AN ASSESSMENT OF THE CRITICAL SOURCE AREAS AND TRANSPORT PATHWAYS OF DIFFUSE POLLUTION IN THE UMNGENI CATCHMENT, SOUTH AFRICA

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Hydrology, in the School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by the Water Research Commission (WRC), under the uMngeni Ecological Infrastructure Partnership Project (WRC K5/2354).

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 reported results are due to investigations carried out by the candidate.

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Date: /   /2018

DECLARATION 1: PLAGIARISM

I, Nantale Nsibirwa, declare that:

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

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

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

d) 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:

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

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

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

f) 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; and

g) 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.

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DECLARATION 2: PUBLICATIONS

This dissertation is written in a paper format, starting from Chapter 2 to Chapter 3. Chapter 2 is a narrative literature review paper and is structured accordingly. The paper found in Chapter 3 includes an Abstract, an Introduction, a Methodology section, a Results section, a Discussion section, as well as a Conclusion and Reference section. My role is indicated in each paper that has been published, submitted, presented or which is still in preparation.

Chapter 2: Publication 1

Nsibirwa, N and Jewitt, G. 2018. A Review of the Available Risk-Based Methods for Assessing Diffuse Pollution in the uMngeni Catchment.

This publication was written by N. Nsibirwa. All of the graphs, tables and photos were produced by N. Nsibirwa, unless otherwise referenced in the text of the paper. The editing of the paper and the advice regarding the interpretation of the results was provided by G. Jewitt. Additional editorial services were provided by S. Rees.

Chapter 3: Publication 2

Nsibirwa, N and Jewitt, G. 2018. The Mapping of Diffuse Pollution Risk in the uMngeni Catchment for the Prioritization of Ecological Infrastructure Protection.

This publication was written by N. Nsibirwa. The data required to conduct the study was accessed by N. Nsibirwa, through the Centre of Water Resources Research (CWRR) and Ezemvelo KZN Wildlife. N. Nsibirwa conducted the mapping, under the guidance of G. Jewitt. All of the graphs, tables and photos were produced by N. Nsibirwa, unless otherwise referenced in the text of the paper. The editing of the paper and the advice regarding the interpretation of the results was provided by G. Jewitt. Additional editorial services were provided by S. Rees. The methodology applied in the study was presented at the 6th Annual Symposium of Contemporary Conservation Practice. Based on the presentation, N. Nsibirwa was awarded the 2017 KwaZulu-Natal Premier's Award.

ABSTRACT

The difficulty in locating and managing diffuse pollution sources and their transport pathways is one of the reasons for the continued degradation of surface water in South Africa. Dealing with this problem is complex, as the sources and transport pathways of the pollutants are often not known because of the diffuse nature of the pollution. This study demonstrates the constraints of conventional diffuse pollution assessment approaches in identifying the Critical Source Areas (CSAs) and transport pathways of diffuse pollution, as applied in the uMngeni Catchment, South Africa. The use of various risk-based modelling approaches are reviewed for identifying the risk of diffuse pollution generation and transportation across a catchment landscape. The Sensitive Catchment Integrated Modelling and Analysis Platform (SCIMAP) Model is a risk-based tool that was developed to give a spatial representation of diffuse pollution sources. In this study, the SCIMAP Model was applied to identify and prioritise the protection and control of nutrient CSAs and transport pathways within the uMngeni Catchment. The results of the study were displayed in a catchment scale web map. The hydrological connectivity risk in the catchment was higher in the high-lying western areas and lower in the middle-eastern areas. The upper and middle parts of the catchment that are dominated by commercial agriculture and built-up urban areas were identified as the most impactful CSAs for intervention. The results are immediately applicable to water managers in the catchment and are strongly linked to the investment efforts in ecological infrastructure. A walkover survey revealed that the SCIMAP Model was able to direct the CSA investigations to the nutrient sources at four out of five locations. The survey also revealed that the accuracy of the modelled transport pathways increased with an increase in the elevation difference. The sensitivity of the SCIMAP Model to input land cover weightings was assessed, using an objective function. A high sensitivity of the modelled high-risk areas was observed on the intermediate diffuse pollution risk map, and a slight sensitivity of the modelled high-risk areas on the final diffuse pollution risk map, when the input landcover weightings were increased and decreased by 5%, 10% and 15%. This implies that caution should be practised in the formulation of the input land cover weightings, as they are a potential source of error in the model outputs. It is concluded that SCIMAP is a valuable tool for identifying the CSAs and transport pathways of diffuse pollution in a catchment. The results of the model can better inform the management of diffuse pollution and guide investments in the protection of the ecological infrastructure in the uMngeni Catchment. However, the establishment of input land cover weightings is very important and should receive priority in similar studies in the future.

ACKNOWLEDGMENTS

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF ABBREVIATIONS

ACRU	=	Agricultural Catchments Research Unit
ACRU-NPS	=	Agricultural Catchment Research Unit – Nitrogen, Phosphorous and Sediments
ASCII	=	American Standard Code for Information Interchange
ALARM	=	Automated Land-based Activity Risk Assessment Method
CSAs	=	Critical Source Areas
CWRR	=	Centre for Water Resources Research
DEM	=	Digital Elevation Model
DWS	=	Department of Water and Sanitation
GIS	=	Geographical Information Systems
HAND	=	Height Above Nearest Drainage
HSAs	=	Hydrologically-Sensitive Areas
HYPE	=	Hydrological Predictions for the Environment
KML	=	Keyhole Mark-up Language
LiDAR	=	Light Detection and Ranging
MAP	=	Mean Annual Precipitation
PEM	=	Phosphorus Export Model
SAGA	=	System for Automated Geographical Analysis
SCIMAP	=	Sensitive Catchment Integrated Modelling Analysis Platform
STI	=	Soil Topographical Index
TWI	=	Topographical Wetness Index
UK	=	United Kingdom

CHAPTER 1: INTRODUCTION

The South African National Water Act (No. 36 of 1998) states that water of adequate quality and quantity is needed for basic human needs and for the functioning of ecosystems. Nonetheless, the difficulty in managing non-point source pollution is one reason for the continued degradation of surface water in South Africa (Miller *et al.*, 2012). Non-point source pollution, also known as diffuse pollution, can be defined as pollution originating from the catchment land surface that is transported into rivers via runoff (DWA, 2014).

1.1 Rationale for the Research

Diffuse pollutants differ and can be found in the form of sediments, pathogens, metals, organic materials and nutrients. Nutrients are a group of diffuse pollutants that are of great concern. They are the cause of eutrophication, an environmental issue that arises when excessive plant nutrients are transported into water bodies, resulting in excessive algal bloom (Nyenje *et al.*, 2010). The complications associated with eutrophication in water bodies include the toxicity of algae, taste and odour problems, oxygen depletion, a loss of biodiversity, decreased aesthetics and an increased cost of water purification (Matthews and Bernard, 2015). One specific catchment that is under threat of major contamination is the uMngeni River Catchment, which is in KwaZulu-Natal, South Africa. High nutrient and bacterial loads from diffuse sources within the catchment are transported, by means of rivers and streams, into water supply dams.

Given that the uMngeni Catchment is an important water source for the growing population residing in the Pietermaritzburg metropolitan area and the City of Durban, scientists are looking at the potential of investing in ecological infrastructure, as a way of enhancing and sustaining water and sanitation delivery (Jewitt *et al.*, 2015; Mander *et al.*, 2017). Ecological infrastructure is defined as "naturally functioning ecosystems that produce and deliver valuable services to people" (Jewitt *et al.*, 2015). In the context of protecting the ecological infrastructure, it is difficult to address the problem of non-point source pollution, as the source areas are often not known because of the diffusive nature of the pollution. Furthermore, the pathways by which nutrients enter the waterbodies differ and they are a complex function of the soil type, climate, topography, hydrology, land use and land management (Hewett *et al.*, 2009).

Lane *et al.* (2009) proposed that diffuse pollution is probably not as diffuse as it is thought to be and that it is rather a product of distinct source areas that connect, to form a risk. In addition, studies by Heathwaite *et al.* (2005), Adams *et al.* (2014) and Schuetz *et al.* (2016) have illustrated that not all areas in a catchment contribute to the observed water quality problems and the delivery of diffuse pollutants to rivers and streams. This thinking forms the basis of relative risk-based modelling approaches in the assessment of diffuse pollution, which are used to identify and prioritise the protection and control of Critical Source Areas (CSAs) within the landscape. A CSA is the terminology used to describe a catchment area that poses the substantial risk of producing and transferring pollutants into waterways (Agnew *et al.*, 2006; Thomas *et al.*, 2016).

The key output and major strength of the application of risk-based approaches in the assessment of diffuse pollution are the maps that are produced of the study catchment. Output maps identify areas that are believed to be the most likely sources of downstream pollution (Lane *et al.*, 2006). For this reason, risk-based methods have become the basis of decision support systems in catchment management (Heathwaite *et al.*, 2005). Such information is practical and can be readily used by water managers in the uMngeni Catchment, to guide investments in ecological infrastructure.

1.2 Research Justification

To date, none of the published works, relating to diffuse pollution in the uMngeni Catchment, have applied risk-based approaches to understand diffuse pollution. Instead, researchers have adopted a conventional approach, which involves quantifying diffuse pollutant concentrations and loads through water quality modelling and routine river monitoring (Breen, 1983; Kienzle *et al.*, 1997; Ngubane, 2016; Namugize *et al.*, 2017). Although conventional approaches have had some success in measuring pollutant concentrations and estimating pollutant loads, difficulties are still being experienced in the identification of the CSAs when applying these methods (Pegram and Görgens, 2000). In particular, current knowledge gaps exist on how nutrients are naturally dispersed and retained in the uMngeni Catchment. The modelling approaches that have been applied in the catchment to date have had little success in addressing the gap.

When considering the problem of diffuse nutrient pollution in the uMngeni Catchment, the thesis of this work is that the adoption of risk-based approaches for investigating diffuse

pollution in the catchment will allow for the identification of the CSAs and transport pathways. In the context of investing in the protection of the catchment and the rehabilitation of its ecological infrastructure, locating the CSAs and transport pathways of nutrients would greatly improve the ability of the water managers within the uMngeni Catchment to ensure that the effort and investment in diffuse pollution mitigation target the most appropriate places. It is, therefore, intended that this research will contribute to a decision support system in the management of the water resources in the uMngeni Catchment, and that it will assist in identifying areas for the investment in ecological infrastructure.

1.3 Research Aim

The primary aim of this research is to identify the CSAs and transport pathways of nutrients in the uMngeni Catchment, utilising a risk-based method for diffuse pollution assessment. The intention is to realise the potential for utilising the generated data to guide the efforts and investments in diffuse pollution mitigation. The study does not seek to quantify the levels of pollutants present in the rivers in the uMngeni Catchment; it simply aims to assess the risk of diffuse pollution generation and transportation in different parts of the landscape.

1.4 Research Questions and Objectives

The following research questions arise from the research aim: a) Can risk-based approaches for diffuse pollution assessment be applied in the uMngeni Catchment to identify the diffuse nutrient CSAs and transport pathways? and b) Where are the CSAs and the transport pathways of diffuse nutrients in the uMngeni Catchment?

To achieve this aim, the following objectives have been established, namely:
a) to review and examine the recent risk-based approaches for assessing diffuse pollution;
b) to consider the applicability of risk-based approaches for diffuse pollution assessment within the uMngeni Catchment;
c) to map the CSAs and transport pathways of nutrients in the uMngeni Catchment, based on a selected risk-based method that is discussed in the literature review; and
d) to develop an interactive web map to inform stakeholders and guide efforts to mitigate diffuse pollution in the uMngeni Catchment.

1.5 Outline of the Dissertation

Following on from this introductory chapter, this document is structured in such a way that the findings of the research are presented in paper format, following the guidelines of the University of KwaZulu-Natal. A narrative literature review paper entitled *A Review of the Available Risk-Based Methods for Assessing Diffuse Pollution in the uMngeni Catchment* is presented in Chapter 2. Chapter 3 is a paper entitled *The Mapping of Diffuse Pollution Risk in the uMngeni Catchment for the Prioritization of Ecological Infrastructure Protection*. The need to give a comprehensive account of the research in each paper has resulted in a certain amount of repetition of information in parts of the document. The dissertation concludes in Chapter 4, where the final synthesis and conclusions are presented.

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CHAPTER 2: A REVIEW OF THE AVAILABLE RISK-BASED METHODS FOR ASSESSING DIFFUSE POLLUTION IN THE UMNGENI CATCHMNENT (PAPER 1)

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2.1 Abstract

Conventional methods used for the assessment of diffuse pollution in the uMngeni Catchment are unable to give an adequate spatial representation of the diffuse pollution source areas and transport pathways. To maximise the return on future investments that aim to reduce diffuse pollution and enhance ecological infrastructure within the catchment, the Critical Source Areas (CSAs) should be spatially identifiable. This will allow for focused mitigation measures that target the most appropriate places within the landscape. With the use of selected case studies, this paper reviews alternative methods that are used to identify and prioritise the protection and control of the CSAs within the landscape. Five risk-based approaches that are used for the assessment of diffuse pollution and explicitly focus on CSAs and hydrological connectivity, are reviewed in this paper. The key criteria that are required for applying the risk-based methods in the uMngeni Catchment are discussed, and the best-suited method is suggested for future assessments. The results indicated that the Sensitive Catchment Integrated Modelling Analysis Platform (SCIMAP) Model was most suited for application in the uMngeni Catchment. The modelling approach was selected for the following reasons: a) It produces a suitable output; b) It can be applied at field and catchment scale; and c) Input datasets are readily-available for the uMngeni Catchment and the SCIMAP software is easily accessible. The findings of this paper make a case for the use of risk-based methods as a means of diffuse pollution assessment in the uMngeni Catchment.

Keywords: Critical Source Areas; Diffuse Pollution Assessment Methods; Hydrological Connectivity; Risk-Based Methods; uMngeni Catchment

2.2 Introduction

The environmental problems surrounding diffuse pollution in the uMngeni Catchment, located in central KwaZulu-Natal, South Africa (Figure 2.1), include eutrophication, high microbial

activity, reduction in water clarity and unpleasant odours (Pillay and Buckley, 2001; Ngubane, 2016). Diffuse pollution varies across the catchment and, unlike point source pollution, it is a function of the topography, land use, land management, soil type, hydrology and climate. Determining the source areas of diffuse pollutants is a major concern, as it has become a land management problem within the uMngeni Catchment (DWAF and Umgeni Water, 1996).

The uMngeni Catchment covers an area of approximately 4 400 km^2 with an elevation range of 0 – 1 913 m above sea level and a relief ratio of 0.0085. The catchment drainage density is between 0.56 – 0.72 km of river per km^2 (Rivers-Moore *et al.*, 2007). The area is characterised by a relatively wet climate with highly-variable rainfall, receiving an average of 878 mm per annum. Land use in the higher-lying western region of the catchment is dominated by commercial and subsistence agricultural land, while the lower-lying eastern coastal plains are primarily industrial and urbanised areas. The uMngeni River is a critical water resource for the Pietermaritzburg metropolitan area and the economic centre of Durban.
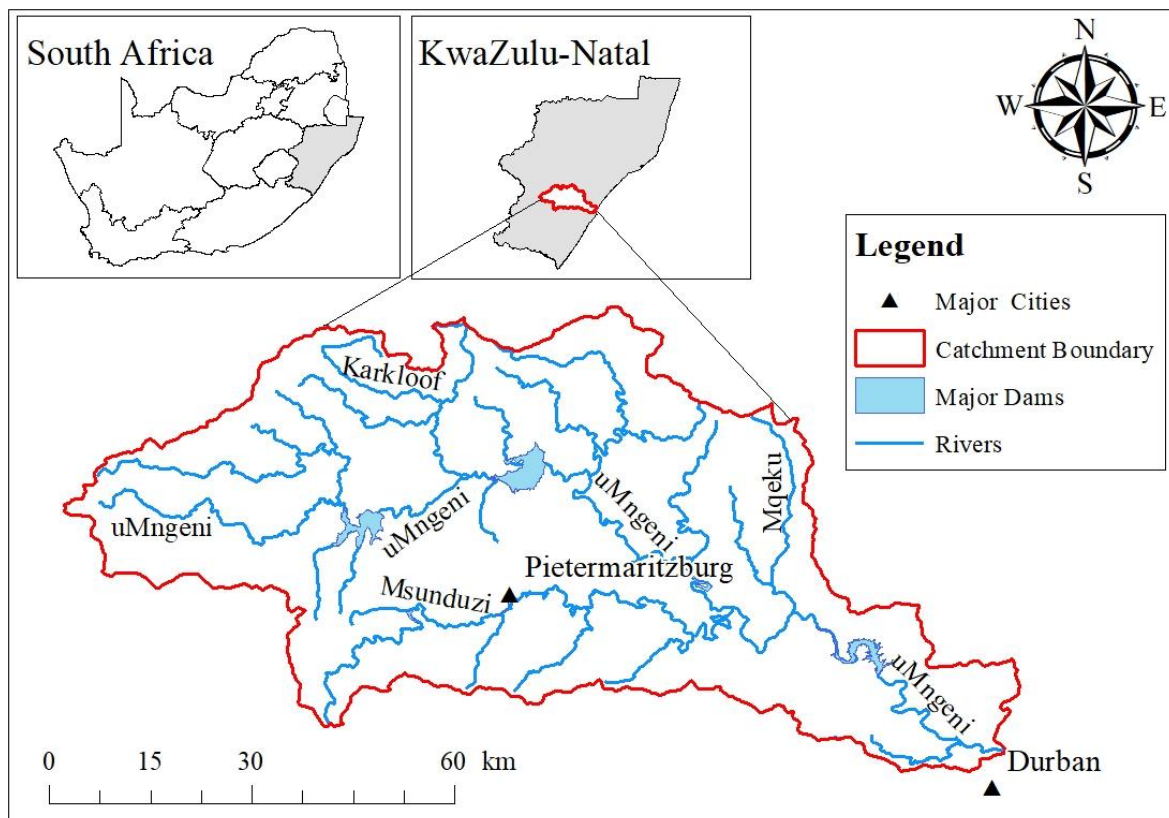
Figure 2.1   Locality map of the uMngeni Catchment in KwaZulu-Natal, South Africa

The estimation of diffuse pollution often involves water quality modelling, while its detection in rivers requires routine monitoring (Sierra *et al.*, 2007). To date, both these research approaches have been successful in quantifying the pollutant loads in rivers and streams in the uMngeni Catchment (Hemens *et al.*, 1977; Breen, 1983; Kienzle *et al.,* 1997; Dabrowski *et al.*, 2013). The limitations of routine monitoring assessments include the difficulty in differentiating between source, transport and delivery areas, even in well-monitored catchments (Pegram and Görgens, 2000).

Looking specifically at the modelling approaches, much effort is placed on producing good fits between the modelled processes and the observed water quality (Namugize *et al.*, 2017), or describing changes in the water quality over a time series at fixed locations within the catchment (Weddepohl and Meyer, 1992; Ngubane, 2016). Milledge *et al.* (2012) draw attention to the problem that these methods do not explain the spatial occurrence of diffuse pollution sources and pathways in a catchment.

