Testing the use of the BASINS PLOAD model to simulate the quality of stormwater runoff from the Kuils River catchment, Cape Town

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Thesis presented for the degree of

MASTER OF SCIENCE

In Environmental and Geographical Science

University of Cape Town

April 2011

Plagiarism declaration

I know the meaning of plagiarism and declare that all of the work in the dissertation, save for that which is properly acknowledged, is my own.

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Ratidzo Dhlembeu

ACKNOWLEDGEMENTS

Without God's amazing providence throughout the past two years I would not have been able to make it this far.

To my parents Chirandu and Davidzo Dhlembeu, thank you for your unwavering support, your love and your selfless sacrifice. Tino and Rufaro, my lovely sisters, you have both been the push I need and my constant helpers. A million thanks to you both. To my friends, you are all my 'solid rocks', thank you for many hours of listening and prayers.

To my supervisors Dr Kevin Winter and Professor Ralph Hamann thank you for your patience and support in teaching me how to become a better researcher.

To my colleagues at the Cape Urban Observatory and the African Centre for Cities, it has been a pleasure and a privilege to work with you and learn from you.

I would also like to express my gratitude to Messrs Nico Meyer, Barry Wood, Rod Arnold and Abdulla Parker and Ms Candice Haskins from the City of Cape Town roads and stormwater department for their contributions to this thesis.

To Dr Mark Dent and Mr Bruce Eady at the University of Kwazulu-Natal, thank you for providing useful guidance on the BASINS system.

Finally, I would like to thank the Cape Urban Observatory at the University of Cape Town for the financial assistance towards this study.

ABSTRACT

The interaction between land use and water quality in urban catchments is closely linked. As pollutants accumulate on land surfaces they are carried in runoff. This has led to increasing concerns that stormwater is responsible for adversely affecting the quality of freshwater resources. Total phosphorus and total suspended solids represent two forms of pollutants that are commonly found in non point source discharge. In South Africa, these pollutants are typically monitored using field based measuring techniques. However, these techniques can be time consuming and place significant demands on the human capacity needed to undertake the assessments.

This study evaluated water quality modelling as an alternative monitoring technique. The study was aimed at determining the potential use of a simple water quality model to evaluate pollution in stormwater runoff. The study was conducted in the Kuils River catchment using the BASINS PLOAD model (PLOAD) to estimate pollutant loads of total suspended solids (TSS) and total phosphorus (TP) in runoff. The catchment was divided into four sub-catchments and simulations of pollutants in runoff were conducted over both annual and monthly time scales.

The results of the annual simulations revealed that the Bottelary sub-catchment (0.12 mg/l) was the only sub-catchment that contributed to TP concentrations that exceeded the discharge quality guidelines of <0.1 mg/l. None of the TSS concentrations in the four sub-catchments exceeded the discharge limit of 18mg/l. The results of monthly load estimates revealed that pollutant concentrations were highest in the month of June. The Bottelary sub-catchment demonstrated the highest estimated concentrations of TP across all the months in 2009, whilst estimates for TSS were most significant in the Bottelary and Eerste-Kuils sub-catchments.

An assessment of pollution from different land uses in the catchment revealed that that for TP pollutant loads the land uses of informal housing and industrial generated the highest pollutant concentrations. Rural / agricultural land uses also demonstrated significant contributions (albeit lower than the former two land uses). Informal housing and industrial land uses were also found to generate the highest concentrations of TSS. These land uses can be classified as key/priority land uses in the catchment which are contributing to the degradation of the Kuils River.

The model estimations were validated using a rank Spearman correlation analysis to compare the estimates made by the model with pollutant concentrations in the Kuils River (which were determined using field based techniques). The result of the correlation confirmed that an association exists between pollutant loads carried in runoff and the in-stream pollutant loads.

Therefore it was concluded that high pollutant loads in runoff contribute significantly to the poor water quality in rivers.

To further assess the potential use of the model, surveys were conducted with experienced individuals from the stormwater management branch of the Cape Town Municipality. The survey respondents noted that the model provided a useful screening tool for stormwater managers however the equations in the PLOAD model were criticised for their simplicity. As such the perceived applicability of the model by stormwater resource specialists was not tangible.

