.197	0.114	0.064	0.052

* represents the sub-catchments with a high correlation coefficient and ** represents downstream

6.4.4 Seasonal distribution of flows and nutrients

An assessment of the seasonal distribution of runoff and the concentration of DIN and TP was undertaken for the period between 1989 and 1999. The results showed some mismatches between the simulated and the observed DIN. They also indicated that the routing and biogeochemical transformation of DIN in-streams is largely driven by the hydrological processes in the HYPE Model. The lowest simulated concentrations of DIN were noted in January-February, as mentioned in Figure 6.6, which is a period of high runoff generation in the catchment (Figures 6.8a and 6.8c). These discrepancies may be ascribed to the high nitrogen uptake by crops, an increase in the denitrification process, due to the high temperature of the water, as well as the possible dilution of the water. Another reason that may explain this is the high turbidity that characterises the water in the catchment, which can speed up the denitrification process. In this regard, these findings are similar to those reported by Jiang *et al.* (2014) and Jomaa *et al.* (2016) in nested mesoscale catchments in central Germany.

In contrast to the DIN, the concentrations of TP followed the streamflow patterns concurrently (Figures 6.7, 6.8b and 6.8c). At these three sites (7, 1510 and 2511), the model under-predicted the peak concentration of TP (January-February), while during the low flow months (May to September), an over-prediction of TP was noted at 2511, with fluctuations in TP at Sites 7 and 1510 (Figure 6.8b). In general, there has been a good fit between the simulated and observed TP and streamflows in the catchment, which indicates the capability of the model to represent the runoff and TP generation in the catchment. The seasonal distribution of runoff was reproduced well, with the highest flow in January-February and the lowest in September, as also reported by Kienzle *et al.* (1997). Moreover, in-stream erosion and soil erosion which are not modelled in HYPE, are reported to contribute significantly to the phosphorus concentration (Pers *et al.*, 2016). In addition, it appeared that HYPE lagged the observations of nutrients (especially TP) and streamflow at sub-catchments 7, 1510 and 2511 (Figures 6.8b and 6.8c). This could be attributed to incremental contribution of upstream sub-catchments (river lengths) and high retention rate of TP in the catchment (Breen, 1983; Lindström *et al.*, 2010).

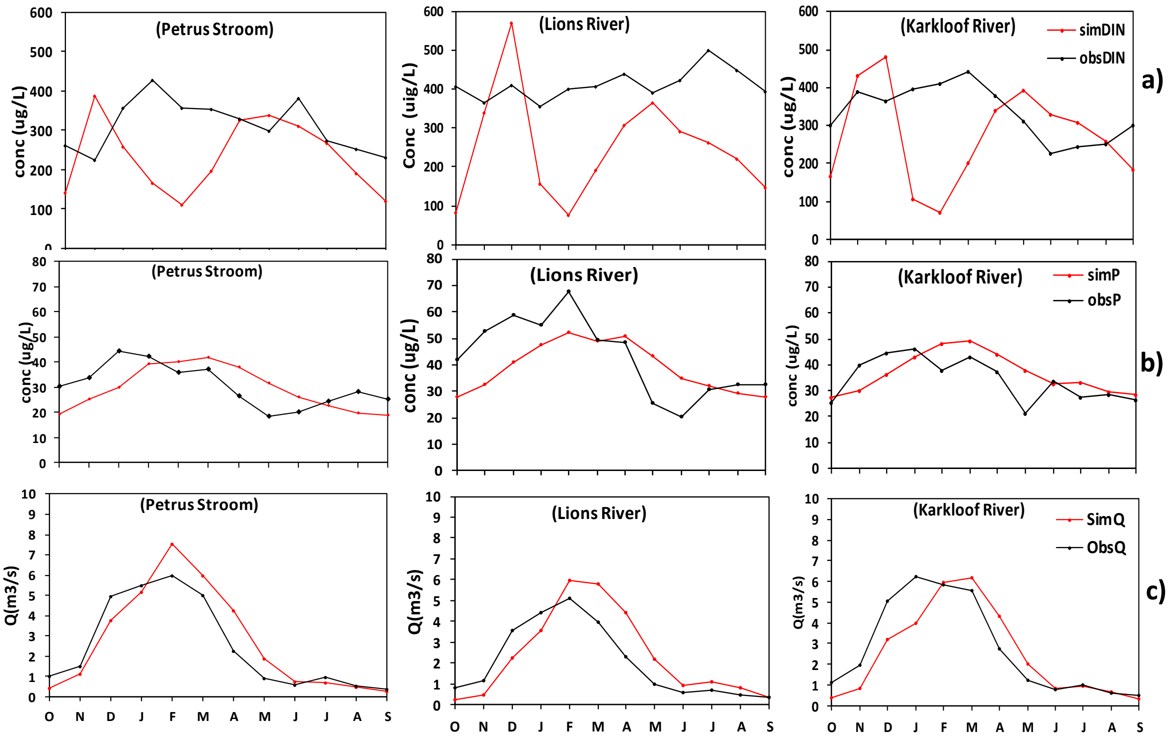

Figure 6.8 Results of water modelling (seasonal distribution) of DIN in (a), TP (b) and flows (c), at Sites 7, 1510 and 2511, for the period (1989-1999). Sim stands for the simulated, Obs represents the observed, Q represents the streamflow, DIN represents the dissolved inorganic nitrogen and P represents the total phosphorus