The anticipated urban and industrial development in the uMngeni system will increase the demand for water, which exceeds the presently-available water resources (Tarboton and Schulze, 1992; Mauck and Warburton, 2014). The role of the ecological infrastructure in enhancing and sustaining water and sanitation delivery in the catchment has been recognised (Jewitt *et al.*, 2015; Mander *et al.*, 2017). Miller *et al.* (2012) noted that the efforts to control diffuse pollution usually involve the development and application of best management practices, which can be equated to an investment in the ecological infrastructure. For management practices to be effective, there needs to be a thorough understanding of the primary diffuse pollutant sources, how pollutants are carried to, and move through, hydrological systems, as well as how different management scenarios will impact pollutant loadings (Miller *et al.*, 2012).

Catchment areas with a high risk of transferring pollutants into waterways are termed Critical Source Areas (CSAs) (Agnew *et al.*, 2006). The concept of CSAs was first developed by Pionke *et al.* (2000) and is now used extensively in diffuse pollution management planning (Heathwaite, 2010). Areas classified as CSAs are characterised by three main conditions: a) a large pollutant source (e.g. fertilisers in agricultural fields); b) a high mobilisation risk (i.e. steep slopes); and c) a high transport risk (i.e. hydrological connectivity) (Figure 2.2). In theory, the CSA is the centre of a Venn diagram, when all three conditions are met.

Similarly, a vital part of catchment management includes understanding hydrological connectivity (Bracken *et al.*, 2013). As it is determined predominantly by topography, hydrological connectivity can be defined as "the water-mediated transport of matter, energy and organisms within, or between, elements of the hydrologic cycle" (Pringle, 2001). The interest in connectivity is not limited to the hydrology field; scientists are also applying the connectivity concepts in disciplines such as geomorphology (Wainwright *et al.*, 2011) and ecology (Freeman *et al.*, 2007). Nevertheless, the key role played by connectivity in the transfer of sediment and nutrient loads that originate from catchments, has been recognised (Kollongei and Lorentz, 2014). As seen in Figure 2.2 below, hydrological connectivity is a condition that features in the concept of CSA.

In recent years, research in the field of diffuse pollution has focused on the relative risk-based approaches that are used to prioritise CSAs and hydrological connectivity within the landscape, rather than focusing on simulating pollutant loads (Lane *et al.*, 2006). In other words, such approaches examine the risk of pollutants being produced and transported in a catchment, rather than providing a specific estimate of the pollution concentration or load, which is the basis of conventional modelling methods. A study by Heathwaite *et al.* (2005) concluded that the outputs of risk-based techniques have become the basis for decision support systems in catchment management.
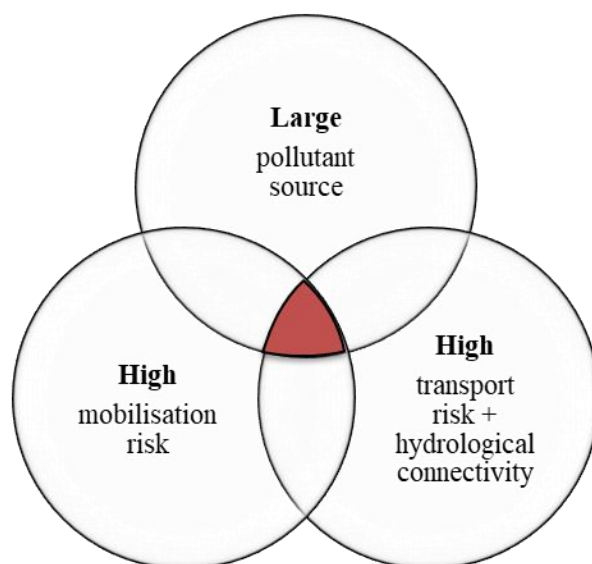
Figure 2.2   Conceptual diagram of the Critical Source Areas (CSAs) of diffuse pollution (after Thomas *et al.*, 2016)

The aim of the paper was to investigate the potential use of risk-based modelling approaches to assess diffuse pollution in the uMngeni Catchment. The intention is that a risk-based method, which is best suited for application in the uMngeni Catchment, will be identified for the future assessment and identification of CSAs. In addition, there is potential for the benefits of applying risk-based approaches to be realised in the context of including the outputs in decision support systems with regards to ecological infrastructure investment. The research questions asked were: a) How do risk-based modelling approaches differ from the conventional modelling approaches? and b) Which risk-based approach is best-suited for application in the uMngeni Catchment for the assessment of diffuse pollution?

2.3 Conventional Methods for the Assessment of Diffuse Pollution in the uMngeni Catchment

Traditionally, the assessment of diffuse pollution has involved measurements and estimates of pollutant concentrations or loads (Pegram and Görgens, 2000). The analysis of trends in pollutant concentrations or loads, over time, have been central to these assessments (Ngubane, 2016). The collected or generated data are typically presented in tables and graphs. This allows for the assessment of aquatic ecosystem health, compared to specific guidelines or changes in the pollutants, over time. In other instances, it is possible to produce maps of average concentrations or loads per sub-catchment. This section gives a broad outline of the two groups of conventional methods that have been applied in literature to assess diffuse pollution in the uMngeni Catchment.

2.3.1 Water quality monitoring

Routine water quality monitoring is conducted in the uMngeni Catchment by Umgeni Water, a parastatal organisation that is responsible for the provision of potable bulk water and sanitation services. Umgeni Water sends the collected data to the Department of Water and Sanitation (DWS) in the region. In addition, the eThekwini Municipality conducts sampling in the eastern lower reaches of the catchment. Sampled data, for a variety of water quality parameters (e.g. electrical conductivity, pH, ammonium, nitrate, soluble reactive phosphorus, total suspended solids, temperature, turbidity and *E. coli*), are available for the receiving water network in a range of time-steps, but most commonly at monthly time intervals. Research in the uMngeni Catchment has made use of the data collected by Umgeni Water, in conjunction with analytical and modelling techniques (Pillay and Buckley, 2001). During the analysis for the uMngeni Catchment Management Plan, the total annual loads of lead, phosphorus and

sediment were calculated in selected sub-catchments from the data that were sampled through the Umgeni Water monitoring programme (DWAF and Umgeni Water, 1996). In other cases, researchers have conducted their own water quality monitoring. A paper by Hemens *et al.* (1977) provides data on the input of phosphorus and nitrogen to Midmar Dam, from March 1973 to February 1974. Water quality monitoring was conducted every four weeks at seven sites, using a 5 l Van Dorn sampler to collect samples from 1 m above the bottom of the dam, 1 m below the surface and at mid-depth (Hemens *et al.*, 1977). The sampling method was followed by laboratory analyses and analytical calculations, which revealed the pollutant concentrations. For example, results obtained for Site 7 (the uMngeni and Lion's River confluence) are presented below in Table 2.1. Overall, the results from all the sites indicated that 0.62 g/m^2/annum total phosphorus and 8.49 g/m^2/annum total soluble nitrogen entered Midmar Dam during the one-year period. The dam was classified as an oligotrophic-mesotrophic water source, which translates to having fairly good water quality.

The advantage of using monitoring methods is that they provide a means for developing inputs for more detailed diffuse pollution assessment techniques (Pegram and Görgens, 2000). The limitations of monitoring assessments include the difficulty in differentiating between the source, transport, and delivery areas, even in well-monitored catchments (Pegram and Görgens, 2000). Furthermore, monitoring programmes that involve the investigation of CSAs are expensive, which means that they are not widely conducted in South Africa (Pegram and Görgens, 2000).

Table 2.1   Monthly variation in nutrient input into Midmar Dam from the uMngeni and Lion's River confluence (after Hemens *et al.*, 1977)

Month of the Year	Total Streamflow ($\times 10^3$ m^3)	Total Soluble Phosphorus (kg)	Total Phosphorus (kg)	Total Soluble Nitrogen (kg)
March 1973	20 807	416	79	9 883
April	33 923	577	567	20 116
May	10 576	127	3	4 516
June	5 532	50	0	2 301
July	3 130	28	18	861
August	3 725	37	18	823
September	3 660	22	14	1 058
October	8 200	57	20	2 427
November	9 555	86	35	4 405
December	7 281	58	25	2 162
January 1974	61 156	1590	400	27 765
February	73 867	1255	179	31 172
Annual Total	**241 412**	**4 303**	**1 358**	**107 489**

2.3.2 Water quality modelling

Empirical models, in the form of export coefficient models, have been applied in the uMngeni Catchment. Breen (1983) conducted a study which assessed the limnology of Midmar Dam, which included deriving the nutrient and sediment loads reaching the dam. For example, the loading pattern of the total suspended solids was markedly seasonal and it was highest during the summer months, from December 1980 to December 1982 (Figure 2.3). Empirical models can be limited in their ability to identify the source of diffuse pollutants. Furthermore, Breen (1983) stated that the infrequency of gauging weirs and limitations in their design contribute to the difficulties of estimating pollutant loads in the uMngeni Catchment.

The Phosphorus Export Model (PEM), the Agricultural Catchments Research Unit (ACRU) Model and the Hydrological Predictions for the Environment (HYPE) Model are physically-based models have been previously applied in diffuse pollution research in the uMngeni Catchment (Weddepohl and Meyer, 1992; Kienzle *et al.*, 1997; Namugize *et al.*, 2017). In 1992, Weddepohl and Meyer applied the PEM to estimate the monthly time series of phosphorus export in the upper sub-catchments. The intention was to use the results as inputs for a reservoir eutrophication model. To estimate the soil loss potential the ACRU modelling system was further developed to the Agricultural Catchment Research Unit – Nitrogen, Phosphorous and Sediments (ACRU-NPS) Model (Kienzle *et al.*, 1997).
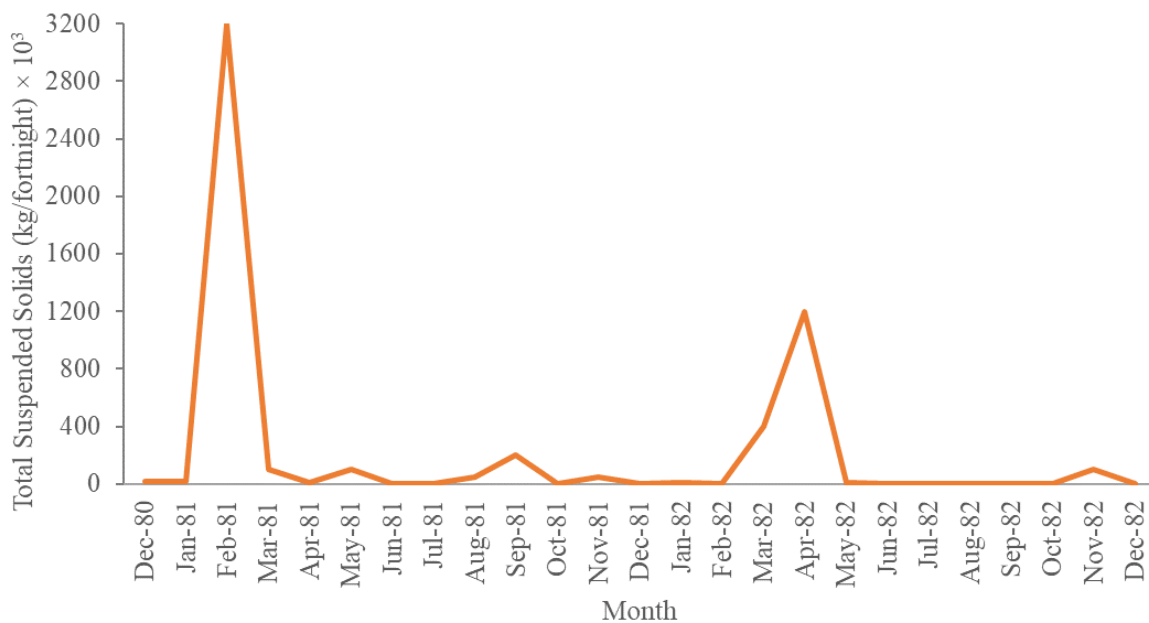
Figure 2.3   Seasonal variations in total suspended solids loads entering Midmar Dam for the period December 1980 to December 1982 (after Breen, 1983)

From this extended modelling system, simulations of water quality and quantity were used to evaluate the potential use of the model for simulating future catchment scenarios (Kienzle *et al.*, 1997). Unlike the PEM and ACRU Models, which were developed in South Africa, the HYPE Model was developed in Sweden. Namugize *et al.* (2017) set up and calibrated the HYPE Model to assess its capability in simulating the streamflow, dissolved inorganic nitrogen and total phosphorus in the Upper uMngeni Catchment. The results of the study showed that runoff and high streamflow events were well-represented during the calibration and validation periods; however, low streamflows were over-simulated by the model. Namugize *et al.* (2017) analysed the mean annual concentrations in each sub-catchment of the Upper uMngeni Catchment, where it was concluded that agricultural activities were the source of dissolved inorganic nitrogen in the Upper uMngeni, while the total phosphorus was mainly ascribed to the point sources of pollution (Figure 2.4).

While the advantage of physically-based models is that they attempt to represent all aspects of pollutant transportation and delivery, in detail, the use of complex models in South Africa does not lead to more accurate model outputs, due to the limited availability of data to support the model inputs and calibration (Malan *et al.*, 2003). Kienzle *et al.* (1997) highlighted the need for adequate water quality monitoring, for producing reliable simulations of water quality parameters, as well as the need for more experimentation that is designed to allow for the observation of the transport mechanisms of sediments, phosphorus and *E. coli*. However, Weddepohl and Meyer (1992) state that the PEM has to be calibrated against observed pollutant and streamflow data and can therefore only be utilised in monitored catchments.
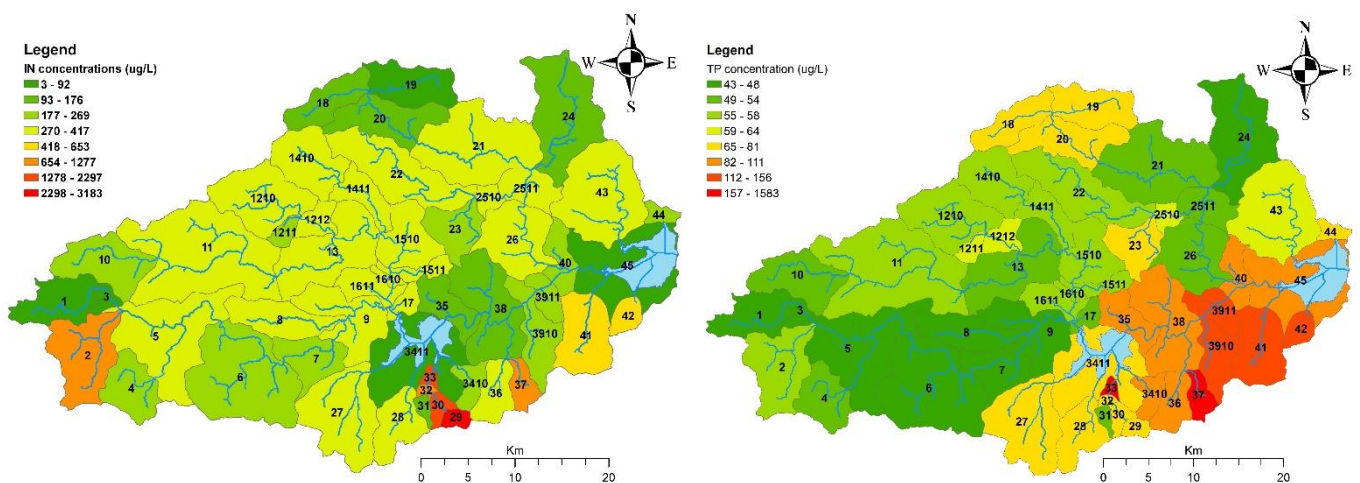
Figure 2.4   Mean annual concentrations of dissolved inorganic nitrogen (a) and total phosphorus (b) in the Upper uMngeni Catchment for the period 1989 – 1999 (Namugize *et al.*, 2017)

2.4 Risk-based Methods for the Assessment of Diffuse Pollution in the uMngeni Catchment

Risk-based assessment methods compute the likelihood and severity of the pollutant contribution, based on the possibility of pollutant available areas coinciding with a hydrological flow path (Lane *et al.*, 2006; Heckrath *et al.*, 2008). The contribution of diffuse pollutants into a stream network depends on the relationship between the source and transport factors (Heathwaite *et al.*, 2005). This leads to the prioritisation of specific landscape units through the identification of the CSAs (Lane *et al.*, 2006).

In other instances, the analysis of hydrological flow paths, i.e. hydrological connectivity, is the sole focus of the assessment and the source of pollutants is inferred from this data (Heathwaite *et al.*, 2005; Hewett *et al.*, 2009). The origins of this modelling approach can be traced back to export coefficient models. However, instead of determining the export as a volume of the material produced, it is defined as a risk of the material being produced (Lane *et al.*, 2006). The simplicity of risk-based approaches allows for their application in a region, without the need for extensive site-specific parameterisation (Cherry *et al.*, 2008). This information is of importance when one considers the limited availability of environmental data in the uMngeni Catchment.

The key outputs are the risk indicator maps that can be displayed in Geographical Information Systems (GIS) (Hewett *et al.*, 2009). Figure 2.5 below illustrates a basic example of a catchment scale potential risk indicator map. The intention of such maps is to keep the message simple and clear, hence only showing the risk level, but no quantified losses (Cherry *et al.*, 2008; Hewett *et al.*, 2009). At a local scale, these maps facilitate highly targeted mitigation strategies (Gburek *et al.*, 2000). In the context of investing in ecological infrastructure within the uMngeni Catchment, mitigation strategies may include controlled cattle grazing and watering, as well as farming on reduced tillage soils, to strengthening the rehabilitation and management of degraded grasslands, hillslope and riparian areas. To ensure an improvement in water quality management at catchment scale, such maps can be used to inform decision-making or guide regional or national policy development (Hewett *et al.*, 2009). It is evident that, at both hillslope and catchment scales, the spatial targeting of diffuse pollution risk indicator maps has the potential to support the maintenance or restoration of ecological infrastructure. Various risk-based approaches are available and a synopsis of five of these methods can be found in the following sections.
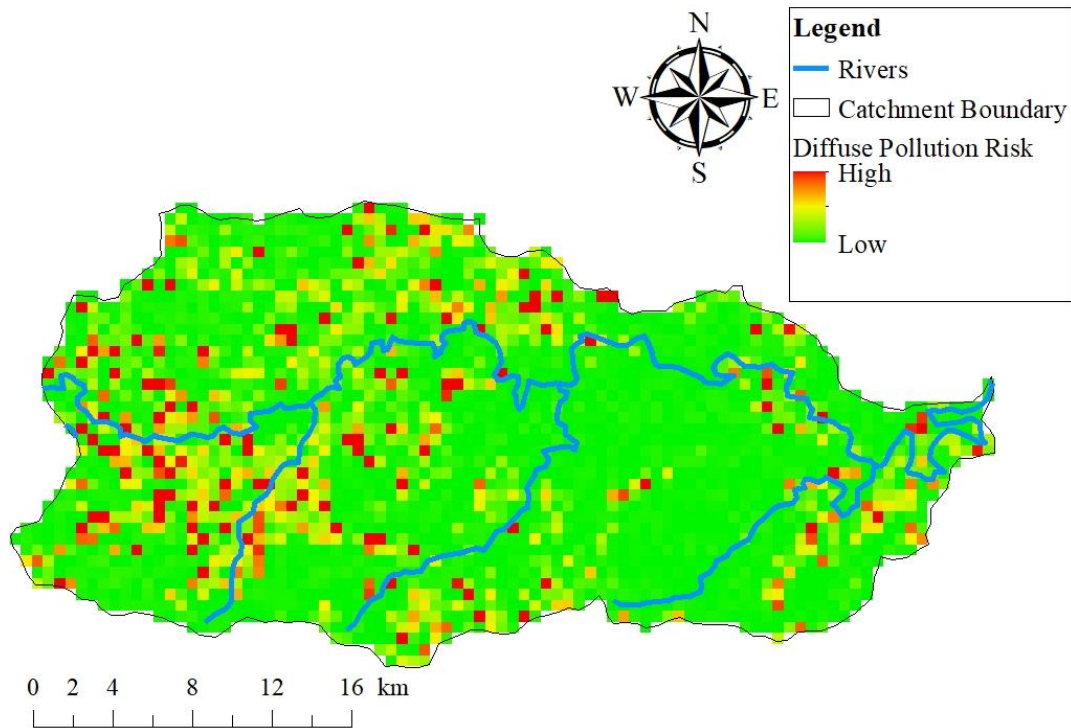
Figure 2.5   Catchment scale potential risk indictor map

2.4.1 Sensitive Catchment Integrated Modelling Analysis Platform (SCIMAP)

The Sensitive Catchment Integrated Modelling Analysis Platform (SCIMAP) Model provides a risk-based estimation of diffuse pollution and it was developed jointly between the Durham and Lancaster Universities (Milledge *et al.*, 2012). The question that the developers of the SCIMAP Model intend to address is as follows: Given the observed degradation of water quality downstream of catchments, which fields or sub-catchment areas are likely to be most responsible (Lane *et al.*, 2006; Reaney *et al.*, 2011)?