TABLE OF CONTENTS

INTRODUCTION

LITERATURE REVIEW

METHODOLOGY

RESULTS OF PLOAD MODELLING PROCESS

POTENTIAL USE OF PLOAD FOR STORMWATER MANAGEMENT IN THE CMA

CONCLUSION AND RECOMMENDATIONS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

BASINS	Better Assessment Science Integrating Point and Non-point Sources
BMP	Best Management Practice
BO	Bottelary sub-catchment
CoCT	City of Cape Town
CMA	Cape Metropolitan area
DEA	Department of Environmental Affairs
DEM	Digital Elevation Model
DWA	Department of Water Affairs
EK	Eerste – Kuils sub-catchment
EMC	Event Mean Concentration
GIS	Geographical Information System
MK	Middle Kuils sub-catchment
NPDES	National Pollutant Discharge Elimination System
NPS	Non Point source
PLOAD	Pollutant load model
RHP	River Health program
SAWS	South African Weather Service
SUDS	Sustainable Urban Drainage Systems
SWMM	Storm Water Management Model
TMDL	Total Maximum Daily Limit
TP	Total Phosphorus
TSS	Total Suspended Solids
UK	Upper Kuils River sub-catchment
USEPA	United States Environmental Protection Agency
USOTA	United States Office of Technical Assistance
WRC	Water Resource Commission
WSUD	Water Sensitive Urban Design
WWTW	Waste Water Treatment Works

CHAPTER 1

Introduction

1.0. BACKGROUND

In urban catchments the interaction between land use and water quality are closely linked. As stormwater flows over the landscape it collects different pollutants that were deposited there by activities from different land uses (Jessel and Jacobs, 2005). As a result, there is increasing concern that stormwater is responsible for adversely affecting water quality management (Tong and Chen, 2002) because of its role in transporting pollutants and that non point sources (NPS) of pollution are a threat to the quality of the receiving waters (Schulz *et al.*, 2001).

Total phosphorus (TP) and total suspended solids (TSS) are two pollutants commonly found in NPS discharge globally (Tsihrintzis and Hamid, 1997). Excessive loading of TP is a factor that contributes to eutrophication in rivers which is manifested by growths of plankton (Jones and Lee, 1982). Although eutrophication is a natural process in the aging of water bodies, it is most often induced by human activities (Walmsley, 2000). It leads to the loss of species diversity and habitats in river systems.

Suspended solid pollution has both a physical and a chemical influence on the receiving water bodies. TSS causes a physical change in the state of a river through increased turbidity/cloudiness of the aquatic system. According to Goonetilleke *et al.* (2005) and Settle *et al.* (2007), the chemical impact of sediments is caused by the fact that these suspended particles act as mobile substrates for other pollutants in a water body. The removal of suspended solids from water is important for controlling the loads of other significant chemical pollutants.

If the concentration of pollutants that enter the receiving waters can be limited through improved management techniques and approaches then the negative impacts could be reduced or even prevented. However the accumulation of these pollutants can be a very complex procedure (Limburg *et al.*, 2002) because of the myriad of processes inherent in the generation of pollutant loads washing off from different types of land uses. The diffuse nature of stormwater means that it is influenced by numerous land use activities that accumulate in flows across the landscape. Activities on the land include a mixture of social and ecological processes. Anthropogenic activities add to the pollutants that would have naturally been available from land surfaces. Different combinations of land use activities will also have different impacts on the pollutants in the resultant stormwater. As these anthropogenic activities are numerous and scattered it becomes difficult to monitor sources of stormwater pollution. In addition there are uncertainties associated with complex systems so that the full range of responses and their consequent implications cannot be predicted accurately (Bohensky and Lynam, 2005).

Stormwater monitoring programs use either field-based or automated techniques to collect data on water quality. The problem, and particularly for local authorities struggling with limited human resources and financial capital in developing cities is that field-based monitoring involves the collection of water samples at numerous points along a river. Stormwater monitoring is costly and is often informed by samples that are insufficiently representative of the situation or infrequently collected (Nagendra *et al.*, 2004; Korfmacher, 1998).

1.1. RATIONALE

In 2009 the City of Cape Town (CoCT) introduced a progressive stormwater policy that focused on reducing pollutant loads of TP and TSS arising from new development sites. The policy simultaneously introduced the principle approach of Sustainable Urban Drainage Systems (SUDS). This CoCT initiative became the primary inspiration for this study because of the implications associated with developing innovative and cost effective means of monitoring water quality in urban river systems. The assumption is that models and modelling can improve the efficiency of managing stormwater monitoring practices.