6.4.5 Distribution of DIN and TP in the catchment

The map of the average-weighted annual distribution of DIN concentrations relates the large values of DIN in sub-catchments with intensive agricultural activities, such as upstream of Site 1611 (Figure 6.9a). It also shows the sub-catchments with significant point sources of pollution (33 and 37) and it highlights a substantial retention of DIN in the Midmar Dam. The highest concentrations of DIN were identified in sub-catchments with a high density of informal settlements (29, 30, 32, 33 and 37), as well as to the waste water treatment works (Figure 6.9a). Thereafter, the sub-catchments with a dominance of agricultural lands, i.e. commercial planted forests (43), as well as irrigated and dryland cultivation (upstream of sub-catchment 17, 27 and 28) (Figure 6.9a and Figure 6.1c). In contrast, very high concentrations of TP are identified in the sub-catchments located in the stretch between the Midmar and Albert Falls Dams (Figure 6.9b). This indicates that TP originates mainly from the point sources of pollution, while DIN comes from both the diffuse and point sources.

These findings confirm the high phosphorus-adsorption nature of the soil in the catchment, which reduces its leaching during runoff (Breen, 1983). Based on these results, an increase in the concentration of TP in the water of the Midmar and Alberts Falls Dams (3411 and 45) could be ascribed to outflows from the surrounding sub-catchments, supplemented by the point sources of pollution upstream of the Albert Falls Dam, such as Cedara, St Anne's, Howick, Mpophomeni Township and many feedlots (Hudson *et al.*, 1993; Kienzle *et al.*, 1997; DWAF, 2008; Taylor *et al.*, 2016).

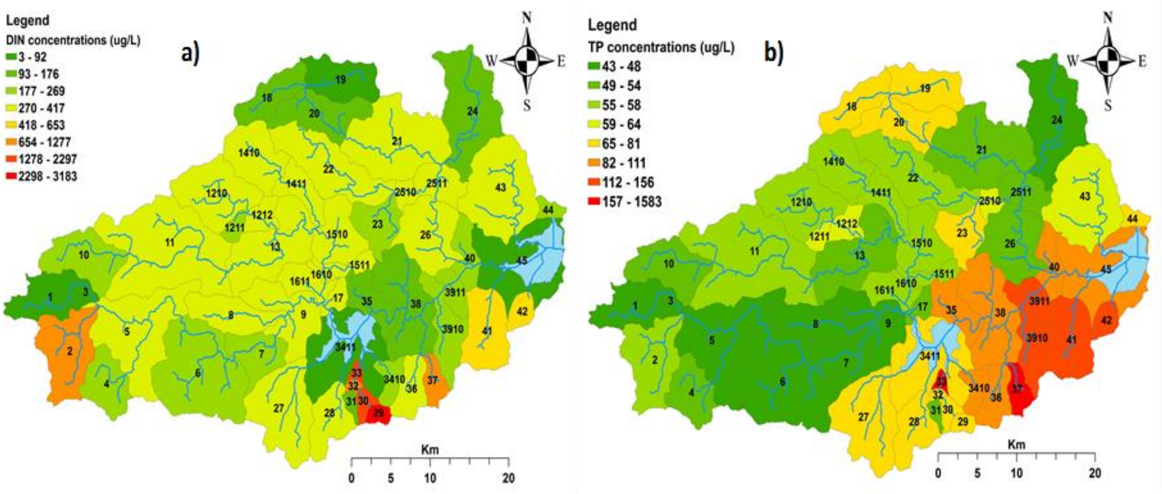

Figure 6.9 Mean annual concentration of DIN (a) and TP (b) in the catchment for the period 1989-1999

In general, large concentrations and loads of DIN are identified in the upstream sub-catchments, where the expansion of agricultural activities, with the subsequent application of fertilisers is dominant (Ngubane, 2016). It is in these sub-catchments where the proportion of agricultural lands ranges between 25% (Site 7) and 47% (Site 2511). Planted forests are dominant in this area, irrigation practices are concentrated upstream of Site 1510 (Cullis *et al.*, 2005) and much of the runoff is generated in these three catchments. In addition, increased trends in concentration of nutrients were reported in Spring Grove Dam and Mearns Weir, the intakes of the inter-basin transfer schemes to the sub-catchment 1210 (DWAF, 2008). Moreover, the steep slopes in the high-land areas of sub-catchments 2, 4, 6, 13 and 1210, can accelerate the transport capacity of DIN, owing to interflow, which is the major process driving the movement of nitrogen in the soil (Jiang *et al.*, 2014). High concentrations of DIN in agricultural sub-catchments were also reported by Ahearn *et al.* (2005), Jiang *et al.* (2014), Arheimer *et al.* (2015) and Yin *et al.* (2016). Therefore, the load and concentration of IN decreases from the headwaters of the catchment to the outlet, due to retention in dams, in-stream retention and the possibility of a high rate of denitrification in the catchment (6.10a).