SCIMAP is made up of two key sets of analyses that are used to generate maps of the risk-based estimation of diffuse pollution (Lane *et al.*, 2006; Reaney *et al.*, 2011). The first set involves the delineation of the CSAs, which is referred to as the generation risk (Lane *et al.*, 2009). To calculate the generation risk, the model requires land cover export weightings to be associated with each cell in a land cover raster layer. The second set examines the risk of the source areas connecting to the river network. The connection risk is computed from a Digital Elevation Model (DEM) and involves the formulation of saturated flow paths. The model requires minimal information and runs by using a DEM and the raster grids of land cover and rainfall data. SCIMAP can be applied from hillslope to catchment scale, with the predictions being relative to the scale at which the model is applied (Milledge *et al.*, 2012). A series of

maps are formulated of the area under investigation, so that the catchment's hydrological connectivity and CSAs are identifiable. Figure 2.6 is an example of the final map produced by SCIMAP for the River Eden Catchment in the United Kingdom (UK) (Dixon, 2013). With this map, one can identify the transport pathways of diffuse pollutants into the main channels. Risk is depicted in multiples of the standard deviation from the mean, where high risk areas are depicted in red and low risk areas in green.

Milledge *et al.* (2012) utilised SCIMAP to identify the diffuse pollution risk pertaining to two main nutrients, namely phosphorus and nitrogen, in eleven UK catchments, ranging from 135 – 3 049 km^2 in size. The SCIMAP framework can operate across all spatial scales, ranging from 1 – 4 000 km^2. Their investigation outlines an alternative approach to understanding the problem of diffuse pollution through the application of the SCIMAP Model. The application of SCIMAP within this study focused on the risks of diffuse pollution generation for each location in a landscape i.e. the generation risk (Milledge *et al.*, 2012). Deriving land cover weightings is a critical step in the approach and, in this instance, Milledge *et al.* (2012) use a Bayesian approach to infer the risk of a land cover surfaces generating pollutants from ecological and water quality datasets. Studies by Reaney *et al.* (2011), Thompson *et al.* (2013) and Porter *et al.* (2017) also focus on the formulation of the land cover weightings that best replicate the spatial arrangement of the diffuse pollutants being studied.

The results from the modelling exercise showed that certain land cover types generate a consistently high risk of diffuse nutrient pollution, while other land cover types generate a consistently low risk (Milledge *et al.*, 2012). The results also showed that the risks associated with various land uses differ within each catchment and that the main sources of nutrients in the catchment are often a result of the spatial arrangement of the land covers. Furthermore, it was noted that not all locations in a catchment contribute equally to the delivery of sediment or nutrients, even if they have the same land cover type.

The SCIMAP Model has the potential to operate as a framework to inform the catchment-scale risks for diffuse nutrient and sediment pollution (Reaney *et al.*, 2011). Milledge *et al.* (2012) argue that the approach challenges the traditional modelling approaches that make quantitative predictions of diffuse pollutants. Although the data requirements of the model are minimal, SCIMAP uses land cover risk weightings, which could potentially be a challenge to calculate in the uMngeni Catchment, where ecological and water quality datasets are limited.
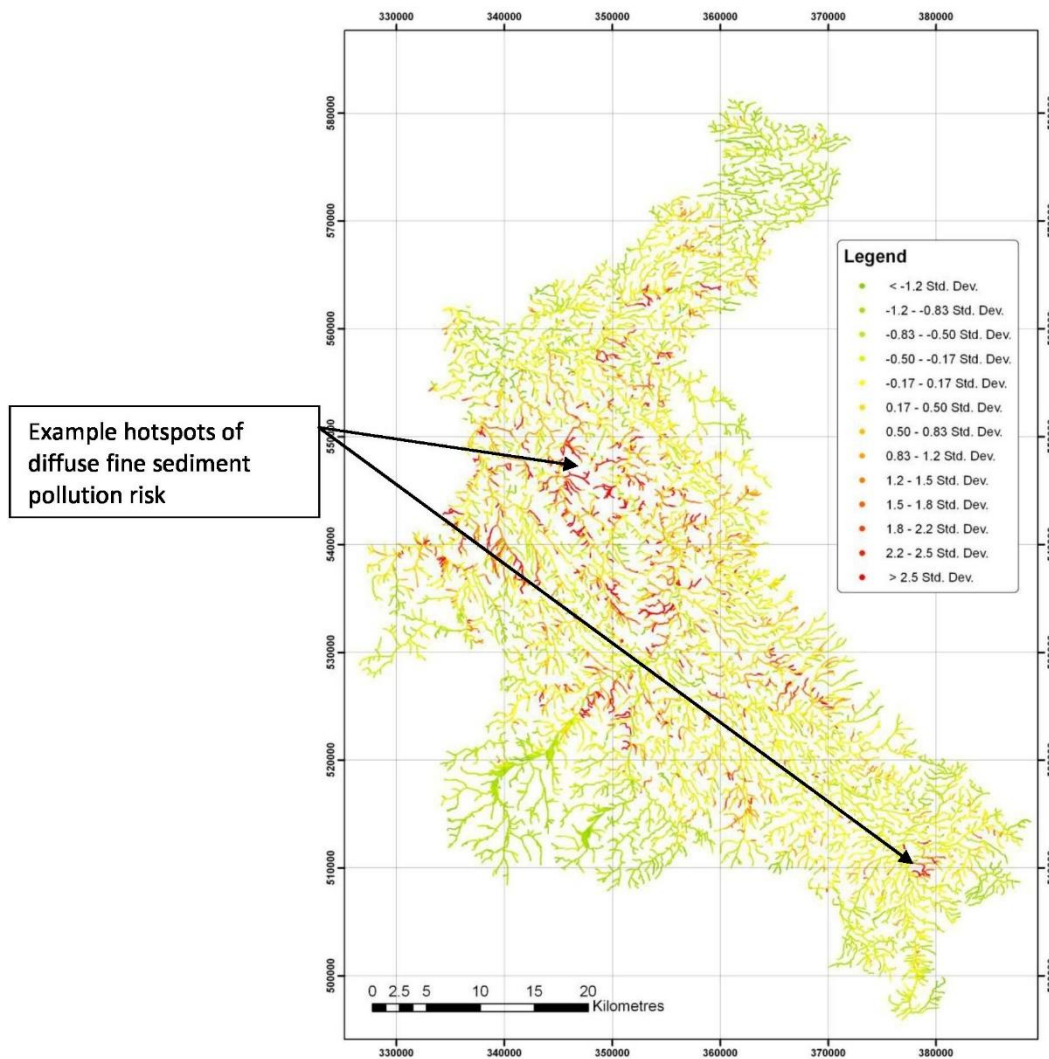
Figure 2.6   Final SCIMAP fine sediment erosion risk output for the River Eden Catchment
(Dixon, 2013)

2.4.2 Analysis of the connectivity of catchment process zones

Several studies in the literature analyse connectivity and focus on the degree to which water and sediment can be transferred across various reach-scale land units, which are referred to as process zones (Hooke, 2003; Kollongei and Lorentz, 2014; Lorentz *et al.*, 2011; Miller *et al.*, 2012). This is a hybrid approach which combines sampling, modelling and risk-based mapping. A comprehensive understanding of particle movement through a catchment is developed, by combining geomorphic, hydrological and geochemical fingerprinting analyses (Miller *et al.*, 2012). The catchment data required for the analysis of the transport pathways include surface soil samples, cored deposition profiles, sediment cores and the stable isotopes of water and nutrients (Lorentz *et al.*, 2011).

18

In 2012, Miller *et al.* conducted a study within the Mkabela Catchment, KwaZulu-Natal, South Africa. This catchment was chosen for the study as it is said to be representative of the catchments in the region. It has a varied range of land uses and is a tributary of the uMngeni River. One of the main nutrient sources in the catchment is agricultural land (Miller *et al.*, 2012). The intention of the investigation was to obtain an understanding of the fine-grained sediment sources in the catchment, as well as their transport and storage (Miller *et al.*, 2012).

The analyses were separated into three key parts, namely, process zone mapping and characterization, the collection and the analysis of sediment cores, as well as source modelling (Miller *et al.*, 2012). The catchment was further divided into sub-catchments and various process zones were represented by defined stream reaches. A series of sediment cores were extracted at specified locations within the catchment. Miller *et al.* (2012) went on to conduct geochemical fingerprinting methods on the sediment cores, to determine the changes in sediment provenance over time. The main reason for using geochemical fingerprinting methods in this diffuse pollution study was that the processes relating to the erosion, transport and deposition of sediment eventually result in a deposit that is representative of a mixture of material that originates from various source areas within the catchment (Miller *et al.*, 2012). A sediment mixing model was then used to determine the relative contribution of sediments from the identified source areas (Miller *et al.*, 2012). The key results of analyses, such as those conducted by Miller *et al.* (2012) include an in-depth description of distinct process zone types of the hydrological processes that occur in the study catchment. While the information provides a useful context for the consideration of connectivity, it is not an approach that can be readily applied elsewhere.

2.4.3 Height Above Nearest Drainage (HAND)

According to Gharari *et al.* (2011), the Height Above Nearest Drainage (HAND) and the surface slope within a catchment seem to be the dominant controls for hydrological connectivity. Catchment data on the HAND and surface slope are readily available from a DEM. HAND, which can be calculated by using most GIS software, normalises the topology according to the local relative heights found along the drainage network (Rennó *et al.*, 2008). In other words, it presents the topology of the relative soil gravitational potentials, or local draining potentials (Nobre *et al.*, 2011). Essentially, the method uses landform characteristics obtained from a DEM and classifies landscapes into three distinct classes, namely wetlands, hillslopes and plateaux (Gharari *et al.*, 2011). These classes are based on the landscape's

dominant runoff mechanisms and are related to three hydrological regimes, namely saturation excess overland flow, storage excess sub-surface flow and deep percolation (Gharari *et al.*, 2011). Two sets of procedures are carried out on a DEM, when using the HAND technique (Nobre *et al.*, 2011). To begin with, a series of computations are applied to define the flow paths and delineate the drainage channels (Nobre *et al.*, 2011). The local drain directions and the drainage network are derived to create a nearest drainage map (Nobre *et al.*, 2011). This finally directs the HAND operator spatially, to produce the normalised topology (Nobre *et al.*, 2011).

There are only a few studies published in literature that use the HAND technique, as the method is relatively new. A summary of these studies is presented below.

a)   Rennó *et al.* (2008) reported on the development of a new topographic algorithm called HAND.

b)   Nobre *et al.* (2011) conducted an assessment of soil water landscape classes in the Amazon Rainforest and explored the relationship between digital topography data and terrain modelling. It was concluded that the HAND technique and the resulting soil water maps can not only aid in the advancement of physically-based hydrological models, but that the technique can also present an opportunity for solving many difficult problems in the hydrology discipline.

c)   The application of HAND is subject to several uncertainties, such as a sensitivity to the resolution size of the DEM (Gharari *et al.*, 2011). This led Gharari *et al.* (2011) to conduct a detailed performance and sensitivity analysis of the HAND method within the Wark Catchment in Luxembourg. It was noted that the knowledge on how HAND relates to other descriptors of landscapes, such as the Topographical Wetness Index (TWI) developed by Beven and Kirkby (1979), is unknown. An analysis of the relationship between HAND and TWI was also made in the study. A 5 m pixel DEM with a vertical resolution of 0.01 m was used in the landscape classification of the Wark Catchment. It was concluded that the HAND method compared well with the TWI.

d)   In other cases, HAND has been used in hydrological modelling exercises to provide the required input data for a soil and vegetation model (Cuartas *et al.*, 2012).

The studies indicate that HAND is a strong indicator of the saturated areas within a catchment, hence it provides the user with an indicator of the connectivity of the area being studied. The

resulting catchment maps of the above-mentioned studies show landscape classification that is presumably associated closely to the dominant runoff generation processes (see Figure 2.7 below). The Wark Catchment illustrated in Figure 2.7 is 82 km^2 in size. Although the catchment is much smaller than the uMngeni, it is believed that the classification technique applied to identify the dominate runoff processes in the Wark may be applied in the uMngeni.
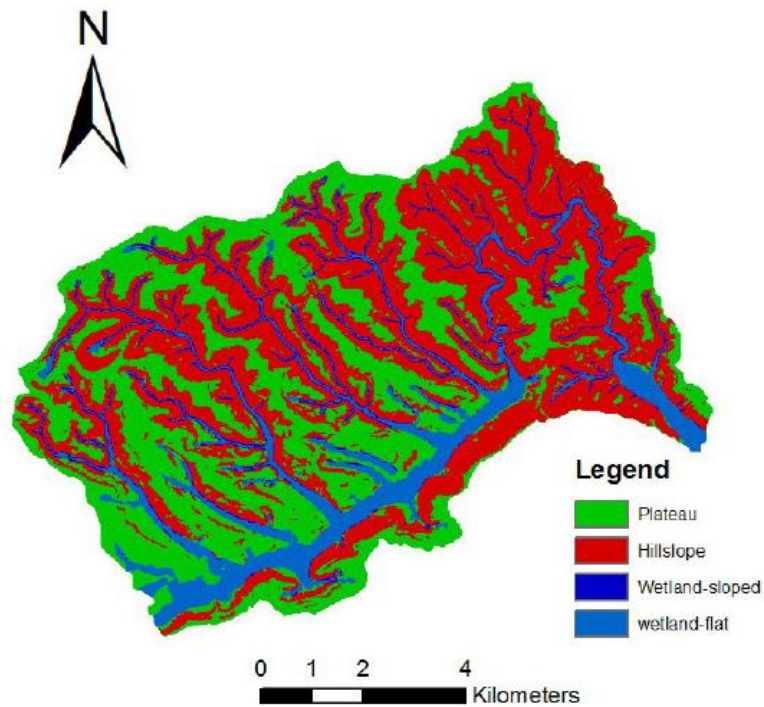
Figure 2.7   Landscape classification for the Wark Catchment, Luxembourg resulting from applying the HAND method (Gharari *et al.*, 2011)

2.4.4 Analysis of Hydrologically-Sensitive Areas (HSAs)

Xue *et al.* (2014) refer to areas with the highest potential for generating surface runoff and a very quick response to runoff as Hydrologically-Sensitive Areas (HSAs). The HSA concept relates to the pollutant transfer continuum, which states that, when pollutant source areas coincide with HSAs, pollutants are transported and delivered via hydrologically-connected pathways (Thomas *et al.*, 2016) (see Figure 2.8).

To locate areas of high and low potential for transporting diffuse pollutants, the analysis of HSAs involves the development of the TWI and the Soil Topographic Index (STI). The indices are derived from a Light Detection and Ranging (LiDAR) DEM (Thomas *et al.*, 2017). LiDAR DEMs are characterised by relatively high spatial resolutions. The use of imagery with a fine resolution is justified for the modelling of flow paths, because of the need to study micro-topographical features i.e. flow sinks (Thomas *et al.*, 2016). From the TWI and STI maps, a HSA Index map is derived to identify specific areas which diffuse pollutants could be transported between agricultural fields, or to the drainage network.

The study by Thomas *et al.* (2016) is based on the premise that topographical indices are typically derived from corrected DEMs that remove all flow sinks. The removal of flow sinks incorrectly assumes that they are a product of the DEM vertical error and that the features do not exist (Thomas *et al.*, 2016). Thomas *et al.* (2017) note that flow sinks can be observed in reality and have a significant effect on the hydrological disconnection of overland flow (see Figure 2.9).
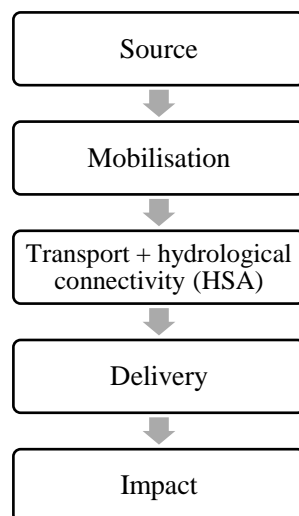
Figure 2.8   Conceptual diagram of the pollutant transfer continuum (after Thomas *et al.*, 2016)

Figure 2.9   Field observation of a flow sink (Thomas *et al.*, 2017)

Four agricultural-based catchments of $7.5 - 12$ km^2 in Ireland were chosen to conduct the investigation. LiDAR DEMs with a resolution of 2 m were used to derive TWI and soil topographic index (STI) maps. The grid resolution was resampled from 0.25 m LiDAR DEMs, with high resolution horizontal and vertical accuracies of 0.25 m and 0.15 m, respectively. DEMs were then hydrologically corrected and TWI maps were then derived. To derive the STI maps, subgroup soils maps were imported into ArcGIS Version 10.0 and they were improved, using DEMs, additional soil sampling and expert knowledge (Thomas *et al.*, 2016). The HSA Index was developed by modifying the STI values to account for the effect of flow sinks on connectivity. The HSA Index was validated by comparing the HSA sizes that were predicted by using the HSA Index, with the HSA sizes that were estimated empirically from rainfall-quickflow observations and measurements during winter storm events (Thomas *et al.*, 2016). Thomas *et al.* (2016) went on to use the HSA maps to identify cost-effective locations for directing diffuse pollution mitigation measures.

The results showed that $16.8 - 33.4\%$ of the catchment areas are hydrologically disconnected from the open drainage channel network (Thomas *et al.*, 2016). Flow sinks were widespread throughout all four catchments and represented a very large overland flow capacity, with volumes ranging from 8 298 to 59 584 m^3. The significance of understanding flow sinks in

mitigating pollutant transfers was demonstrated and it was noted that mitigation measures at hydrologically disconnected areas are unnecessary and should be avoided. Directing the mitigation measures to the proposed areas reduced the potential cost of mitigating diffuse pollution by 66% over one year and 91% over five years, when compared with a comprehensive implementation (Thomas *et al.*, 2016).