The CoCT has used the Storm Water Management Model (SWMM) for over ten years as a stormwater management tool. SWMM was developed by the US EPA as a hydrological system that can simulate the quantity and quality of urban runoff. This model has been used in CoCT largely as a tool for hydrological analysis and serves as both a single event and a continuous simulation model for rainfall events (Temprano *et al.*, 2007). Detailed information of the modelling capabilities of this system are described in the SWMM v5.0 manual and will not be discussed further in this study, suffice to indicate that the SWMM is a complex model and that the application and operation of the model is often outsourced to private consultants by the CoCT. This has financial implications for the City. The complex nature of the model means that the user must have extensive training in order to be able to operate the model. This study seeks to understand the potential to use an alternative model, one that relies on a simple modelling structure demanding minimal data requirements but which could prove adequate for the purpose of managing the stormwater policy in the CoCT. Thus far, simple models have not been widely used in the City for stormwater monitoring. However, it is argued that simple models could be used to overcome the challenges and constraints of more complex modelling practice.

The Better Assessment Science Integrating Point and Non-point Sources (BASINS) model, which has been selected for this study, was developed in the United States as a basic screening model for stormwater monitoring. This model is introduced in Section 1.3 of this chapter and described in detail in Chapter 3. In this study the model is applied in an urban South African context to simulate stormwater quality.

1.2. AIMS AND OBJECTIVES

The aim of this study is to test the use of a model to simulate pollutant loads in runoff. The pollutants selected for evaluation are total phosphorus (TP) and total suspended solids (TSS) which were identified as target pollutants in the CoCT stormwater policy. The study area is in the Cape Metropolitan Area (CMA) located in the Western Cape Province, South Africa (Figure 1). Pollutant concentrations in runoff will be evaluated from a selected urban catchment in the CMA. A threefold set of objectives will be used to support the aim, namely to:

- Demonstrate the use of the model to simulate and analyse the relationship between water quality (TP and TSS concentrations in runoff) and different land uses in the catchment.
- Assess the validity of the model estimations of pollution loads against pollution values measured using field based techniques, in order to determine the potential of the model as a reliable tool for stormwater monitoring.
- Evaluate the judgement of industry professionals on the potential use of the BASIN PLOAD model for the CoCT.