A contrasting observation was noted for the load and high concentrations of TP, which are released from the major point-sources of pollution (Figures 6.1 and 6.10b). The commonly-known hot-spots of pollution in the catchment, i.e. the Mpophomeni Township (sub-catchments 29 to 33), as well as the area between the Albert Falls and Midmar Dams, are where human activities are concentrated (4.6 to 23 kg/ha per year of TP). The retention of phosphorus in Midmar Dam does not have a significant effect on TP export in downstream sub-catchments. The presence of the major point sources of pollution mentioned, provides a full justification for this phenomenon.

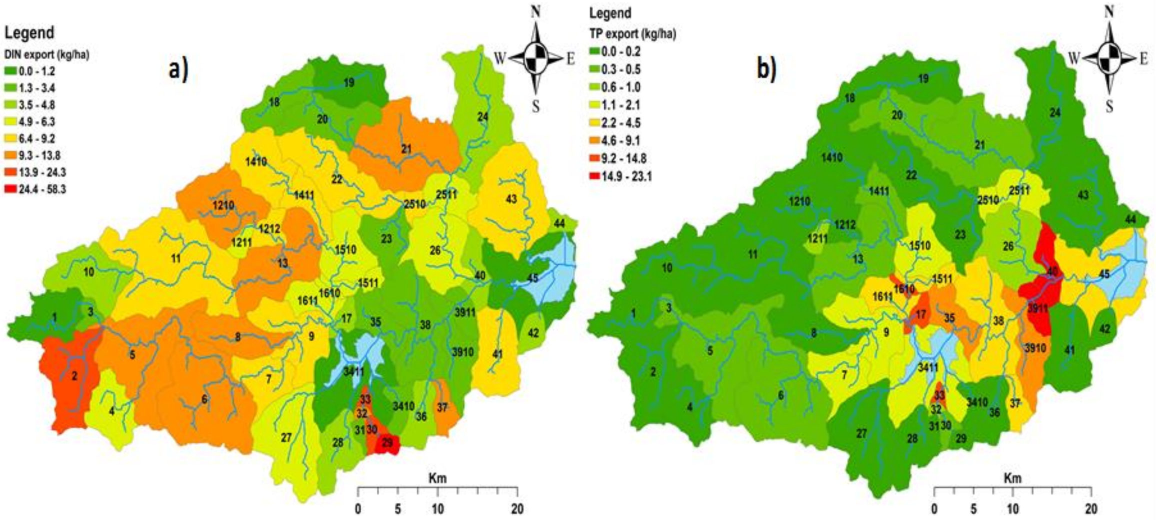

Figure 6.10 Average area-weighted annual DIN (a) and TP (b) loads for each sub-catchment (1989-1999)

The loadings of TP noted upstream of the Albert Falls Dam are consistent with the findings of another modelling study carried out in the catchment for the period 1989-1993, which reported the average annual phosphorus loading values as ranging between 0.5 and 850 kg/km^2, although they are slightly less than the findings of this study (Kienzle *et al.*, 1997). Moreover, a number of flood events that occurred after 1993 provided more information on such increased yields of TP. Previous research studies in the catchment (Kienzle *et al.*, 1997;

Dabrowski *et al.*, 2013), as well as the current study, lead to a general conclusion that the area between the Midmar and Albert Falls Dams is the largest source of TP yield in the upper reaches of uMngeni Catchment.

6.4.6 The way forward on applications of the HYPE model in the upper reaches of the uMngeni Catchment

The application of the HYPE model in the upper reaches of uMngeni Catchment has involved the collection of data from various sources and no field work was carried out. Possible errors in the observed data were anticipated, which may lead to uncertainties in the model outputs. The model has represented high steamflow events very well, but low streamflows were oversimulated in most of the cases. Therefore, there is a need to improve this performance of the model, especially at Node 7, where an over-simulation of streamflow was noted.

Overall simulations of streamflow in the area provided acceptable results, as indicated by the statistical performance criteria, where NSE > 0.0 at eight of the nine stations for a daily time-step and NSE ≥ 0.5 at six sites for a monthly time step. The poor performance of the model was noted in some sub-catchments downstream of Midmar Dam, which could be influenced by some urban development and the simplification of processes that drive the spatial variations of evapotranspiration in HYPE model, the simplification of water abstraction, as well as releases from dams and inter-basin transfers in the model.

More than 100 parameters reflect the routing and dynamics of water and nutrients, and many of these are specific to the northern hemisphere climatic, topographic and hydrological conditions (for example, shallow groundwater, thick soil, many lakes, seasonality, agricultural management and water management practices). An adjustment was made to some of them, to reflect the local conditions. Of course, a number of these parameters were used by default in the model calibration and this may increase uncertainties in the model outputs.