Thomas *et al.* (2016) concluded that the HSA Index can be used as a reliable transport component within a field scale CSA model. The HSA approach is well-suited as a tool to support sustainable agricultural intensification. Furthermore, the approach highlights the importance of high-resolution DEMs in diffuse pollution modelling frameworks, although this may be a constraint for its application in larger catchments.

2.4.5 TopManage Model

TopManage has been described by Hewett *et al.* (2009) as a flow visualisation tool that is based on simple hydrological flow path concepts and a high-resolution GIS terrain analysis toolkit. It is driven by a DEM and allows for dominant flow paths to be characterised, assessed and altered for the management of runoff (Heathwaite *et al.*, 2005). The terrain analysis theory of TopManage is based on the multiple flow direction theory of Quinn *et al.* (1991). The main landscape feature computed in TopManage is the upslope accumulated area, which is calculated in m^2 (Hewett and Quinn, 2003). As flow converges, the value of the upslope accumulated area increases, therefore areas receiving substantial amounts of overland flow can be made visible (Hewett *et al.*, 2009). The tool functions optimally at a hillslope scale and at a grid resolution of 0.5 – 2 m.

Flow connectivity modelling was conducted with the TopManage Model by Heathwaite *et al.* in 2005. The model was used to predict the spatial distribution of the risk of diffuse nutrients reaching waterways from agricultural fields. Furthermore, the application of the model allows for a range of land management scenarios to be analysed (Heathwaite *et al.*, 2005), hence scenarios were created and analysed for a set number of agricultural fields in the UK. It should be noted that a high spatial resolution DEM (2 m × 2 m) was used in the approach taken by Heathwaite *et al.* (2005), but it was suggested in the discussion that it is not a fixed requirement for the analysis of every field in a catchment.

The main output of TopManage is a digital terrain map, which provides a close representation of the topography at a field scale (Hewett *et al.*, 2009). Figure 2.10 (b) shows a map that was generated for a field, based on this analysis. The map shows how the flow moves across the field and in which direction the pollutants will possibly be carried (i.e. the dark grey areas). Outputs from the model emphasise the importance of land management features (e.g. field drains) in the risks that are associated with the delivery of nutrients or sediment to the surface waters (Heathwaite *et al.*, 2005). The approach seeks to find the possible ways of manipulating flow paths at a local scale, through environmental engineering, to mitigate diffuse pollution. It is possible to identify inexpensive and simple changes to land use and land management practices that could potentially disconnect the flow and to use storage ponds or wetlands to buffer nutrient and sediment transport within the fields (Hewett *et al.*, 2009). Heathwaite *et al.* (2005) clearly state that topographical analyses should be linked to diffuse nutrient models in the future, to evaluate the implications of nutrient attenuation, rather than only considering flow attenuation.

TopManage proved to be valuable for understanding runoff processes at the field and hillslope scale; however, attempting to scale-up for the investigation of larger areas will introduce uncertainty (Heathwaite *et al.*, 2005; Hewett *et al.*, 2009). Heathwaite *et al.* (2005) therefore advise that the application of the model be set for the scale at which it was developed i.e. at a hillslope or field scale.

(a) (b)
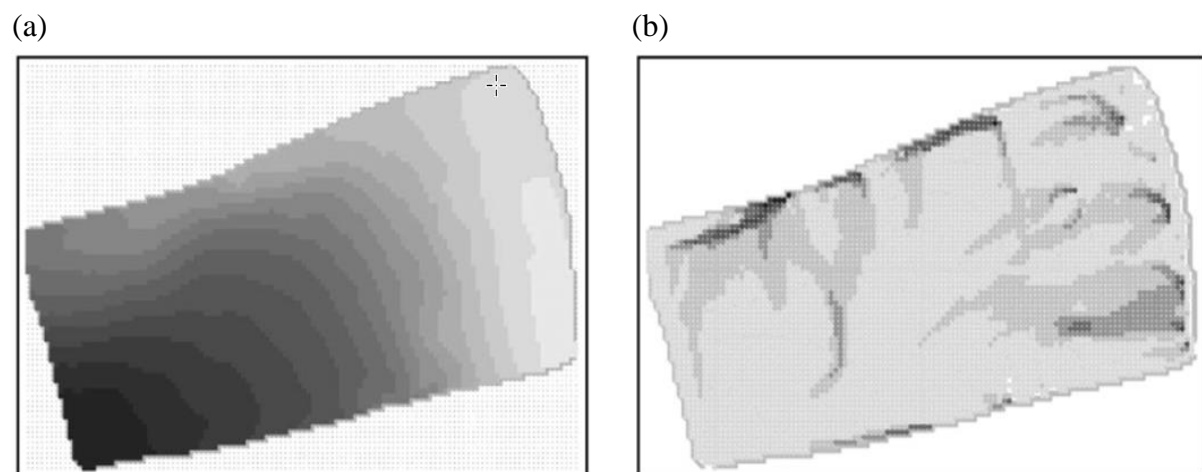
Figure 2.10 (a) 5 m Digital Elevation Model (DEM) of a field prepared for TopManage analysis and (b) digital terrain map where the darkest areas indicate high flow accumulation (Hewett *et al.*, 2009)

2.5 Discussion

The results in this paper indicate that the conventional approaches that are used for diffuse pollution assessment differ from the relative risk-based approaches in the following ways:

Firstly, measuring the pollutant concentration and estimating the pollution load is the basis of conventional modelling methods. River monitoring requires the sampling of water, followed by a laboratory analysis of the chemical constituents. In addition, conventional modelling aims to simulate in-stream concentration/loads in the river, in response to particular catchment management decisions or climate conditions. However, the basis of relative risk-based approaches is in examining the probable sources of pollutants and their transport pathways in a catchment. The approach moves the investigation from the known in-river problems to the CSAs. This result is consistent with what was found by researchers such as Lane *et al*. (2006), who recognise the quantitative approach of conventional diffuse pollution assessments and that the new models of diffuse pollution are characterised by connectivity.

Secondly, it was found that the CSAs and hydrological connectivity within a catchment are easily identified when applying risk-based methods, when compared to conventional methods. As noted by Pegram and Görgens (2000), even in well-monitored catchments, the limitations of routine monitoring assessments include the difficulty in differentiating between the source, the transport and the delivery areas. This is due to the fact that most river monitoring programmes and studies focus on in-stream observations and provide integrative information at specific points in the catchment (Hemens *et al.*, 1977). In other cases, diffuse pollution sources are broadly inferred for each sub-catchment from a detailed analysis and the modelling of in-stream concentrations, as in Figure 2.4. This information is not available at the spatial and temporal scales, which are necessary for catchment planning. In the reviewed studies on the uMngeni Catchment, it is evident that much effort is being placed on developing a water quality time series (Weddepohl and Meyer, 1992), or producing a good correlation between the modelled output and the measured water quality (Kienzle *et al.*, 1997; Namugize *et al.*, 2017). These findings are in line with what is suggested by the literature, i.e. that the traditional methods of diffuse pollution assessment do not explain the spatial occurrence of diffuse pollution sources and pathways in catchment (Milledge *et al.*, 2012). On the other hand, central to risk-based modelling approaches are the concepts of CSAs and connectivity (Reaney *et al.*, 2011; Miller *et al.*, 2012; Thomas *et al.* 2016). These both lead to the identification and

prioritisation of areas where the land use most readily transmits pollutants to the river network, as seen in Figure 2.6.

It was found that there are existing approaches for determining the risk of diffuse pollution generation and transportation from landscapes, ranging from the relatively simple methods (Heathwaite *et al.*, 2005; Milledge *et al.*, 2012) through to relatively complex methods (Miller *et al.*, 2012). To aid the discussion about which risk-based method is best suited for application in the uMngeni Catchment, Table 2.2 below provides a comparison of the risk-based methods that have been reviewed in the previous sections. Four main criteria were considered for selecting a risk-based approach to apply in the uMngeni Catchment. These criteria are listed below:

a) The key outputs of the method;
b) The spatial scale at which the method can be applied;
c) The input data requirements; and
d) The access to the modelling software.

As this paper aims to guide investments in ecological infrastructure, in order to reduce and mitigate diffuse pollution, it is imperative that the outputs provide the areas that generate pollutants and their connection to the main river channels. Furthermore, the output of the selected method needs to be relatively simple for stakeholders to understand and formulate decisions. CSAs and their connectivity can be identified when applying the SCIMAP Model. Catchment process zone studies, using various geophysical and soil pedological analyses, have proved to be useful in providing a detailed description of the processes for water, sediment and nutrient delivery (Kollongei and Lorentz, 2014). When considering the application of the HAND, the analysis of the HSAs and the TopManage Model, the key outputs of these methods include maps that identify runoff generating areas (i.e. HSAs). These methods are good indicators of hydrological connectivity; however, to identify CSAs, these methods need to be developed further. As noted by Thomas *et al.* (2016), methods that solely evaluate hydrological connectivity could be coupled with CSA models that consider the land cover/use characteristics of the area under study.

Table 2.2   Comparison of the recent methods for the assessment of diffuse pollution potential

	Sensitive Catchment Integrated Modelling Analysis Platform (SCIMAP)	Analysis of the Connectivity of Catchment Process Zones	Height Above Nearest Drainage (HAND)	Analysis of Hydrologically Sensitive Areas (HSAs)	TopManage
Authors	Milledge *et al.* (2012)	Miller *et al.* (2012)	Nobre *et al.* (2011) and Gharari *et al.* (2011)	Thomas *et al.* (2016)	Hewett *et al.* (2009)
Key Outputs	Critical Source Areas (CSAs) and their connectivity in the form of a risk indicator map	A detailed description of the catchment's drainage network characteristics, sediment sources and basin connectivity	Topology mapped according to the HAND method. Landscape classification maps dividing the catchment area into wetland, hillslope and plateau areas	HSAs and their connectivity and discontinuation in the form of a HSA Index map	HSAs and their connectivity and discontinuation in the form of a digital terrain map
Spatial Scale Applied	$1 - 4\,000$ km^2	$\pm\,41$ km^2	$13 - 519$ km^2	$7 - 12$ km^2	$\pm\,4$ km^2
Data Requirements	Digital elevation model (DEM) – 5 m to 30 m resolution Land cover data coupled with risk weightings Time integrated rainfall patterns	Various satellite images and 1:10 000 aerial photography On-site meteorological data Sediment samples and cores	DEM – no specified resolution	LiDAR DEM – maximum of 2 m resolution Soils data	DEM – maximum of 2 m resolution
Software and Resource Requirements and their Accessibility	SCIMAP Model – easily acquired Optional: ArcGIS – easily acquired	Micromass Platform ICP-HEX-MS, ArcGIS and a sediment mixing model – acquirable Meteorological weather station equipment – acquirable High-tech laboratory equipment – partially accessible	ArcGIS – easily acquired	ArcGIS – easily acquired	TopManage Model – easily acquired ArcGIS – easily acquired

After reviewing various methods for application in the uMngeni Catchment, those that can be applied across the entire catchment (i.e. $\pm 4\,400$ km^2) are most favourable. The SCIMAP framework can operate across all spatial scales, ranging from $1 - 4\,000$ km^2. Miller *et al.* (2012) applied the process zone analysis at a medium catchment scale of ± 41 km^2. In addition, the studies using HAND were all carried out at a catchment scale of <519 km^2. Analysis of the HSA and TopManage methods both focus on understanding the sources and sinks of pollutants at a hillslope and field scale (i.e. <12 km^2). It is advised that the application of the TopManage Model be set at a hillslope or field scale due to the high uncertainty associated with up-scaling the method (Heathwaite *et al.*, 2005).

The SCIMAP framework can easily be downloaded from an online website. The procedure that was conducted by Miller *et al.* (2012) requires computer software, which can be acquired; however, the laboratory equipment that is needed to carry out the sediment core analysis is only partially accessible in South Africa. This makes it an approach that cannot be readily applied in the uMngeni Catchment. The HAND can be computed and the HSAs can be identified on several GIS software programmes, which are easily accessible. From the studies, it is believed that a DEM of any resolution can be applied to compute the HAND, which is an advantage, when one considers the difficulty in accessing high-resolution DEMs for the uMngeni Catchment. However, in the study by Thomas *et al.* (2016), the identification of HSAs required a high-resolution LiDAR DEM. TopManage can easily be downloaded from online websites. However, just as in the identification of HSAs, TopManage requires a high-resolution LiDAR DEM.

For the reasons discussed above, catchment process zone analysis, the HAND, the analysis of HSAs and the TopManage Model have in this case been excluded for application in the uMngeni Catchment. The SCIMAP framework has been selected, for the following reasons:
   a) It can identify the CSAs of diffuse pollutants and catchment hydrological connectivity without the need for further development;
   b) It can be applied at field and catchment scale;
   c) The datasets are readily-available for the uMngeni Catchment; and
   d) SCIMAP software is easily accessible.

This selection does not limit the application of risk-based modelling approaches in the uMngeni Catchment to the SCIMAP Model. It does, however, make a case for the use of SCIMAP as

the best option for the application at hand. Previous research has emphasised that the formulation of the land cover weightings is a critical step in the modelling approach (Milledge *et al.*, 2012; Porter *et al.*, 2017). A sensitivity analysis of the SCIMAP Model to the land cover weightings should be conducted, to provide an indication of the attention that is required, in terms of their calculation, quality and associated error.

2.6 Conclusion

In response to the difficulty of identifying diffuse pollution source areas in the uMngeni Catchment, this paper has demonstrated an alternative approach for diffuse pollution assessment, i.e. the application of risk-based modelling approaches. Conventional approaches that have been applied to assess diffuse pollution in the uMngeni Catchment have focused on measuring and estimating pollutant concentrations or loads and include the difficulty in identifying pollutant source areas. Future investments aiming to reduce diffuse pollution and enhance ecological infrastructure within the uMngeni Catchment will be strengthened by the ability to identify catchment CSAs. This will allow for focused mitigation measures that target the most appropriate places within the landscape. It is therefore recommended that risk-based methods, which have been developed explicitly to identify the CSAs and hydrological connectivity, be applied in the catchment. The review of five risk-based approaches for diffuse pollution assessment reveals that the SCIMAP Model is an appropriate risk-based method for identifying CSAs in the uMngeni Catchment. The SCIMAP framework can identify CSAs and hydrological connectivity, it operates at both a fine and coarse spatial scale, the data required is readily available and the software is accessible. It is recommended for future use in the investigations of diffuse pollution. These findings make a case for the use of risk-based methods as a means of diffuse pollution assessment in the uMngeni Catchment. Future work should focus on the application of SCIMAP in the uMngeni Catchment and testing the sensitivity of the model's output to changes in the input land cover weightings.

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CHAPTER 3: THE MAPPING OF DIFFUSE POLLUTION RISK FOR THE PRIORITISATION OF ECOLOGICAL INFRASTRUCTURE PROTECTION (PAPER 2)

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3.1 Abstract

Risk-based modelling approaches that are used for diffuse pollution assessment, link well with the efforts to conserve ecological infrastructure, as they can identify and prioritise the Critical Source Areas (CSAs) of non-point pollution within a landscape. In this paper, a relative risk-based approach, the Sensitive Catchment Integrated Modelling and Analysis Platform (SCIMAP) Model, was applied in the uMngeni Catchment to identify the CSAs and transport pathways of nutrients. An interactive web map was created from the model's outputs. The hydrological connectivity risk in the catchment is higher in the high-lying western areas and is lower in the middle-eastern areas. The upper and middle parts of the catchment are dominated by commercial agriculture and built-up urban areas are identified as the most impactful CSAs. Walkover survey observations in the Midmar sub-catchment reveal that four of the five locations that were identified as being a high risk for nutrient delivery could potentially contribute to nutrient diffuse pollution. Furthermore, the survey revealed that the accuracy of the modelled transport pathways increased with an increase in the elevation difference. The assessment of the sensitivity of the SCIMAP Model to input land cover weightings was achieved by using an objective function. A high sensitivity of the modelled high-risk areas was observed on the intermediate diffuse pollution risk map, and a slight sensitivity of the modelled high-risk areas on the final diffuse pollution risk map, when the input landcover weightings were increased and decreased by 5%, 10% and 15%. It was concluded that SCIMAP is a valuable tool for identifying the CSAs of diffuse pollution in a catchment. Furthermore, caution should be practised in the formulation of the input land cover weightings, as they are a potential source of error in the model outputs.

Keywords: Critical Source Areas; Diffuse Pollution Risk; Hydrological Connectivity; Nutrients; SCIMAP Model; uMngeni Catchment

3.2 Introduction

The deteriorating water quality in the river systems of the uMngeni Catchment, KwaZulu-Natal, South Africa, has been documented over 40 years (Hemens *et al.*, 1977; Ngubane, 2016). This decline has been ascribed to the rapid land use and land cover changes that have occurred in the catchment since the arrival of European settlers in 1850 (Moll, 1965). Several studies report diffuse pollution as a major contributor to the degradation of rivers and streams in the catchment, and they have raised concerns that the impoundments of the catchment could become eutrophic (Breen, 1983; Pillay and Buckley, 2001; Matthews and Bernard, 2015). Furthermore, the uMngeni River, a primary freshwater resource for the Durban economic axis, has been recognised as a system whose decline in water quality is associated with serious health risks to people and agriculture (Rivers-Moore *et al.*, 2016). There is a great need to identify the Critical Source Areas (CSAs) in the catchment landscape i.e. areas that produce and transport pollutant material to the drainage network (Pionke *et al.*, 2000).

In response to the water quality problems and the growing demand for potable water in the uMngeni Catchment, catchment planning and management approaches are now focusing on integrating ecological infrastructure solutions (Jewitt *et al.*, 2015; Mander *et al.*, 2017). Ecological infrastructure refers to the parts of the catchment that produce and deliver valuable goods and services to people (Costanza *et al.* 2014). As they are important parts of the landscape, it is important to protect or rehabilitate the ecological infrastructure. The type of interventions that are necessary to protect ecological infrastructure, and where to apply them, is still an ongoing research issue in the uMngeni (Jewitt *et al.*, 2015). In order to manage diffuse pollution, the intervention measures should focus on reducing the delivery of pollutants from the source areas, which should improve the ecological infrastructure and limit catchment degradation (Heathwaite, 2010; Milledge *et al.*, 2012).

To locate CSAs, a risk-based modelling framework, called the Sensitive Catchment Integrated Modelling and Analysis Platform (SCIMAP) Model, provides a calculation of diffuse pollution risk (Milledge *et al.*, 2012). The SCIMAP Model is based upon the notion that catchments can be conceptualised as a set of flow paths that connect the distributed sources of possible pollutants across a landscape, to receiving rivers (Lane *et al.*, 2006). Fundamentally, the model focuses on the environmental degradation associated with diffuse pollutant losses, from the land to the water, where source areas combine with the high probability of connection to the river network (Milledge *et al.*, 2012). The outputs of SCIMAP are a series of maps that identify

land units that are most likely to be causing an observed downstream pollution problem (Lane *et al.*, 2006). The maps give an indication of where to prioritise diffuse pollution mitigation activities. This links well with the efforts that are being made to invest in ecological infrastructure, as they identify the areas in which the protection, control and rehabilitation of ecological infrastructure should be prioritised.