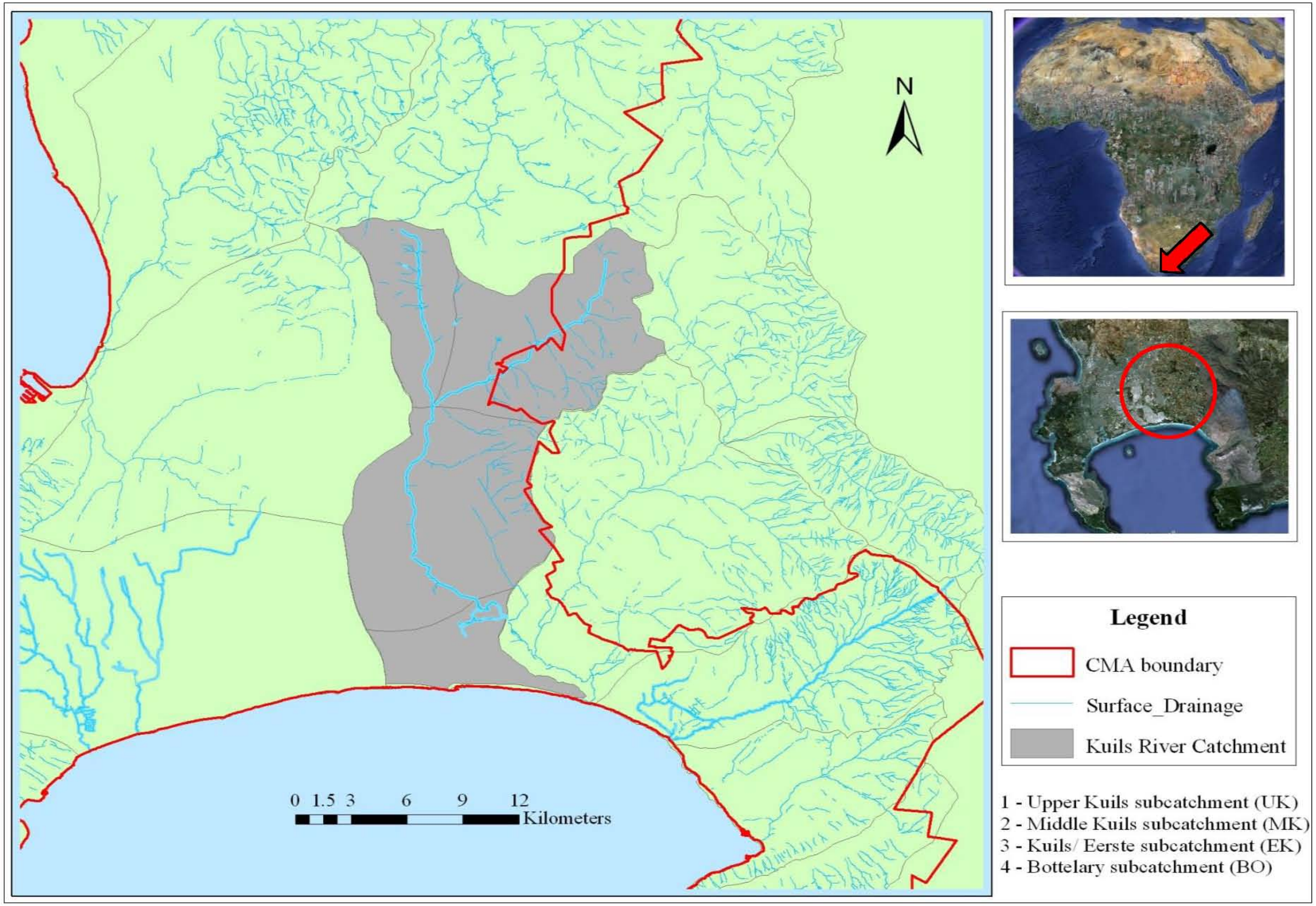

Figure 1 Map location of study site

Figure 1 illustrates the location of the Kuils River catchment. The majority of the catchment area is within the City of Cape Town Municipal jurisdiction however a section of the north-east portion of the catchment falls within the jurisdiction of the Stellenbosch Municipality. The main river, the Kuils River is shown in light blue linear delineations in the catchment area (shaded in grey). The image also illustrates the location of other surface drainage features within the catchment area.

1.3. RESEARCH DESIGN

The selected study area was divided into four sub-catchments. The delineation of each sub-catchment is described in detail in Chapter 3. The selected model was applied to simulate pollutant loads in runoff over annual and monthly time scales. The pollutant load from the various land uses was simulated from the model. The output was then tested using statistical analysis techniques to meet the first and second objectives of the study. Additionally a survey was conducted to elicit the opinions of five stormwater management officials who were asked to consider the potential of the model to contribute to stormwater management within the CoCT. A detailed description of the methodology is presented in Chapter 3.

1.3.1. The modelling process

The selection of an appropriate model for this study was informed by the research question and the main aim of this study in the context of the local authority that is operating in a developing city and country in a data scarce environment. In these circumstances, a simple model was considered an appropriate choice for the study because of the relative high cost associated with generating data requirements of more complex (detailed) models. Although a modelling approach has been used in the CoCT for stormwater monitoring, it was evident that the models used were highly resource intensive and operated at high cost to the City. The Pollutant Load Estimator Model (PLOAD) was selected from a review of the literature as a suitable model that met the criteria and context. BASINS PLOAD is considered to be one of the simplest models which could be used to address the study aim, that is, to consider the potential use of a model to simulate pollutant loads in runoff.

The PLOAD model requires meteorological, land use and event mean concentration (EMC) data to generate a simulation. The model uses this data to link load generation to land uses at a catchment and sub-catchment scale. The design of the model incorporates the following processes as described below and schematically represented in Figure 2:

- Data collection: locate historical data on nutrient loads observed in stormwater (event mean concentration); daily rainfall over a one year period; land use coverage maps; and impervious coverage data. Rainfall data was sourced from the South African Weather Service (SAWS) and land use shapefiles were obtained from the City of Cape Town Roads and Stormwater Department. Data on impervious coverage was obtained from a review of the literature as this data was not available for the selected catchment.
- Model input preparation: data were converted to the correct format. This included using available data to delineate the catchments under review; compiling event mean concentration data tables; and converting units from SI unit standard to non-metric system.
- Parameter evaluation: determining the parameters that influence the rainfall–runoff generation process.
- Calibration: using empirical runoff data to test model parameters. Historical runoff data for 2009 was used to determine an adjustment factor for the runoff volume which is calculated by the model to match the runoff volume observed in the catchment.
- Validation: graphical images and statistical comparisons between estimated and empirical data were used to test the accuracy of the model output.