6.5 Conclusion and recommendations

The HYPE model was tested in the upper reaches of the uMngeni Catchment to simulate streamflow, DIN and TP at a daily time-step, using historical climate data. The model was calibrated, following a stepwise approach. The most important factors affecting the predictions of runoff in the model were crop coefficient (Kc) (land use dependent), the recession coefficients of the two upper soil layers (rrcs1 and rrcs 2) and the variables related with the water storage of the soil (field capacity, wilting point and effective porosity). The most sensitive parameters in the simulation of DIN and TP were denitrification (denitrlu and denitwl for DIN), the initial pools of nutrients (resn, resp, humusPO, humusNO, partPO), crop uptake (up1) and the mineralisation of decay of fastN and fastP.

Results indicated that the model represented the water balance well, especially in the headwaters of the catchment where urban development activities are limited. High flow events were captured well, with a general over-simulation of base flow events. An under-estimation of streamflow was identified in the outlet sub-catchments, due to a simplified spatial variation of evapotranspiration processes in the model. However, the model has provided acceptable simulations of streamflows, and the good fits between modeled and measured values, especially at the monthly time-step, where NSE values of ~ 0.7 were noted in four out of the nine sites.

The simulations of DIN and TP in the model are largely influenced by the hydrological and biogeochemical process representations within the model, which indicate that poor performance in runoff simulations in turn affect the dynamics and transport of nutrients. Positive correlation coefficients between simulated and measured DIN and TP were noted in eight of the twelve monitoring sites. Mismatches between the simulated and observed DIN were identified during high flow events, for both the calibration and validation periods, with an overall under-simulation of DIN. The results indicate that the processes driving the loss and retention of nitrogen (denitrification and plant uptake) are intensified during the summer months (where low concentrations of DIN are noted), which is also a period of high temperatures and streamflow in the catchment. The spatial distribution of loads and the concentration of IN showed high values in the upstream sub-catchments, where agricultural and forest lands are dominant, and they decrease from upstream to downstream.

In contrast to DIN, the concentrations of TP followed the streamflow patterns, with spiked concentrations during high flow events. Good fits between simulated and observed TP were noted, which show the large contribution of soil and in-stream erosion to the transport and dynamics of TP in the area. Across the catchment, TP concentrations and loads are released from sub-catchments that have the major point-sources of pollution, and it was clear that they increase from upstream to downstream. The model has provided better predictions of TP, in comparison to those of DIN.

Overall, the testing of the HYPE model in simulating streamflow, DIN and TP has been successful in the upper uMngeni Catchment. The model has represented the streamflow and its seasonal variation in the area well. In addition, the model outputs of average concentrations of DIN and TP and their spatial distribution reflects the reality in the catchment. This has indicated that DIN is attributed to agricultural activities and the point sources of pollution; while TP originates from the point sources of pollution. However, an application of HYPE in the catchment has some caveats related to:

- Simplification of the processes driving evapotranspiration in the model is a key challenge which affects the simulations of runoff in the catchment.
- Moreover, due to the simplification of inter-basin transfer, water abstraction and release in the model, it would make sense to expand the application of the HYPE model to the greater uMngeni Catchment. This will provide a bigger picture of water quality deterioration.
- A lack of updated climate data has limited our study on the simulation of streamflow and nutrients to a period up to 2000. Since then, many transformations have occurred in the catchment, such as the raising of the Midmar Dam wall in 2004 (Hay, 2017), a shutdown of the Mpophomeni waste stabilisation ponds, the construction of inter-basin water-transfer schemes, a decline of water quality in the upper reaches of the catchment (GroundTruth, 2012; Ngubane, 2016) and the conversion of the natural vegetation to residential, agricultural and forest lands (Mauck and Warburton, 2013; Jewitt *et al.*, 2015a; Namugize *et al.*, submitted). Therefore, there is a need to update the model simulations to the more current situation, so that recent developments can be reflected in the simulation. There is also an opportunity to consider scenario analysis of nutrient concentrations, as a result of land use change and land management practices.

Finally, as this study was a first step in the application of the HYPE model in the catchment, there is a need to collect additional data that are required for nutrients simulation in future research, such as wet and dry deposition of DIN and TP, survey on fertiliser application and crop distribution, initial pools of phosphorus and nitrogen of the soil.

6.6 References

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6.7 Appendices

Appendix 6.A

A list of the parameters which affect the in-stream processes, their physical meaning and their calibrated values

Parameter	Physical meaning	Unit	Value
deadl	Dead volume in the local watercourse	$m^2\ km^{-2}$	0.8
deadm	Dead volume in the main watercourse	$m^2\ km^{-2}$	0.005
rivvel	Celerity of flood in watercourse	$m.s^{-1}$	1
damp	Fraction of delay in the watercourse which also causes damping	-	0.5
denitwl	Denitrification in local watercourse	$kg\ m^{-2}\ d^{-1}$	0.000018
denitwrl	Denitrification in lake	$kg\ m^{-2}\ d^{-1}$	0.00012
denitwrm	Denitrification in main watercourse	$kg\ m^{-2}\ d^{-1}$	0.00012
fastN0	Initial concentration of fastN in soil pool	$mg.m^{-3}$	250
fastP0	Initial concentration of fastP in soil pool	$mg.m^{-3}$	200
sedon	Sedimentation of ON in lake	$m.d^{-1}$	0.0099
sedpp	Sedimentation of PP in lake	$m.d^{-1}$	0.007