The primary aim of this study was to identify the CSAs and transport pathways of nutrients in the uMngeni Catchment, using the SCIMAP Model. The intention is that the generated outputs will be used to guide the future efforts and investments in the protection of the ecological infrastructure. Despite having readily-available input datasets for the application of SCIMAP in the uMngeni, deriving input land cover weightings was noted in Paper 1 as being a potential challenge in the modelling process. Furthermore, previous research has emphasised that the formulation of the land cover weightings is a critical step in the modelling approach (Milledge *et al.*, 2012; Porter *et al.*, 2017). It is therefore important to assess how uncertainty, with regards to the land cover weightings, may influence the SCIMAP Model outputs. This is the secondary aim of the study. The following research questions arise from the research aims: a) Where are the CSAs and the transport pathways of diffuse nutrients in the uMngeni Catchment? and b) What is the influence of the possible errors (i.e. over- or underestimation) in developing land cover weightings on the SCIMAP Model outputs?

3.3 Methodology

3.3.1 Study area

The uMngeni Catchment is situated on the eastern coast of South Africa (Figure 3.1) and covers an area of approximately 4 400 km^2. The catchment is located at an average elevation of 750 m above sea level with a relief ratio of 0.0085. The catchment drainage density is between 0.56 – 0.72 km of river per km^2 (Rivers-Moore *et al.*, 2007). The area is characterised by highly-variable rainfall, receiving an average of 878 mm per annum. Most of the rainfall is received in the summer months, while the winter months are relatively drier. The average maximum temperature in the summer months is 24°C and 13°C in the winter months whereas the average minimum temperature in the summer months is 22°C and 8°C in the winter months. The annual potential evaporation varies from 1 567 mm to 1 737 mm per annum. The landscape in the catchment's western upper reaches is known for its deep, permeable, well-drained and fertile soils. The soils and the fairly consistent rainfall make the area well-suited for agricultural

production (DWAF and Umgeni Water, 1996). Hence, land use in the western region of the catchment is dominated by intensive commercial agricultural land, in the form of crop and livestock farms and forestry plantations. The eastern coastal plains of the catchment are primarily industrial and urbanised areas and are characterised by grey and red sand silt deposits, with a lower permeability than what is found in the upper reaches of the catchment (DWAF and Umgeni Water, 1996). An approximate area of 2 600 km^2 of the catchment is covered by natural land cover, but has lost its ability to provide water-based ecosystem services at an optimal level (Jewitt *et al.*, 2015).
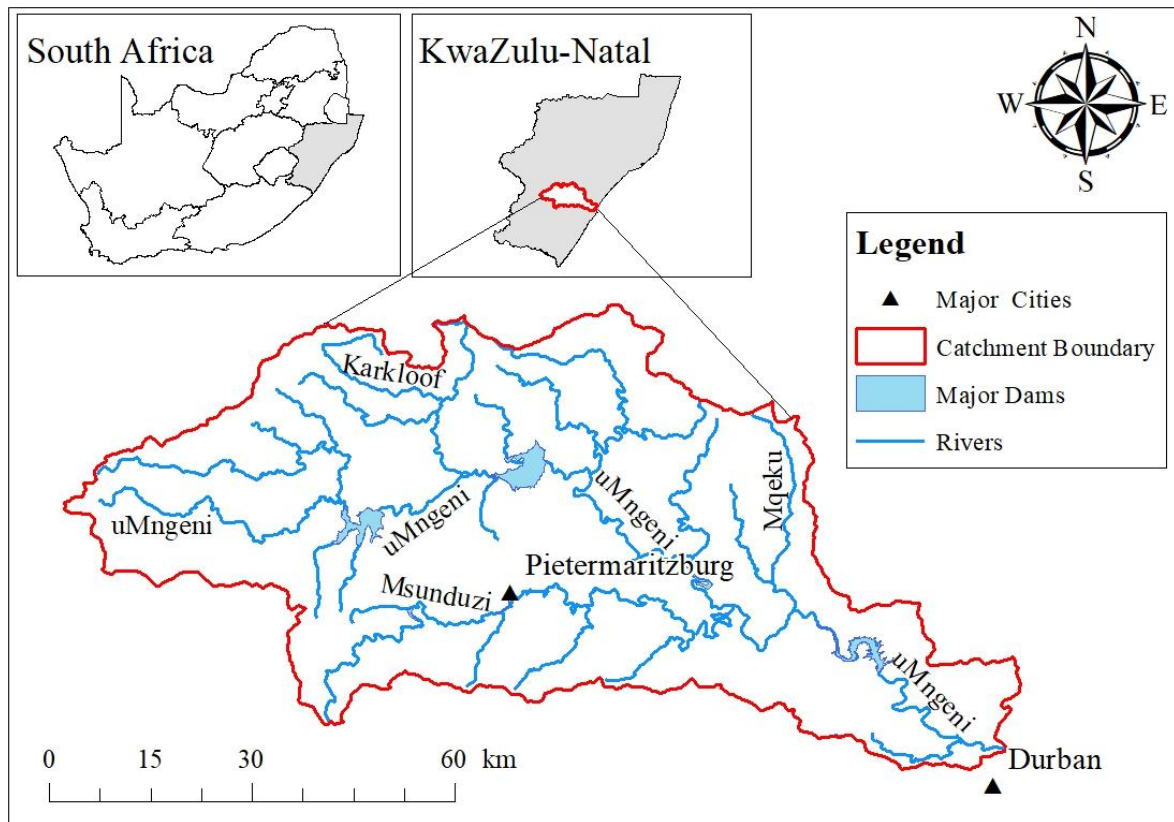

Figure 3.1   Locality map of the uMngeni Catchment in KwaZulu-Natal, South Africa

3.3.2 The SCIMAP Model

The SCIMAP framework has a five-step processing structure (see Figure 3.2).

1) The first step in the analysis involves determining the generation risk (P^g_i), which is defined as the likelihood that a point location in the study area can generate risk (Milledge *et al.*, 2012). To calculate the P^g_i, SCIMAP requires a raster land cover map, with the associated land cover export weightings.

2) The second step is the determination of the connection risk (P^c_i) for the travelling pollutants. In this step, the model calculates a network index from a Digital Elevation Model (DEM), using the topographical wetness index developed by Beven and Kirkby (1979). The output is an indicator of hydrological connectivity and the likelihood of connection to the river channel.

3) Step Three involves combining the generation and connection risks, to determine the locational risk of the delivery of the generated pollutants to the drainage network (P^{gc}_i). Thereafter,

4) Steps Four and Five involve routing, accumulating and diluting the locational risk. Once the locational risk is accumulated along flow paths, a risk loading (L_j) is determined.

5) The possible dilution of pollutants in the catchment is then accounted for by creating the risk of concentration factor (C_j) from a rainfall raster map. Step Five results in the final diffuse pollution risk map.

SCIMAP is implemented as a module in the System for Automated Geographical Analysis (SAGA) framework. The software can be downloaded from the open source website: http://www.scimap.org.uk/.
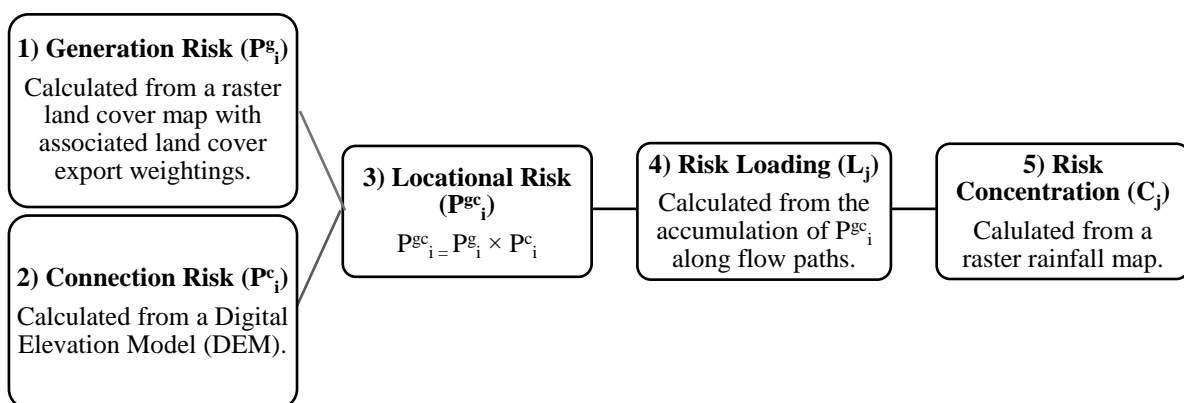

Figure 3.2   The SCIMAP Model five-step processing structure (after Milledge *et al.*, 2012)

3.3.3 Data requirements

SCIMAP requires three main data layers to compute the diffuse pollution risk, namely, a DEM, land cover and rainfall raster data. In this study, the ArcGIS suite Version 10.4 was used to pre-process the input model data and to visualise the modelled outputs.

3.3.3.1 Digital Elevation Model (DEM)

Coarse DEM resolutions (1 – 30 km) usually result in the reduced predictive capability of models and a decline in the reliability of model outputs (Lane *et al.*, 2003). For this reason, a high-resolution DEM was sought. High resolution DEMs have been difficult to access for the uMngeni Catchment in the past, but a 20 m × 20 m pixel DEM, produced by the Department of Rural Development and Land Reform (2017), is now available and it was used in this modelling exercise. Figure 3.3 depicts the DEM data for the uMngeni Catchment.

The pre-processing of the DEM data includes filling in the pits or depressions, which are a result of imperfections in the DEM. Pits and depressions influence the delineation of a drainage network by affecting the prediction of the stream network location (Al-Yami, 2014). The spatial analyst tools within the ArcMap Toolbox were applied for this task. It is important to note that the filled DEM is only used to calculate the upslope contributing areas and flow pathways (Reaney *et al.*, 2011). A non-filled DEM layer is used to calculate the catchment slope, which considers the natural sinks and areas of disconnection (Reaney *et al.*, 2011). The SCIMAP Model requires that the data be in the American Standard Code for Information Interchange (ASCII) file format. Once the data was clipped to the catchment boundary, a conversion was made to the ASCII format, using the ArcMap toolset.
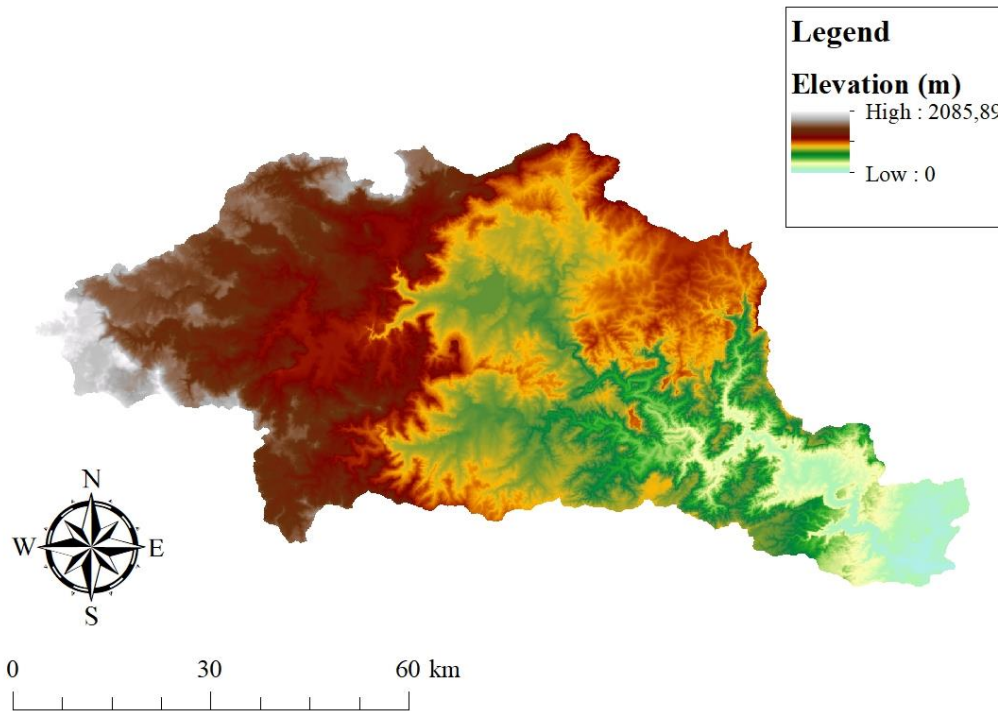
Figure 3.3   Digital Elevation Model (DEM) of the uMngeni Catchment (Department of Rural Development and Land Reform, 2017)

3.3.3.2 Land cover dataset

A 2011 land cover dataset was supplied by Ezemvelo KZN Wildlife for this study (Figure 3.4). The dataset contains 47 land cover classes which were derived from 2011 SPOT5 multispectral single date imagery. The map has a reliable level of confidence, scoring an overall land cover mapping accuracy of 83.51% (Ezemvelo KZN Wildlife and GeoTerraImage, 2013). The map grid has a resolution of 20 m × 20 m, which matches the DEM used in this investigation. The data was clipped to the catchment boundary and converted to the ASCII format, using the ArcMap toolset.

The model requires that each land cover class is assigned a weighting, which describes the export potential. The SCIMAP interface allows the user to enter weightings scaled between 0 (low risk of exporting pollutants) and 1 (high risk of exporting pollutants). Extensive research was undertaken by scientists at the Institute of Natural Resources to develop the Automated Land-based Activity Risk Assessment Method (ALARM), and this resulted in estimates of diffuse pollution export potentials (DWA, 2014). Using export coefficient data from a large database of published literature, they worked to establish reliable export potential indicators for different land use categories and five pollutant groups across South Africa (DWA, 2014). Land uses with a high risk of generating pollutants were given a relative score of 1 and those

with a low risk a score of 0 (see Table 3.1). The ALARM export coefficients do not have a connectivity or pollutant transportation factor embedded within them (DWA, 2014), making them suitable to use in this modelling exercise.

To utilise the ALARM export coefficients, it was necessary to group the 47 land cover classes of the Ezemvelo KZN Wildlife dataset into the 14 ALARM land use categories (see Table 3.2). Furthermore, the urban commercial and urban industrial land use categories were combined, as both land use types are classified as built-up dense settlements on the Ezemvelo KZN Wildlife map. This adjustment meant that the export potentials from those land use categories had to be combined as well. Thus, an average of the urban commercial and urban industrial potential export values was calculated for the nutrients group. The new export potential was 0.700.
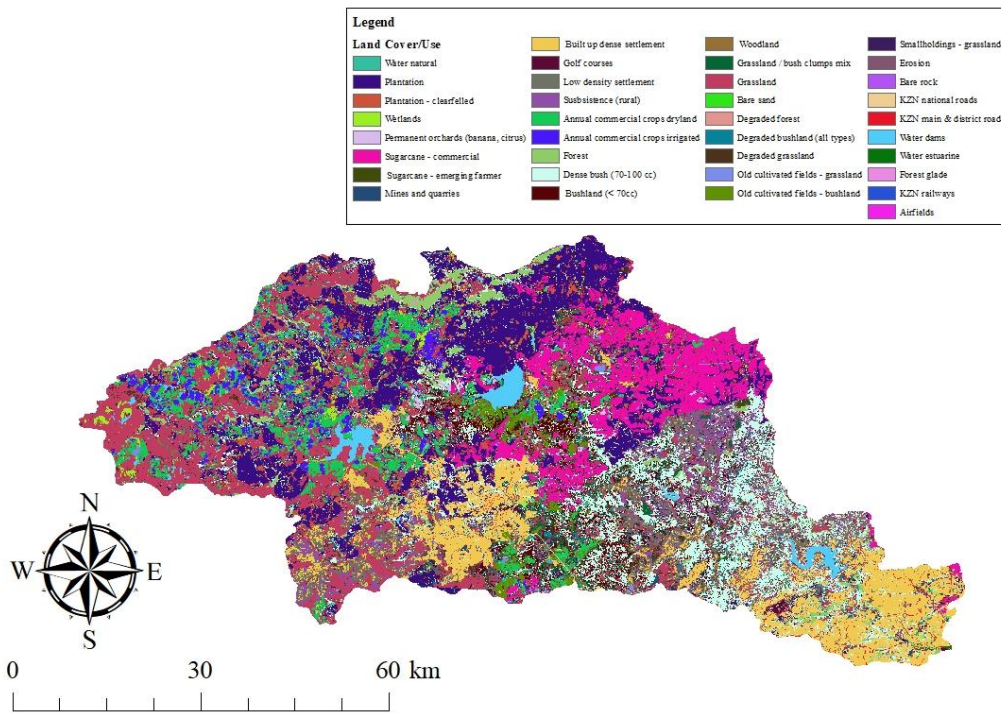

Figure 3.4   Land cover map of the uMngeni Catchment (Ezemvelo KZN Wildlife and GeoTerraImage, 2013)

Table 3.1   ALARM export potentials for the generation of diffuse pollution for various land
use categories (after DWA, 2014)

Land Use Category	Nutrients	Suspended Solids	Dissolved Salts	Microbiological	Toxins
Natural unimpacted	0.010	0.002	0.002	0.020	0.005
Natural degraded	0.015	0.974	0.023	0.600	0.006
Wetlands	0.005	0.140	0.004	0.020	0.001
Plantations	0.020	0.400	0.027	0.040	0.010
Dams and rivers	0.001	0.006	0.001	0.020	0.001
Irrigated commercial agriculture	1.000	0.302	0.100	0.300	0.250
Dryland commercial agriculture	0.800	0.214	0.100	0.300	0.200
Subsistence agriculture	0.600	0.600	0.031	1.000	0.150
Sparse settlement	0.500	0.257	0.004	0.600	0.050
Urban open space	0.200	0.194	0.004	0.400	0.150
Urban residential	0.400	0.006	0.010	0.720	0.250
Urban commercial	0.500	0.084	0.014	0.560	0.500
Urban industrial	0.900	0.200	0.015	0.920	1.000
Mines and quarries	0.200	1.000	1.000	0.480	1.000

Table 3.2   Classification of the Ezemvelo KZN Wildlife land cover classes into the ALARM
land use categories

Land Use Category	Ezemvelo KZN Wildlife Land Cover Classes
Natural unimpacted	Forest, Dense bush (70-100 cc), Bushland (< 70cc), Woodland, Grassland / bush clumps mix, Grassland, Bare rock, Forest glade, Alpine grass-heath,
Natural degraded	Degraded forest, Degraded bushland (all types), Degraded grassland, Rehabilitated mines – high vegetation, Old cultivated fields – grassland, Old cultivated fields – bushland, Erosion, Bare sand, Bare sand coastal
Wetlands	Wetlands, Wetlands-mangrove
Plantations	Plantation, Plantation clear felled, Old plantation – high vegetation, Old plantation – low vegetation
Dams and rivers	Water natural, Water dams, Water estuarine, Water sea
Irrigated commercial agriculture	Permanent orchards (banana, citrus) irrigated, Annual commercial crops irrigated
Dryland commercial agriculture	Permanent orchards (cashew) dryland, Permanent pineapples dryland, Sugarcane – commercial, Sugarcane – emerging farmer, Annual commercial crops dryland
Subsistence agriculture	Subsistence (rural)
Sparse settlement	Smallholdings – grassland
Urban open space	Golf courses, Airfields, KZN national roads, KZN main and district roads, KZN railways
Urban residential	Low density settlement
Urban commercial and industrial	Built up dense settlement
Mines and quarries	Mines and quarries, Rehabilitated mines – low vegetation