Appendix 6.B

A list of the selected soil parameters which affect the simulation of streamflow and water quality, their physical meanings and their calibrated values

Parameter	Physical meaning	Unit	Loam	sand clay loam	sand loam	Silty loam	Waterbody
rrcs1	Soil runoff coefficient for the upper most layer	d^{-1}	0.0934	0.1218	0.1341	0.1016	0.0739
rrcs2	Soil runoff coefficient for the lowest layer	d^{-1}	0.0039	0.0036	0.0044	0.0033	0.0021
wcwp	Wilting point as a fraction	-	0.128	0.159	0.093	0.121	0.01
wcfc	Fraction of soil available for evapotranspiration but not for runoff	-	0.123	0.095	0.096	0.151	0.01
wcep	Effective porosity as a fraction	-	0.213	0.148	0.2295	0.218	0.01
soilcoh	Characteristic of soil for calculation of soil cohesion	kPa	0.77	0.165	0.165	0.33	16.5
soilerod	Characteristic of soil for calculation of soil erodibility	$g.J^{-1}$	0.143	0.220	0.242	0.154	0.055
freuc	Parameter in Freundlich equation (coefficient)	kg^{-1}	1680	1540	1610	1680	2660

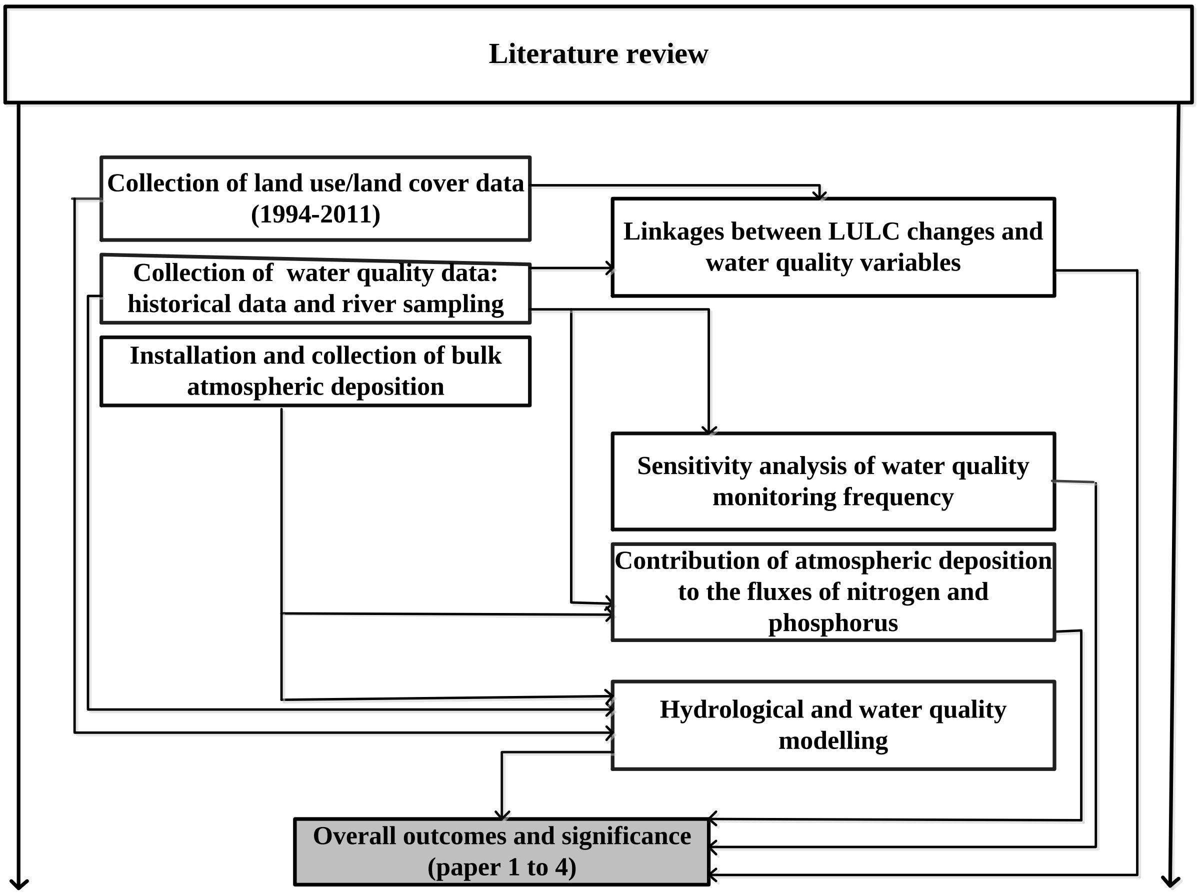
Appendix 6. C

A list of the selected land use dependent parameters for calibration, their physical meanings and their values

Parameter	Physical meaning (unit)	Factor	Indigenous forest	Thicket bushland	Natural grassland	Planted grassland	Planted forest	Bare rock	Cultivated dryland	Cultivated irrigated	Residential	Mines /quarries	Waterbodies	Wetlands
Kc	Crop coefficient for PE model (-)		0.625	0.84	0.76	0.595	0.76	0.255	0.7	0.7	0.66	0.255	2.08	1.6
degradhn	Decay of humus to fastN (d^{-1})	x10-^{5}	0.66	0.66	0.33	0.33	0.66	0.33	0.33	0.66	0.33	0.79	0.79	0.50
degradhp	Decay of humus to fastP (d^{-1})	x10-^{5}	0.23	0.30	0.54	0.54	0.38	0.54	0.54	0.38	0.54	0.51	0.34	0.51
denitrlu	Denitrification in soil layers (d^{-1})	x10-^{2}	0.81	0.78	0.81	0.81	0.69	0.59	0.79	0.81	0.72	0.77	0.89	0.81
dissolfn	Decay of fastN to DON (d^{-1})	x10 $^{-3}$	0.38	0.38	0.38	0.38	0.00	0.00	0.00	0.00	0.00	0.38	0.38	0.38
dissolfp	Decay of fastP to dissolved PP (d^{-1})	x10^{-3}	0.15	0.15	0.15	0.15	0.01	0.00	0.01	0.01	0.00	0.15	0.15	0.15
dissolhn	Decay of humusN to DON (d^{-1})	x10-^{5}	0.50	0.50	0.13	0.13	0.50	0.13	0.13	0.50	0.13	0.45	0.45	0.48
dissolhp	Decay of humus to fastP (d^{-1})	x10-^{5}	0.10	0.25	0.05	0.05	0.25	0.05	0.05	0.25	0.05	0.45	0.45	0.22
humusN0	Initial concentration of humusN in soil (mg.m^{-3})	x10 ^{3}	270.00	270.00	810.00	1417.50	439.20	283.5	283.50	439.20	180.00	27.00	2.70	270.0
humusP0	Initial concentration of humusP in soil l (mg.m^{-3})	x10 ^{3}	13.00	45.50	109.69	109.69	39.00	21.94	21.94	31.72	6.50	13.00	0.07	1.95

Preface to Chapter 7

This chapter presents the conclusions and recommendations of this thesis. It provides the key findings and contribution to the knowledge base. It also highlights the major challenges and caveats of this research, as well as areas for future studies.



CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

The results presented in this thesis are an outcome of an ongoing literature review and three years of field research and modelling studies conducted in the upper reaches of the uMngeni Catchment, in KwaZulu-Natal province, South Africa. The main objective of the research was to assess if a relationship exists between land use and land cover changes and water quality in the fast-developing upper catchment of the uMngeni River. This study started with a literature review on the nature of the associations between land use and water quality variables, evaluation of the driving forces of land use and land cover changes and concentration of nitrogen, phosphorus and *Escherichia coli* in the area. This study also analysed existing water quality monitoring programmes, the contribution of bulk atmospheric deposition to loading of nutrients in the catchment and the application of a streamflow and nutrients modelling system. The responses to the above-mentioned research questions were presented and discussed in their respective chapters. The following section presents the conclusions, starting with issues regarding land use and land cover changes, water quality deterioration and finally with modelling of runoff and nutrients.

7.1 Key conclusions

Changes in land use and land cover are mainly caused by a growth in population with subsequent conversion of the natural vegetation into agricultural and residential lands (Chapter 2). Changes of LULC are key driving forces of water quality deterioration in a water body and they affect the chemical composition of the atmosphere and can influence local climates. Thus, the relationships between LULC and water quality variables are complex, site-specific and vary from one region to another around the globe. High levels of nitrogen and phosphorus are largely released from agricultural lands, due to the application of fertilisers, while forested lands reduce the concentrations of nutrients into the waterbody (Chapters 2 and 3).

The major challenge in the assessment of LULC changes were related to the lack of uniformity in LULC classification in South Africa. In our LULC reclassification, the highest proportions of land use types from 1994 to 2011 were natural vegetation, cultivation and forested lands which occupy about 85% of the catchment (Chapter 3). In a period of two decades, the catchment has lost approximately 17% of its natural landscape, which coincided with an expansion of residential, forested and cultivated lands. However, sub-catchments immediately adjacent to the major impoundments are mostly affected by human disturbances, resulting from an increase in the population of those living in these rapidly growing formal and informal settlements. Consequently, high concentrations of dissolved inorganic nitrogen and phosphorus exceeding the eutrophication and recreational guidelines for water bodies are discharged from those disturbed sub-catchments. High spatial and temporal variability in concentrations of nutrients and *Escherichia coli* were noted across the catchment. The two dams in the catchment (Midmar and Albert Falls) are significant sinks of nutrients, sediments and allow die-off *Escherichia coli*. This has positive effects on the reduction of the cost of raw water treatment at the treatment plants, but this nutrient removal function in impoundments will not last forever. However, this also has long-term impacts on the life span of these impoundments. Relationships between LULC classes and the concentration of nutrients and *E. coli* exist in the catchment. However, these relationships vary from one sub-catchment to another so that a firm conclusion for the whole catchment could not be drawn (Chapter 3). The major issues in the assessment of the association between LULC and water quality variables were related to missing data at several sampling points, due to inconsistencies in existing monitoring programmes and the aforementioned LULC classification problems. It is suggested that a harmonisation of LULC classification and an installation of automatic or event based water samplers at key strategic sites is needed. In this chapter, the sub-catchments that need more focus in terms of water resources protection and management are highlighted (Chapter 3).