3.3.3.3 Rainfall dataset

A rainfall dataset is needed to calculate the dilution potential of the runoff on the pollutants. A raster dataset of the Mean Annual Precipitation (MAP) was accessed through the Centre for Water Resources Research (CWRR) (see Figure 3.5 below). The dataset was developed for the years 1950 to 1999 by Lynch (2004) and contains a daily time series of rainfall for several rain gauges, the missing values of which have been patched and infilled. The data were generated using a dataset of 49 years, and the derived means were stable indicators of the dilution potential. The interpolation technique used to transform the rainfall data into a continuous raster map was the geographically weighted regression approach (Lynch, 2004). The raster grid is available at a pixel resolution of 1 700 m and was resampled to 20 m in ArcMap. It was then clipped to the catchment boundary and converted to the ASCII file format.
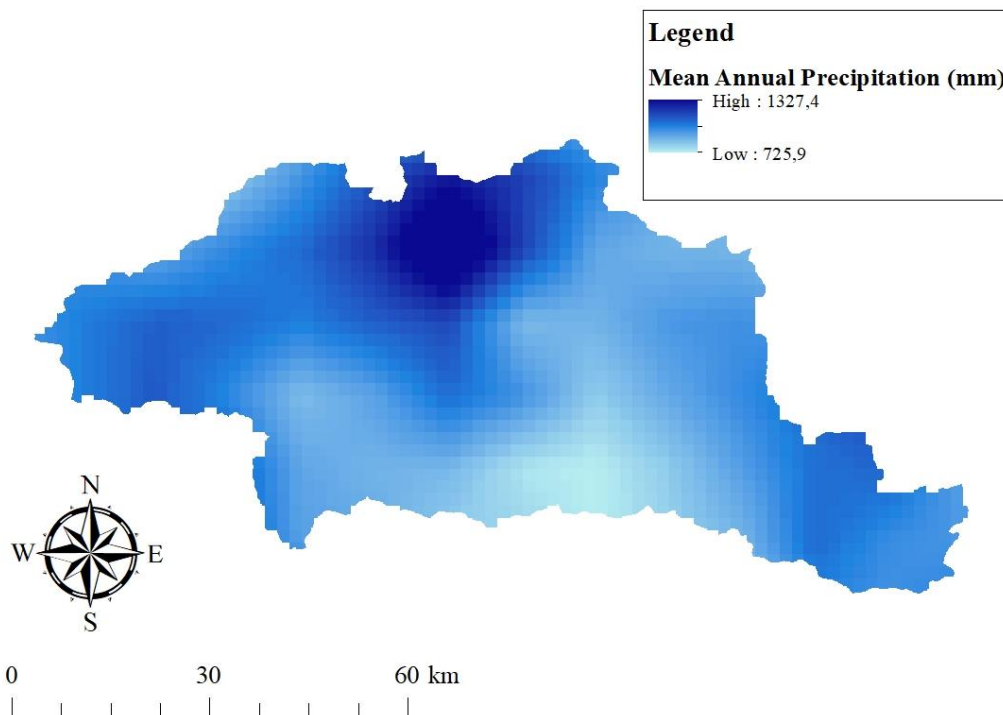

Figure 3.5   Mean Annual Precipitation (MAP) map of the uMngeni Catchment (Lynch, 2004)

3.3.4 Verification

Lane *et al.* (2006) identified and discussed the potential methods for testing the predictions of models like SCIMAP. In the absence of environmental data for validation, the use of local knowledge is recommended (Lane *et al.*, 2006). Furthermore, a study by Higgins (2011) makes use of local land owner knowledge, in conjunction with walkover surveys, to test the performance of the SCIMAP Model in predicting diffuse pollution risk. Testing the predictions of diffuse pollution models in this manner is uncommon in the existing scientific practice (Lane *et al.*, 2006). As diffuse pollution models become capable of providing a spatial representation of the CSAs, in the way that SCIMAP does, it has become necessary to consider alternative methods for testing the predictions of models (Lane *et al.*, 2006).

Following this approach, a walkover survey was carried out on the 26th of October 2017 for five locations in the Midmar Dam sub-catchment, to confirm model outputs. A locality map of the five locations surveyed surrounding Midmar Dam is depicted in Figure 3.6. The Midmar sub-catchment was selected for the survey, because previous research conducted in the area meant that there was an existing local knowledge base and experience. Model outputs were imported into Google Earth and they were overlain with aerial photography for the analysis. The selection of the locations focused on areas that SCIMAP suggested may deliver nutrients within the sub-catchment. Furthermore, during the selection process a variety of land cover types were considered. Access to the landscape areas was also considered during the selection process. During the walkover assessment, descriptions of the land cover, land use and elevation were recorded. Furthermore, checks were done in the area for gullies, channels, drains and furrows in order to match the modelled pathways.
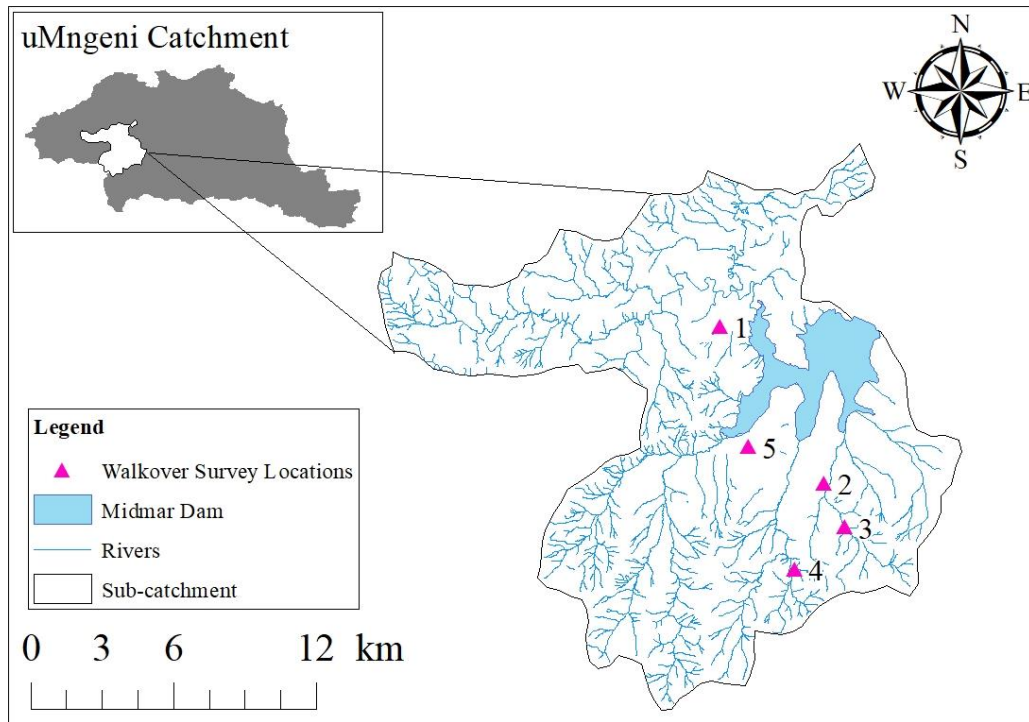
Figure 3.6   Locality map of the locations surveyed during the walkover in the Midmar sub-catchment

3.3.5 Sensitivity analysis

A sensitivity analysis is useful for identifying the input parameters to which a model is most sensitive (Beven, 1979). Furthermore, Lane *et al.* (1994) noted that attention must be given to whether a change in an input parameter produces a significant change in the model prediction. As highlighted in Paper 1, the sensitivity analysis of the SCIMAP Model to input land cover weightings will provide an indication of the attention that is required, in terms of their calculation, quality and associated error. The sensitivity analysis in this study is intended to give an indication of how the potential errors associated with the application of the SCIMAP Model in the uMngeni Catchment influence the model outputs.

To assess the sensitivity of the SCIMAP Model to the land cover weightings, researches have applied the Bayesian method in their study catchments (Milledge *et al.*, 2012; Thompson *et al.*, 2013; Porter *et al.*, 2017). This method involves inferring a range of land cover weightings in a Monte Carlo sampling framework and conducting thousands of model runs with randomly selected land cover weightings (Milledge *et al.*, 2012). Thereafter, a comparison is made between the outputs from the multiple model runs and spatially observed in-stream pollutant measurements. In the uMngeni Catchment, where ecological and water quality datasets are

spatially limited, this approach cannot be adopted with confidence. Therefore, an alternative method was sought to assess the sensitivity of the SCIMAP Model to the land cover weightings.

Equation 3.1 below is the simple objective function applied in this study to identify how sensitive the CSAs and transport pathways modelled by SCIMAP are, in terms of the input land cover weightings. The use of this objective function follows an approach adopted by Schulze (1995) and is recognised in the evaluation of hydrological models.

$$\Delta O\% = \frac{(O - O_{Base})}{O_{Base}} \times 100 \qquad\qquad (3.1)$$

Where,

$\Delta O\%$ = percentage change in output;

O = output from a specified percentage change in a selected input parameter; and

O_{Base} = output from the baseline condition input.

The effect of a 5%, 10% and 15% increase and decrease of the land cover weightings on the diffuse pollution risk was measured and compared with the diffuse pollution risk that was originally modelled i.e. the baseline condition. The rationale for observing slight differences in the input land cover weightings was to ensure that the influence of variation in weightings within each ALARM land use category could be observed. The aim was not to change the weighting to the extent of changing the ALARM land use category, but to explore the influence of the potential errors in the export weighting derived for each land use class. In the cases where an increase in a land cover weighting exceeded the maximum value of 1 set in the SCIMAP Model, the value was capped at 1, to stay within model limits.

The changes in diffuse pollution risk were analysed by observing the percentage changes in the modelled high-risk areas (see Figure 3.7). For the intermediate map of the diffuse pollution risk, the changes were observed in the areas with a diffuse pollution risk value ≥ 0.70. For the final map, depicting in-stream diffuse pollution risk, the changes were observed in the areas with standard deviations from the mean ≥ 2.20.
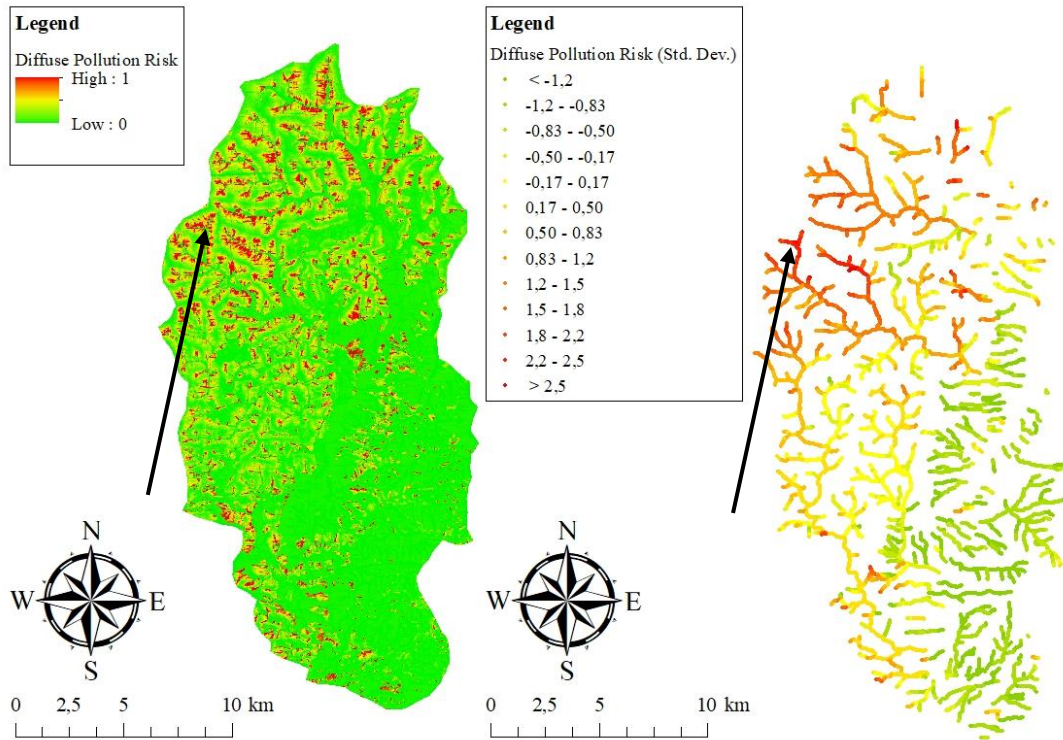
Figure 3.7   Catchment scale diffuse pollution risk maps with arrows depicting the modelled high-risk areas

3.3.6 Interactive web map

It is necessary that the information that has been generated to support sustainable water resources management be made more accessible to water resources decision-makers and stakeholders in the uMngeni Catchment (Mitchell *et al.*, 2014). In addition, the information that is shared should be readily accessible and it should be presented in a manner that is simple enough for decision-makers and stakeholders to comprehend (Liu *et al.*, 2008). For this reason, an interactive web map of the diffuse pollution risk in the uMngeni Catchment was created as a part of this study.

Using the ArcGIS Online platform, the map consists of an aerial photography base map, with a layer depicting hydrological connectivity, as well as a layer for each nutrient diffuse pollution risk model output. The methodology used to create the web map is found in Appendix A. In relative terms, the map allows for the identification of the quaternary catchments that need to be prioritised, followed by the sub-catchments, and finally, the associated land units or fields. In terms of protecting ecological infrastructure, the purpose of the web map is for users to concentrate on identifying the plots of land or fields that are highly likely to contribute to the diffuse pollution problem. This action has the potential to support the development of site-

specific mitigation measures for prioritised areas. Furthermore, the web map provides a platform for stakeholders to discuss and investigate the results being produced by the SCIMAP Model.

3.4 Results

The maps in this section depict the uMngeni Catchment that has been subdivided into the 12 quaternary catchments delineated by the Department of Water and Sanitation (DWS) in South Africa. The interactive web map of the results can be located, using the following web address: https://arcg.is/9CC5X.

3.4.1 Hydrological connectivity

Figure 3.8 shows a network index map that represents the hydrological connectivity risk for the uMngeni Catchment. This map is an intermediate layer that is generated during the SCIMAP modelling process and is a calculation of the P^c_i. The network index map indicates the modelled spatial pattern of soil moisture, hence identifying areas that are most likely to drain by saturated excess flow. Areas with a relatively high and low likelihood of connecting to the river network are depicted in red (with a risk value of 1) and blue (with a risk value of 0) respectively.
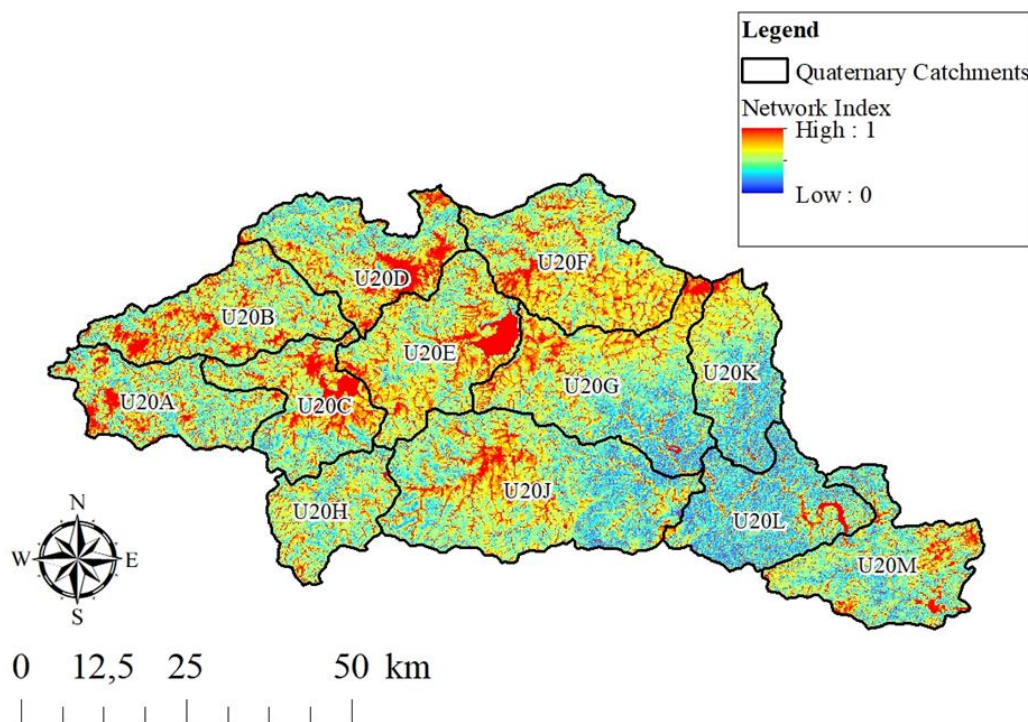

Figure 3.8   Network index map representing hydrological connectivity in the uMngeni Catchment (Step 2 of the SCIMAP processing structure)

The map illustrates that the areas with a higher risk of connectivity are found in the higher-lying western region of the catchment. Areas with the least risk of connectivity are found in the central-eastern region of the catchment. U20B, U20C, U20D, U20E and U20F have the highest connectivity risk and U20L has the lowest connectivity risk. Overall, 36% of the entire catchment area has been assigned a risk of between 0.80 – 1, and 10% of the catchment area has been assigned a risk of between 0 – 0.20.

3.4.2 Diffuse pollution risk

The diffuse pollution risk map is also an intermediate layer that is generated during the modelling process and it is a calculation of the P^{gc}_i. SCIMAP combines the hydrological connectivity risk and the land use export potentials to locate the CSAs. The diffuse pollution risk map of the CSAs of nutrients in the uMngeni Catchment is shown in Figure 3.8. High risk areas are depicted in red (with a risk value of 1) and low risk areas in green (with a risk value of 0).

The final map output produced by the model is shown in Figure 3.9. The map includes the calculation of the C_j and indicates the expected in-stream diffuse pollution risk that considers the effect of rainfall dilution. The layer is a combination of the connectivity, the land use export potentials and the rainfall dilution potentials of the catchment area. With this layer, one can identify the transport pathways of diffuse pollutants into the main channels. Risk is depicted in multiples of the standard deviation from the mean, to identify areas where the diffuse pollution risk is greater than the dilution potential. High risk areas are depicted in red (indicating that the risk is greater than the dilution potential) and low risk areas in green (indicating that the risk can be alleviated by the dilution potential).

Figures 3.9 and 3.10 illustrate that the important areas for the generation and transfer of nutrients are found in the central regions of the catchment. Regions with the least CSAs of nutrients are located mostly in the western headwaters of the catchment. Quaternary catchments U20F, U20G, U20H, U20J, U20K and U20M have the highest diffuse pollution risk, and U20A and U20D have the lowest diffuse pollution risk. Overall, 0.56% of the entire catchment area has been assigned a diffuse pollution risk of between 0.70 – 1, and 92% of the catchment area has been assigned a diffuse pollution risk of between 0 – 0.20.