From these challenges regarding the lack of sufficient water quality from existing water monitoring programmes in the area, recreational and eutrophication water quality indices were developed and applied in the catchment. This followed the Canadian Council of Ministers of Environment Water Quality Index (CCME WQI) approach (Chapter 4). It was demonstrated that the higher the monitoring frequency, the lower the water quality indices. This suggests poor reporting of water quality in the catchment, due to a declining monitoring frequency. The water quality of ten of the eleven sites considered in this evaluation are ranked between “marginal” and “fair”, but predominantly marginal, with exception of the site in the

Mphophomeni Township which was always of “poor” water quality. This also confirmed a deterioration of water quality from the headwaters to the outlets of the catchments, as mentioned in Chapter 3. Furthermore, *E. coli* counts and the turbidity of water are key parameters which affect the recreational and eutrophication indices, respectively, but the concentration of nutrients (nitrate, ammonium and TP) is highly variable (Chapter 4). WQI techniques were identified as useful tools for summarizing a large dataset of water quality information into one single value understandable to a bigger audience comprising of scientists, policy makers and the public. However, this method should be combined with other methods of water quality interpretation for effective management decision-making. Due to high variability in water quality status, some improvements were suggested to fill the gaps in an existing database of water parameters to be monitored, such as the parameters indicative of organic pollution, i.e. dissolved oxygen and biochemical oxygen demands as well as the sites where automatic sampling equipment should be installed.

With regards to the contribution of bulk atmospheric deposition and surface inflows to the loading of nitrogen and phosphorus in the Midmar Dam Catchment, results indicated that high loads of phosphorus and nitrogen occur during the rainfall period in the catchment. Surprisingly, the concentrations of ammonium, nitrates and total phosphorus were higher in bulk deposition than in river flows (Chapter 5). This suggests high retention of these nutrients in the landscape. In drought conditions, bulk deposition remained a significant source of the ammonium load to the Midmar Dam (approximately 54% of NH_4 loading to the dam), while nitrate and total phosphorus mainly came from river flows. The bulk deposition loading of nutrients (dissolved inorganic nitrogen (DIN) and total phosphorus (TP)) of this study are higher than those of the previous studies, i.e. those conducted in 1977 and 1983, indicating that expansion of agricultural activities, biomass burning and livestock farming have resulted in increased emission of nutrients in the atmosphere. The annual specific loads of DIN are in the same ranges of other monitored stations of China and the USA, but smaller in comparison to other polluted sites in South Africa. In addition, a slight increase of riverine load of DIN with stable loads of TP confirms the phosphorus-cohesion nature of the soil in the catchment (Chapter 5). Overcoming uncertainties related to the collection of bulk atmospheric deposition, i.e. contamination, biodegradation and volatilisation of the samples, under- or over-estimating of nutrient fluxes, an automatic dry/wet collector was recommended to provide a more accurate information.

In Chapter 6 of this thesis the HYPE model was tested for its ability to simulate streamflow, inorganic nitrogen and total phosphorus in the catchment. The most important criterion that led to the selection of this model is its inclusion of in-stream processes of transport and nutrient dynamics in the model routing (Chapter 2), atmospheric deposition of nutrients, access to the model documentation and expertise from the Swedish Meteorological and Hydrological Institute (SMHI), resulting from the bilateral collaboration between South Africa and Sweden in water resources management. Furthermore, the model is being widely applied in several water quality modelling studies at varying catchment scales and is attractive in terms of its relatively limited model data requirements. The HYPE model successfully simulated the daily streamflow at acceptable level in comparison to the observed record. High streamflow events were represented very well in the model, while a general over-simulation of baseflow was noted. The model effectively captured the severe drought and flood events that occurred in the catchment in 1983 and 1987, respectively (Chapter 6). The model evaluation statistics for the period 1961-1999, for daily simulations of streamflow provided acceptable values with NSE greater than 0 at eight out of the nine stations. For monthly simulations of the flow, the NSE values greater than 0.5 were noted at seven sites out of nine. Overall, at the three sites used for calibration of the model, the water balance was represented well during the validation period where the percentage of under-or over-simulation of stream flow was less than 15% (PBIAS $\leq$ 15%). In addition, linear relationships between the modelled and measured streamflow during the calibration and validation periods were always positive in all the nine sites ($r > 0.7$) (Chapter 6). For the simulations of DIN and TP, a general under-estimation of DIN and acceptable simulations of TP was noted. Assessment of seasonal distribution of runoff, DIN and TP showed that high simulations of DIN appeared during the dry period, due to low rates of denitrification, during the low winter temperatures. This is in contrast with the concentrations of TP which follow the patterns of modelled streamflow. The most important processes driving the concentration of DIN in the model are the denitrification, crop uptake of DIN and the initial stocks/sources of nitrogen in the soil. The same processes are applicable for TP, apart from denitrification. These results also indicated that LULC is an important driver of water quality, as discussed in Chapter 3. The simulations of the HYPE model attributed high loads of DIN at upstream sub-catchments, where expansion of agricultural activities and livestock farming are predominant, as well as the informal settlement areas of Mpophomeni as also illustrated and discussed in Chapters 3, 4 and 5. Due to the high retention of phosphorus of the soil in the catchment, high export of TP are released in sub-catchments having significant point sources of pollution and a high rate of human disturbance, i.e. area downstream of the Midmar Dam and the Mpophomeni Township (Chapter 6).