A close-up view of the Midmar sub-catchment (U20C) results is shown in Figure 3.11. The map depicts a combination of the intermediate and final diffuse pollution risk layers. Key areas for the generation and transfer of nutrients are found in the central and eastern parts of the sub-catchment. The areas that are least at risk for transferring nutrients into the river network and impoundment are found in the southern-most reaches of the sub-catchment. It was found that 0.82% of the sub-catchment area has been assigned a diffuse pollution risk of between 0.70 – 1, and 94% of the sub-catchment area has been assigned a diffuse pollution risk of between 0 – 0.20.
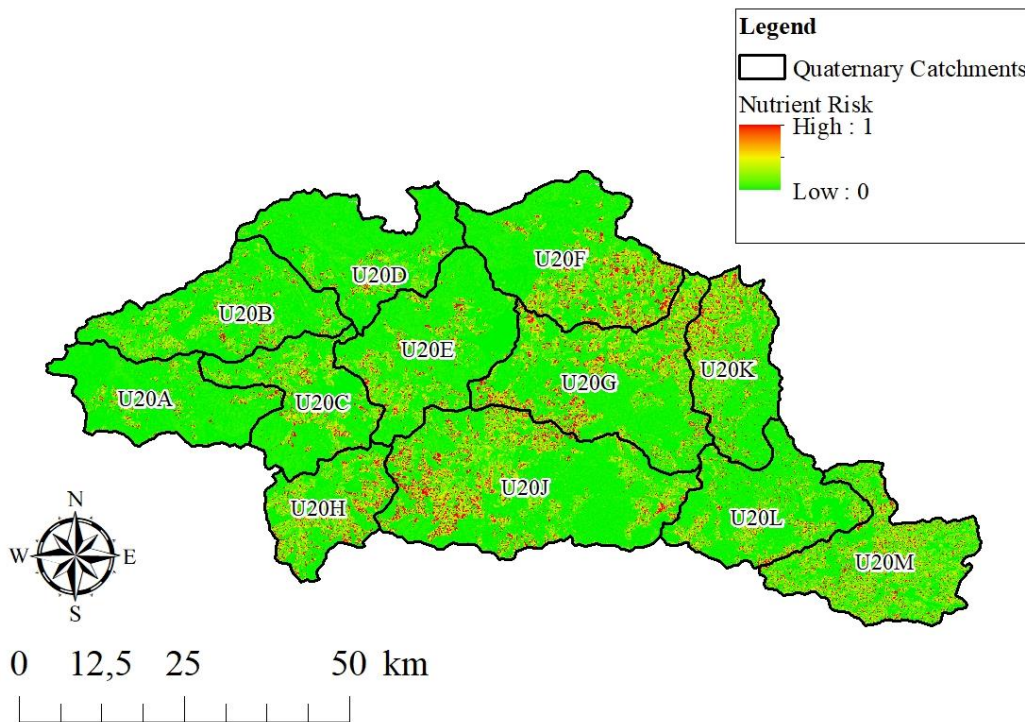

Figure 3.9   Diffuse pollution risk map of the Critical Source Areas (CSAs) of nutrients in the uMngeni Catchment (Step 3 of the SCIMAP processing structure)
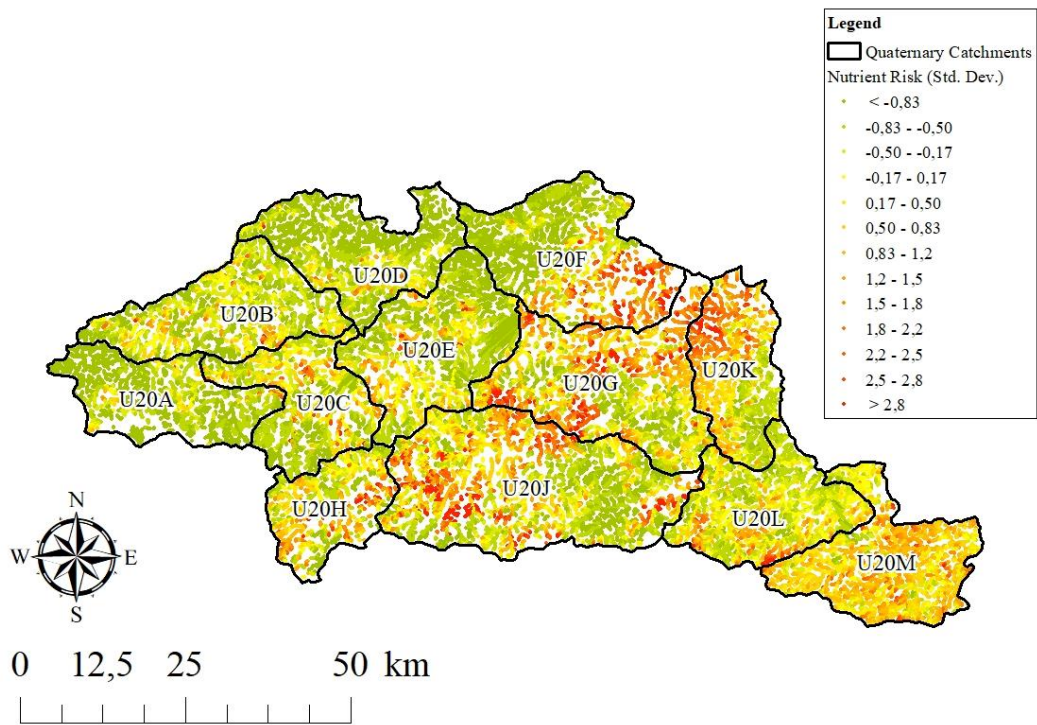
Figure 3.10 In-stream diffuse pollution risk map of the Critical Source Areas (CSAs) of nutrients in the uMngeni Catchment (Step 5 of the SCIMAP processing structure)
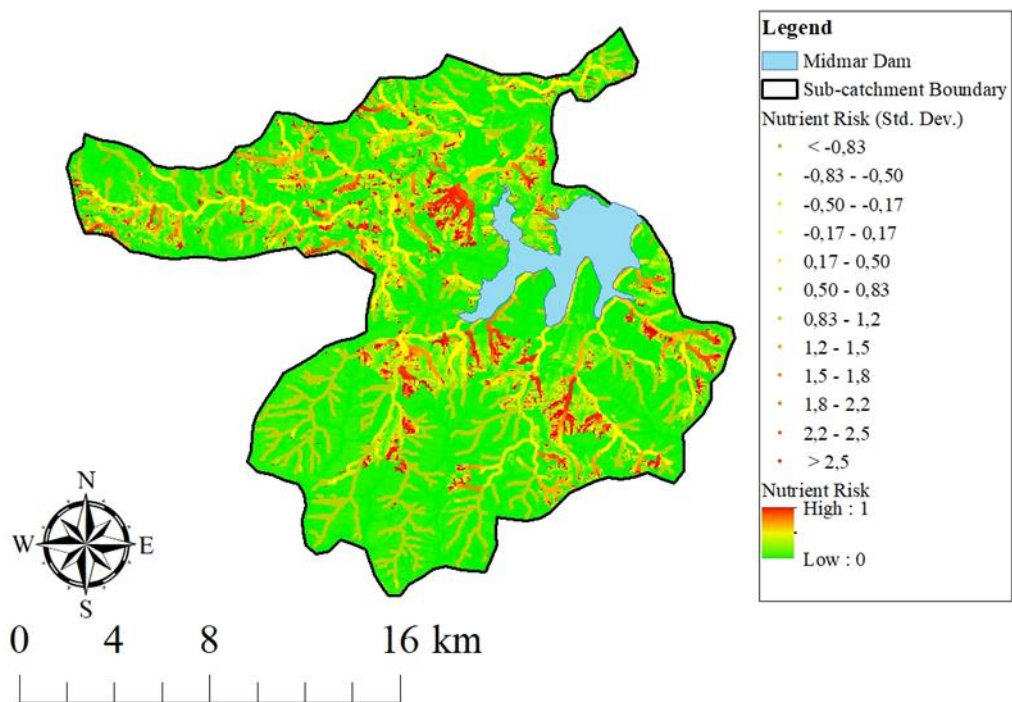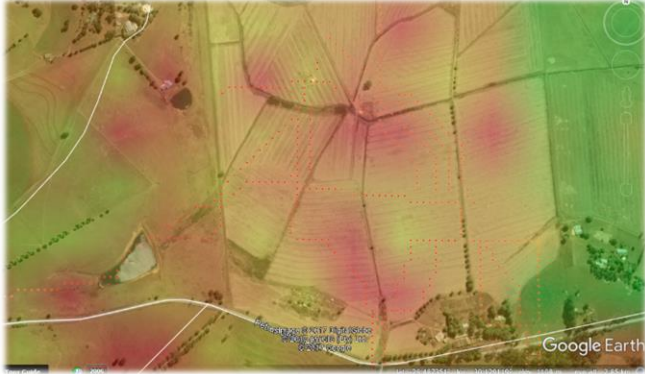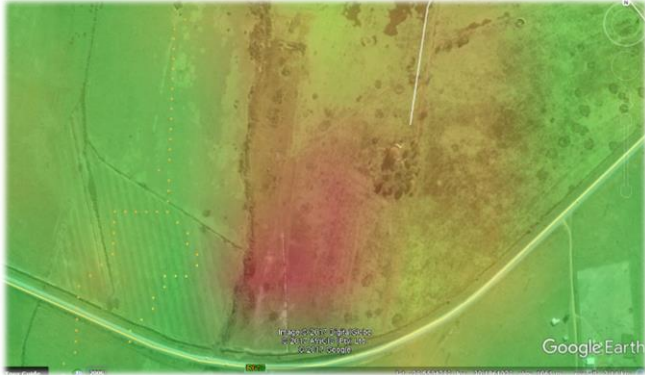

Figure 3.11 Diffuse pollution risk map of the Critical Source Areas (CSAs) of nutrients in the Midmar sub-catchment

53
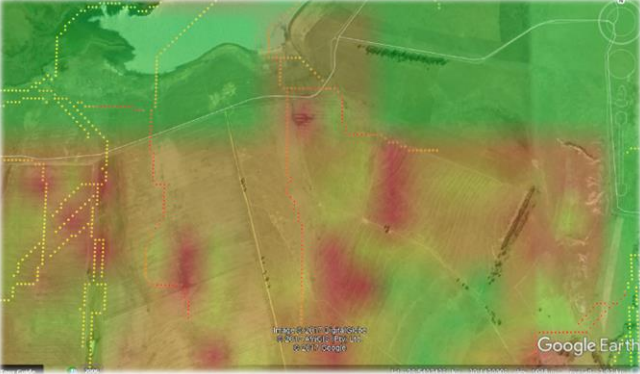
3.4.3 Walkover survey

Table 3.3 presents the findings of the walkover survey and includes the SCIMAP output map of each location. The pictures illustrate the benefits of overlaying model outputs with aerial photography and zooming into a sub-catchment/field scale, which makes the CSAs clearer and more identifiable. The results confirm that the land covers identified at Locations 1, 2, 3 and 4 could potentially contribute to nutrient diffuse pollution. At Location 5, the grassland vegetation appeared to not be a source of nutrients. Transport pathways were found to be reasonably accurate in all locations except at Location 1, where a manmade drainage system was found. Furthermore, the accuracy of the modelled transport pathways increased, with an increase in the elevation difference. The accuracy of the identified transport pathways decreased in locations with flatter landscapes and smaller differences in elevation.

Table 3.3   Results recorded during the walkover survey in the Midmar sub-catchment

		SCIMAP Output	Site Description	Land Cover / Use Description	Transport Pathways Description
Location 1			Coordinates: -29.494719° 30.141131° Elevation: 1 073 m Slope: Relatively flat/low-lying area	Farmland / Cropland (no tillage). Dryland maize (harvested). Irrigated pastures, which are used for cattle grazing. Cattle appear not to have access to the main river channels, instead have troughs for watering.	Farm dam spillways connect to a man-made drainage system. Man-made drainage ditches across the property converge at a central place. Each ditch was identified in the SCIMAP model output. Discrepancies were found in the transport pathways derived by SCIMAP. The model identified more pathways than what was present in reality.
Location 2			Coordinates: -29.554752° 30.188459° Elevation: 1 066 m Slope: Relatively flat/low-lying area	Degraded grassland area located downstream of a built-up urban area (Mpophomeni Settlement). Drained wetland area used by the local farmers for grazing and watering cattle. Stream banks within the area are not fenced and cattle have direct access to the stream.	All transport pathways derived by SCIMAP were found and are in reality small streams. This includes the Mthinzima River.

	SCIMAP Output	Site Description	Land Cover / Use Description	Transport Pathways Description
Location 3		Coordinates: -29.571130° 30.194423° Elevation: 1 103 m Slope: Gently-sloping terrain 	Built up urban area (Mpophomeni Settlement). Households located near streams have small subsistence agriculture gardens. Riparian area of the Mthinzima River has dead tree trunks of exotic plants holding the banks together.	Modelled pathways over the grassland were found to be streams. This includes the Mthinzima River. There was no evidence of the transport pathways derived by SCIMAP over the built up urban area.
Location 4		Coordinates: -29.586844° 30.172867° Elevation: 1 183 m Slope: Steeply-sloped hills. 	Grassland area downstream of a rural low-density settlement area (Cedarge Settlement). Bush and shrub land. Subsistence agriculture.	All transport pathways derived by SCIMAP were found and are small streams.

	SCIMAP Output	Site Description	Land Cover / Use Description	Transport Pathways Description
Location 5		Coordinates: -29.540382° 30.153218° Elevation: 1 051 m Slope: Relatively flat/low lying area 	Conserved grassland area surrounding Midmar Dam. Area is grazed by buck and zebra.	All transport pathways derived by SCIMAP were found and are wet grassed gullies.

3.4.4 Sensitivity analysis

Figure 3.12 depicts the percentage changes in the nutrient high-risk areas on the intermediate diffuse pollution risk map, for a 5%, 10% and 15% increase and decrease in the land cover weightings, from the baseline values. The results reveal that the modelled high-risk areas on the intermediate diffuse pollution risk map are highly sensitive to changes in the land cover weightings. Changes of 39.62%, 73.57% and 105.79% are observed in the high-risk areas, when land cover weightings were increased by 5%, 10% and 15%, respectively. Changes of -33.21%, -58.43% and -69.59% are observed in the high-risk areas, when land cover weightings were decreased by 5%, 10% and 15%, respectively. Furthermore, the intermediate diffuse pollution risk map is relatively equally sensitive to both an increase and a decrease in the land cover weightings. A positive correlation is observed between the percentage changes in the nutrient high-risk areas and the changes in the land cover weightings.

Figure 3.12 Percentage changes in the nutrient high-risk areas on the intermediate diffuse pollution risk map, for a 5%, 10% and 15% increase and decrease in the land cover weightings, from the baseline values

Figure 3.13 depicts the percentage changes in the nutrient high-risk areas on the final diffuse pollution risk map, for a 5%, 10% and 15% increase and decrease in the land cover weightings, from the baseline values. The results in Figure 3.13 reveal a slight sensitivity of the modelled high-risk areas on the final diffuse pollution risk map, to changes in the land cover weightings. Changes of -0.21%, -4.43% and -8.37% are observed in the high-risk areas, when land cover weightings were increased by 5%, 10% and 15%, respectively. When the land cover weightings were decreased by 5%, 10% and 15%, changes of 8.63%, -17.02% and -0.09% are observed in the high-risk areas, respectively. Unlike the changes observed in the high-risk areas of the intermediate diffuse pollution risk map, the changes in the final diffuse pollution risk map have a varied trend. When the land cover weightings were increased, the percentage changes in the nutrient high-risk areas decreased. For a decrease in the land cover weightings, no relationship was observed between the percentage changes in the nutrient high-risk areas and the changes in the land cover weightings. The percentage changes in the nutrient high-risk areas on the final risk map were of a smaller magnitude than those observed on the intermediate risk map.

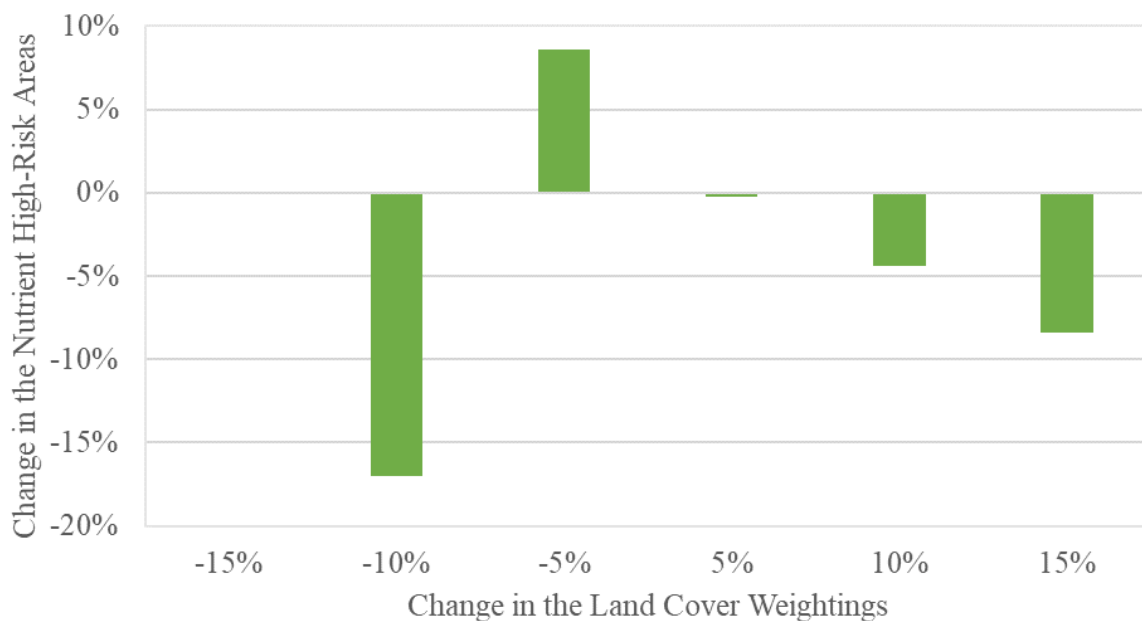Figure 3.13   Percentage changes in the nutrient high-risk areas on the final diffuse pollution risk map, for a 5%, 10% and 15% increase and decrease in the land cover weightings, from the baseline values

3.5 Discussion

The results in this paper indicated that the central-west quaternary catchments (i.e. U20B, U20C, U20D, U20E and U20F) were highly connected to the river network and pollutants

would therefore most likely to be transported into the rivers via runoff. The relatively gentle slopes found in these quaternary catchments act as a mode of channelling saturated-excess water off the landscapes. This may then result in diffuse pollution being delivered into the receiving rivers. Studies by Dixon (2013) and Al-Yami (2014) show that areas with a high connectivity risk are associated with gently-sloped landscapes. This is due to the fact that the degree of connectivity in an area is governed by the probability of a continuous saturated flow path to form to the river network (Reaney *et al.*, 2011). The SCIMAP Model identified that the quaternary catchment with the least connection to the river network was U20L. The pollutants in this area are therefore the least likely to be transported into rivers via runoff. This could be attributed to the relatively steep slope and elevation gradients in the quaternary catchment. Such topography causes a disconnection of the saturated overland flows, as the rainfall in these areas will have limited time to infiltrate, due to the high speeds at which it will move laterally under gravity (Dixon, 2013).

U20F, U20G, U20H, U20J, U20K and U20M were highlighted as being critical quaternary catchments for the generation and transportation of nutrients. The CSAs in these quaternary catchments increase notably around areas where agricultural practices are most dominant and in the vicinity of the urban centres of Pietermaritzburg and Durban. According to Namugize *et al.* (2017), agricultural lands are responsible for a high proportion of nutrient loads in the uMngeni River and its tributaries. The use of nutrients is necessary for high crop yields in commercial farming, but these are often excessively applied (Hewett *et al.*, 2009). It was found that quaternary catchments U20A and U20D have the lowest diffuse pollution risk. These quaternary catchments make up the Upper uMngeni system. Land cover in these quaternary catchments is predominantly natural grassland, forestry plantations, indigenous forests and wetlands. Although U20A and U20D were identified by SCIMAP as having a relatively low nutrient risk, previous research has raised concerns of the increase in nutrient loading, with the growth of agricultural and urban areas in the Upper uMngeni system (Hemens *et al.*, 1977; Ngubane, 2016).

An examination of the results at a field scale revealed a correlation identified between areas deemed to be the most at risk of nutrient pollution by SCIMAP and the field observations. On visiting the five locations surrounding Midmar Dam, the results confirm that the land cover/use identified at Locations 1, 2, 3 and 4 could potentially contribute to the diffuse pollution problem. Locations 1, 2, 3 and 4 are characterised by the following land cover/use: dryland

commercial agriculture, degraded grasslands, urban residential areas and rural residential areas, respectively. It is unclear why SCIMAP highlighted Location 5, which is a natural grassland area, as a nutrient hotspot. Unless Location 5 is intensely grazed, it is not a potential source of nutrient pollution. It was thought that this model output error may have been a result of a misclassification in the land cover map. However, when examining Location 5 on the Ezemvelo KZN Wildlife land cover map, the area was found to be classified as a grassland. In this study, it was not possible to show that the SCIMAP Model outputs always matched the field observations. There is a need for spatially adequate water quality monitoring that will allow for a more robust attempt at comparing the SCIMAP Model with catchment observations. In addition, more sites should be examined in the uMngeni Catchment and the Cohen's Kappa statistic applied, to rigorously compare modelled and observed data. However, the results from the walkover survey indicate that the SCIMAP Model directed the nutrient source area investigations to mostly the right locations. Furthermore, research by Reaney *et al.* (2011) has suggested that the model does provide a good fit with field observations.

The results from the walkover survey also suggest that the model over-estimates transport pathways in areas where man-made features, such as drainage ditches, are present (e.g. at Location 1). Historically, drainage ditches in the Midmar sub-catchment were constructed to lower the water table and to create larger areas for planting crops. Furthermore, it was observed that the accuracy of the modelled transport pathways increased, with an increase in the elevation difference. This could be as a result of the DEM resolution. The use of finer resolution (< 20 m) data is likely to improve the ability of the model to determine transport pathways in areas with man-made features and with a small difference in the elevation. Al-Yami (2014) investigated the influence of the DEM resolution on the delineation of channel networks and flow accumulation pathways. The results of the study suggest that a DEM, with a resolution of ≤ 5 m is a prerequisite for any reliable assessment of local overland water pathways (Al-Yami, 2014). In addition, Cuartas *et al.* (2012) noted that the low spatial resolution of topographic data in a study area can introduce errors that are reflected in the final model results.

In the context of investing in ecological infrastructure, the results from the modelling exercise prioritise areas for diffuse pollution mitigation interventions. Opportunities for reducing diffuse pollution risk at specified locations can now be identified. Local catchment interventions, such as fencing off watercourses and providing cattle with designated troughs for watering, could potentially reduce the risk of diffuse nutrients entering the streams. At

Location 2, an opportunity to reduce diffuse pollution risk was identified. It is believed that the rehabilitation of the wetland in the area could offer a strong buffer against the flow of pollutants.

A foreseen challenge and potential error source in the application of the SCIMAP Model in the uMngeni Catchment included the calculation of the input land cover weightings. Based on the sensitivity analysis results, the percentage changes in the nutrient high-risk areas on the intermediate diffuse pollution risk map reveal that the SCIMAP Model is highly sensitive to the input land cover weightings. With regards to the final diffuse pollution risk map, the percentage changes in the nutrient high-risk areas reveal that the SCIMAP Model is slightly sensitive to the input land cover weightings. The percentage changes in the nutrient high-risk areas on the final risk map were of a smaller magnitude than those observed on the intermediate risk map. This could be due to the role of the dilution effect in the in-stream risk on the final diffuse pollution map.

The high sensitivity of a parameter is only desirable if that parameter can be determined accurately and without difficulty (Schulze, 1995). In addition, Thompson *et al.* (2013) argue that CSA models, where land use risk is used as a primary driver of diffuse pollution, could overestimate the potential diffuse pollution risk. SCIMAP users need to be aware and take caution in the formulation of the land cover weightings. Whether deriving the weightings using the Monte-Carlo sampling approach and fitting the weightings to observed in-stream concentrations (Milledge *et al.*, 2012; Porter *et al.*, 2017), or relying on thorough investigations of the diffuse pollution source areas (Dixon, 2013), the uncertainty in the model outputs associated with the weightings should be recognised. In this study, the results of a thorough investigation were available to direct the formulation of land cover weightings (DWA, 2014). The use of the export potentials from the ALARM land use categories reduced the uncertainty that arises from simple reasoned estimates that seek to establish what the export potential of a land cover should be. In future, spatially applicable in-stream water quality data should be collected to apply the Bayesian approach, to formulate and investigate the input land cover weightings in the uMngeni Catchment. To strengthen and further develop the results obtained from this sensitivity analysis, future work is required to analyse the changes in diffuse pollution risk when each land cover class weighting is varied in turn. Furthermore, assessing the changes in the location of the modelled CSAs in the catchment, with changes in the land cover weightings would prove valuable.

3.6 Conclusion

Water resources managers in the uMngeni Catchment are seeking to identify the CSAs and transport pathways of diffuse nutrient pollution. Risk-based modelling methods, such as the SCIMAP Model, have become increasingly useful for providing a spatial representation of the diffuse pollution risk. In this paper, the SCIMAP Model was applied to examine nutrient CSAs and transport pathways in the uMngeni Catchment. The results of this study highlighted that the hydrological connectivity risk in the uMngeni Catchment is highest in the high-lying western region and that it is lowest in the middle-eastern region. The priority areas with a high nutrient risk are found in quaternary catchments U20F, U20G, U20H, U20J, U20K and U20M. Quaternary catchments U20A and U20D generate a relatively lower risk of diffuse nutrient pollution. Walkover survey observations in the Midmar sub-catchment reveal that four of the five locations that were identified as being a high risk for nutrient delivery could potentially contribute to nutrient diffuse pollution. For the most part, the SCIMAP Model was able to direct the nutrient source area investigations to the correct locations. Furthermore, the survey revealed that the accuracy of the modelled transport pathways increased, with an increase in the elevation difference. The results of the sensitivity analysis in this study revealed the potential uncertainty and sources of error involved in the application of the SCIMAP Model in the uMngeni Catchment. A high sensitivity of the modelled high-risk areas was observed on the intermediate diffuse pollution risk map, and a slight sensitivity of the modelled high-risk areas on the final diffuse pollution risk map, when the input landcover weightings were increased and decreased by 5%, 10% and 15%. Caution should be practised in the formulation of the input land cover weightings, as they are a potential source of error in the model outputs. Preferably in future, an evaluation should be carried out to ascertain whether using the Bayesian approach to formulate the land cover weightings would better model the CSAs and transport pathways of nutrients in the uMngeni Catchment. This will require water quality monitoring, to form a dataset that will support the modelling process and the verification of the results. Furthermore, to improve the ability of the model to determine transport pathways, finer resolution DEMs (i.e. < 20 m) should be considered. Future work is also required to evaluate the use of the modelled results to guide investments in ecological infrastructure and the possible land management practices that could be adopted to mitigate the nutrient risks in the uMngeni Catchment.

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CHAPTER 4: SYNTHESIS AND CONCLUSIONS

This study has investigated the CSAs and transport pathways of diffuse nutrients in the uMngeni Catchment, using a risk-based approach for diffuse pollution assessment. The intention was to realise the potential for utilising the generated data to guide the efforts and investments in diffuse pollution mitigation and the protection of ecological infrastructure. Previous research pertaining to diffuse pollution in the uMngeni Catchment, has had some success in measuring pollutant concentrations or quantifying pollutant loads (Breen, 1983; Kienzle *et al.*, 1997; Ngubane, 2016; Namugize *et al.*, 2017). However, difficulties are still being experienced in the identification of the CSAs in the catchment, when applying conventional methods. It was therefore important to investigate: a) If risk-based approaches for diffuse pollution assessment could be applied in the uMngeni Catchment, to identify the diffuse nutrient CSAs and transport pathways? and b) Where the CSAs and the transport pathways of diffuse nutrients are in the uMngeni Catchment? The research objectives were designed to:

a) review and examine the recent risk-based approaches for assessing diffuse pollution;

b) consider the applicability of risk-based approaches for diffuse pollution assessment within the uMngeni Catchment;

c) map the CSAs and transport pathways of nutrients in the uMngeni Catchment, based on a selected risk-based method that is discussed in the literature review; and

d) develop an interactive web map to inform stakeholders and guide efforts to mitigate diffuse pollution in the uMngeni Catchment.

This chapter briefly outlines how each of the research objectives was examined and highlights the key results. The end of this chapter focuses on making recommendations for future research.

4.1 Review and Examination of the Recent Risk-Based Approaches for Assessing Diffuse Pollution

In Chapter 2, this study reviewed and examined the use of five risk-based approaches in the assessment of CSAs and transport pathways of diffuse pollution. The review focused on gaining a better understanding of how each risk-based method operates, by summarising selected case studies. The five risk-based methods reviewed included the SCIMAP Model, the analysis of the connectivity of catchment process zones, the HAND Method and the analysis of HSAs. A summary of the results from the reviewed risk-based methods was provided in Table 2.2. Furthermore, the results indicated the main differences between the conventional

approaches used for diffuse pollution assessment and the relative risk-based approaches. The basis of risk-based approaches is in examining the probable sources of pollutants and their transport pathways in a catchment. This differs from conventional approaches that make quantitative predictions of in-stream diffuse pollutants. In addition, it was found that the CSAs and hydrological connectivity within a catchment are easily identified when applying risk-based methods, when compared to conventional methods. The review formed the basis for selecting a method to be applied in the uMgneni Catchment; the results of which will be discussed in Section 4.2 below.

4.2 The Applicability of Risk-Based Approaches for Diffuse Pollution Assessment within the uMngeni Catchment

In reviewing the available risk-based approaches for diffuse pollution assessment, the applicability of each method for application in the uMngeni Catchment was discussed. Four main criteria were considered for selecting a risk-based approach to apply in the uMngeni Catchment. These criteria are listed below:

   a) The key outputs of the method;
   b) The spatial scale at which the method can be applied;
   c) The input data requirements; and
   d) The access to the modelling software.

The SCIMAP Model was selected as the best option at hand, to inform the catchment-scale risks for diffuse pollution in the uMngeni Catchment. The attributes of the SCIMAP modelling process were identified and include: a) the ability to identify the CSAs of diffuse pollutant and catchment hydrological connectivity; b) the application of the model at field and catchment scale; and c) model runs are performed using readily-available data and software.

4.3 Mapping the CSAs and Transport Pathways of Nutrients in the uMngeni Catchment

It was a hypothesis of this research that the adoption of risk-based approaches for investigating diffuse pollution in the uMngeni Catchment would allow for the identification of the CSAs and transport pathways. Using the SCIMAP Model the CSAs and transport pathways of nutrients were mapped for the uMngeni Catchment. The intermediate maps and the final map generated from the SCIMAP Model were analysed independently of each other to see which areas had: a) the highest risk of connecting to the river network; and b) the highest nutrient risk.

Hydrological connectivity was assessed in the SCIMAP Model through the development of a network index map. The network index map indicates the areas that are most likely to drain by saturated excess flow, therefore identifying the areas that are most or least likely to transport pollutants into rivers via runoff. From the modelling results it was found that areas with the highest hydrological connectivity were found in the wide, gently sloping landscapes of the central-west region of the catchment. The network index map identified that the areas with the least connection to the drainage network were found in the middle-eastern regions of the catchment.

To locate the CSAs for diffuse pollution, the SCIMAP Model combines the hydrological connectivity risk and the land use export potentials. The results from applying SCIMAP in the uMngeni Catchment depict areas at greatest risk of contributing to the nutrient diffuse pollution problem in the river network in the central reaches of the catchment. These areas are where catchment management resources would be best targeted to minimise nutrient risk. The nutrient risk was found to increase notably around agricultural and urban areas. It was found that the headwater quaternary catchments in the Upper uMngeni Catchment have the lowest diffuse pollution risk. Land cover in these quaternary catchments is predominantly natural grassland, forestry plantations, indigenous forests and wetlands.

Following the recommendations made by Lane *et al.* (2006), a field walkover survey was conducted to test the predictions of SCIMAP. On visiting five locations surrounding Midmar Dam, the results confirm that the land covers/uses identified at four out of five locations matched the modelled results and could potentially contribute to the diffuse pollution problem. The SCIMAP Model was able to direct the nutrient source area investigations to the correct locations, for the most part. The results from Location 1 indicate that the model over-estimates transport pathways in areas where man-made features, such as drainage ditches, are present. Furthermore, the model predictions of the transport pathways in the Midmar sub-catchment proved to be less accurate in areas with flatter landscapes and smaller differences in elevation. It was observed that with an increase in the elevation difference, the accuracy of the modelled transport pathways increased. The possible reason for this occurrence could be as a result of the DEM resolution. Al-Yami (2014) and Cuartas *et al.* (2012) note that the use of course resolution topographical data can introduce errors that are reflected in the final model results.

It is noted in Chapter 2 that a potential challenge of mapping diffuse pollution risk in the uMngeni Catchment, using the SCIMAP Model, could be the formulation of the input land cover weightings. In Chapter 3 of this study, land cover weightings were derived using the ALARM export coefficients. In addition, an investigation on the sensitivity of the of the SCIMAP Model to the land cover weightings was conducted. This work was undertaken to evaluate the influence of the potential errors associated with the use of SCIMAP, to map diffuse pollution risk in the uMngeni Catchment. Sufficient water quality data was not available to apply the Bayesian approach to assess the sensitivity of SCIMAP to the land cover weightings. Instead, an objective function was applied to observe the effect of a 5%, 10% and 15% increase and decrease of the land cover weightings, on the modelled high-risk areas. The SCIMAP Model was found to be highly sensitive to changes in the land cover weightings on the intermediate diffuse pollution risk map. When compared to the changes detected on the intermediate diffuse pollution risk map, the final diffuse pollution risk map was only showed a slight sensitivity to changes in the land cover weightings. The results confirmed the need to practice caution in the development of land cover weightings. The establishment of input land cover weightings is very important and should receive priority in similar studies in the future. Using the export potentials from the ALARM land use categories, which were formed in a thorough investigation, reduced the uncertainty in the modelled CSAs. In future, to test and derive the input land cover weightings in the uMngeni Catchment, it was advised that spatially applicable in-stream data be collected, to support the application of the Bayesian method.

4.4 The Development of an Interactive Web Map

An interactive web map of the diffuse pollution risk in the uMngeni Catchment was created as a part of this study (https://arcg.is/9CC5X), using the ArcGIS Online platform. The map consists of an aerial photography base map, with a layer depicting hydrological connectivity, as well as a layer for each nutrient diffuse pollution risk model output. The map includes tools that allow users to select the layer and region of interest, to set the transparency of the layers, make measurements on the map, as well as share and print the map. The intention behind the web map was to make the data produced in this study available to the stakeholders within the catchment. Stakeholders can use these maps to formulate decisions and also to discuss and investigate the results produced by the model.

4.5 Recommendations for Future Research

This study demonstrated that SCIMAP is a valuable tool for identifying the CSAs and transport pathways of diffuse pollution in the uMngeni Catchment. However, to further develop and improve the results obtained from this study, the following recommendations for future research are made. Furthermore, these recommendations can be viewed as suggestions on how to best apply the SCIMAP Model in other South African catchments.

The lack of spatially applicable water quality data meant that firstly, the validation process had to rely on local knowledge and secondly, an alternative approach was required in the investigation of the model's sensitivity to the land cover weightings. Therefore, the main recommendation for future research would be to carry out detailed water quality monitoring in the uMngeni Catchment to support the application of the SCIMAP Model. There is a need for spatially adequate water quality monitoring that will allow for a more robust attempt at comparing the SCIMAP Model with catchment observations, and a more robust sensitivity analysis. Monitoring sites should cover more rivers and streams in the catchment than is covered at present. To improve the ability of the model to determine transport pathways, it is advised that finer resolution DEMs (i.e. < 20 m) be considered for future modelling exercises. Future work is also required to analyse the effectiveness of using the modelled results to guide investments in ecological infrastructure and the possible land management practices that could be adopted to mitigate the nutrient risks in the uMngeni Catchment.

4.6 References

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APPENDIX A

This appendix provides the methodology applied to create the interactive web map of the modelled results in this study, as referred to in Chapter 3, Section 3.3.6.

A.1 Selection of a Platform to Create the Web Map

Many platforms exist to create and display web maps, but for this study, three platforms were considered, namely Google Earth, Leaflet and ArcGIS Online. The software of all three of these platforms can be downloaded from open source websites.

Google Earth was the primary choice for this study, as it has become a reliable platform for examining and sharing geospatial data. However, it was found that the modelled data from this study would not be accessible to individuals without prior installation of the software on their computers. Furthermore, there would be no web map product, rather access to the layers within a shared folder.

Leaflet is used to develop high quality web map applications. Wu and Lane (2017) previously used Leaflet, to map the connectivity of wetlands. To use this platform, experience and knowledge on computer programming and Java Script writing is required. This experience was not available, unless assistance was out sourced.

ArcGIS Online, an expression of the ArcGIS desktop suite, has been widely accepted by researchers, educators and the public, as a collaborative platform that allows for the creation and sharing of spatial information. The capabilities of ArcGIS Online provide a basis to create an openly available web map that will support the investigation of high-risk nutrient source areas and transport pathways in the uMngeni Catchment. The ArcGIS Online platform was selected for use in this study.

A.2 Creating a Map using the ArcGIS Online Platform

The first step involved setting up an ArcGIS Online account. A public account was created using personal credentials. An ArcGIS Online account enables the user to sign in with privileges to create and share content. Step Two involved the conversion of the modelled output into the Keyhole Mark-up Language (KML) file format. This was achieved using the ArcGIS suite Version 10.4. The third step included adding the KML files to the My Content page on

the ArcGIS Online platform. Thereafter, Step Four involved the creation of the map. An aerial photography base map was selected and the KML file layer depicting the modelled hydrological connectivity risk, as well as each layer depicting the modelled nutrient diffuse pollution risk were added from the My Content page. Details, such as the map title and description, were included and the map was then saved as an item on the My Content page.

A.3 Creating a Web Map Application using the ArcGIS Online Platform

Using the Create a Web App wizard on the ArcGIS Online platform, an interactive web map app was created that can be opened in standard web browsers, mobile devices and desktop map viewers. The Basic Viewer template was selected to display the map created in Section A.1. Furthermore, app configurations included adding tools that allow users to select the layer and region of interest, to set the transparency of the layers, make measurements on the map, as well as share and print the map.

A.4 References

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