The results of this study show that rapid LULC changes in the catchment have occurred and will continue. These changes in LULC result in high concentrations of pollutants in waterbodies (i.e. nitrogen, phosphorus and *Escherichia coli*) and also affect the chemical composition of precipitation. But the nature of the relationship varies from one sub-catchment to another and becomes impossible to evaluate in sub-catchments with large impoundments, because of the retention of pollutants in the dams. However, availability of LULC information, lack of uniformity in land cover classification, inconsistencies in water quality data collection and high variability in nutrient contents of rivers and precipitation samples have limited our confidence in drawing firm conclusions. Thus, continuation of grab sampling of rivers, supplemented by event-based sampling approach of rivers and installation of automatic dry/wet collectors should provide improved information on increased levels of nutrients in the catchment. This information would be used in future applications of water quality models. As agricultural activities and point sources of pollution are the major sources of nitrogen and phosphorus, respectively, land use management strategies should focus on agricultural intensification rather than extensification. Crop intensification will lead to an increase in food production, it will reduce pressures on the natural vegetation and will also reduce emissions of greenhouse gases (Burney *et al.,* 2010). However, this should be coupled with soil conservation and management practices to mitigate its consequences on water resources and ecological functions of the soil in the catchment (Matson *et al.,* 1997; Donald *et al.,* 2001; Burney *et al.* 2010). In addition, there is also a need to evaluate the compliance of significant point sources of pollution relative to the national effluent guidelines and where possible to update them according to the current state of water quality in the catchment.

7.2 Contributions to the knowledge base

Assessment of effects of LULC changes on water quality in the upper uMngeni Catchment provided the following key contributions to the knowledge base:

(i) Better understanding of the current state of LULC changes and the nature of their relationships with water quality in the upper reaches of the uMngeni Catchment as well as an identification of shortcomings in existing water quality database and land use classification in South Africa.

(ii) New insights into the role of impoundments in sequestration and retention of pollutants in the catchment (impoundments retain over 85% of *E. coli* and over 20% of TSS, TP, SRP and nitrate) and the sub-catchments that are prone to high levels of pollution, where much resources need to be deployed.

(iii) Information on the spatial and temporal variability of water quality in the catchment and the gaps of existing water monitoring programmes and subsequent weaknesses in water quality reporting system.

(iv) Clarification on the dynamic nature of water quality in the catchment and the role of bulk atmospheric deposition to nutrient loading of the Midmar Dam; and

(v) The successful application of the HYPE model in the Southern Hemisphere physiographic and climatic conditions, which is the first water quality model applied in the catchment, with the capability of simulating processes driving the transport and dynamics of nitrogen and phosphorus in a river and waterbody.

7.3 Future studies

Given the importance of the upper uMngeni Catchment to the population of the country, its exposure to dramatic changes of LULC and subsequent decline in water quality, future research should focus on:

(i) Harmonisation of land use and land cover classification approaches,

(ii) Installation of automatic or event-based samplers on the gauging weirs of the Lions, Petrus and Karkloof Rivers. This will capture high flow events not represented by existing grab sampling of rivers mainly carried out in the morning, while much of rain in the catchment falls in the afternoon,

(iii) Monitoring of atmospheric deposition of nutrients in the catchment and when possible the use of the other methods of atmospheric deposition (separating dry and wet deposition). Such approaches once coupled with investigations on biological, chemical and hydrological processes which drive the transformation and removal of nitrogen and phosphorus in the Midmar and Albert Falls Dams, will provide firm conclusions for decision-making,

(iv) Update the HYPE model to the current situation when climate data are available and expand the study area to the greater uMngeni Catchment to include the inter-basin transfer schemes that provide approximately 4.5 m^3/s to the catchment; and

(v) Finally, operationalisation of abandoned or poorly maintained streamflow gauging weirs and sampling sites. This will reduce the level of uncertainties in models' outputs inherent from the observations.

7.4 References

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