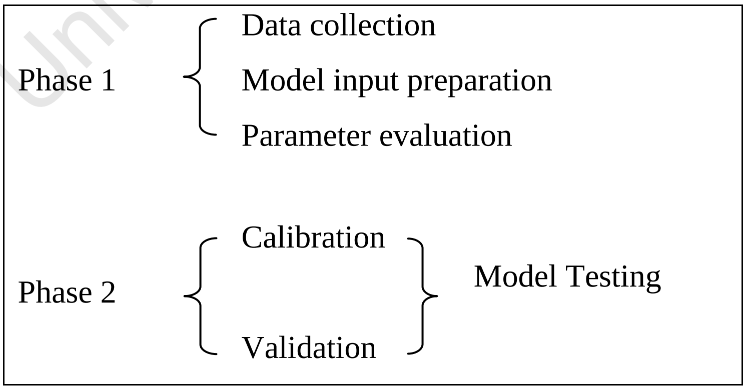

Figure 2 Outline of the modelling stages in BASINS PLOAD (USEPA, 2010).

1.3.2. Testing the potential use of the model

Pollutants loads in runoff have not been monitored in most of the river catchments in the Western Cape. Most pollutant monitoring is conducted as part of short term monitoring programmes and as a result the pollutant load estimates using the PLOAD model could not be compared to measured loads in runoff. The PLOAD model output was statistically analysed against in-stream pollutant loads which were measured and monitored using field based monitoring techniques. These values are referred to as the known in-stream pollutant loads in the text. The analysis technique used was the Spearman rank correlation test to compare known in-stream values and PLOAD estimations of pollutant loads occurring over monthly and annual time periods. This approach was used because of the constraints associated with obtaining reliable data on the runoff water quality in the Kuils River catchment. The data constraints associated with this project are discussed in detail in Chapter 3. Chapter 3 also highlights the approaches taken to overcome the uncertainties and errors in the model estimation as a result of the data constraints. Efforts to address the constraints of the model included calibrating the model; testing the PLOAD model design for flaws in the simulation process; and eliciting professional judgement on the potential application of the model in stormwater monitoring in the CoCT.

The model was calibrated using data from a proxy site located near the study catchment which exhibited similar characteristics to the Kuils River catchment. The calibration process reduced the error associated with the calculation of the runoff during a rainfall event. The model was tested using an automated version of the PLOAD model. The output from the automated modes and the output from the original model were compared to identify any significant difference between the two values. This approach was adapted from a similar approach used in a study conducted by Young (2006).

Finally, the potential to use the model was determined by eliciting the opinion of officials in the local authority so as to determine the potential to operationalise BASINS PLOAD model in the CoCT. The daily experience obtained from working in the field of stormwater management meant that these individuals were best placed to answer questions about the potential applications of the model in Cape Town.

1.5. THESIS STRUCTURE

Chapter 2 discusses the literature on stormwater modelling and includes a review of the complex nature of systems and the use of modelling as a tool for integrated management. The methodology chapter gives a detailed outline of the methods used to achieve the aims of the thesis. It includes a detailed site description, as well as a description of the modelling process, data requirements and modelling algorithms. The calibration and validation techniques used in this project are introduced at the end of the chapter. The fourth chapter is a review of the results and includes an evaluation of the model. This is followed by a discussion which includes an evaluation of the responses given to the survey. The final chapter synthesises the work and focuses attention on whether the objectives of the thesis were met and also offers recommendations for further study.

CHAPTER 2

Literature Review

2.0. INTRODUCTION

This chapter commences with a discussion on the complexities associated with monitoring stormwater and how this challenge has shaped approaches to monitoring diffuse pollution. This is followed by a discussion on the role of models as tools for integrated assessments of complex natural systems. It will also include a discussion on the types of models used in stormwater assessments and the application of models in stormwater management. The chapter concludes with a discussion on the limitations of the model and what still needs to be developed in water quality monitoring to improve the feasibility of applying models in stormwater management.

2.1. COMPLEXITY OF STORMWATER MONITORING

Stormwater pollution occurs as a result of two processes - ‘build-up’ and ‘wash-off’ (Chiew *et al.* 1997). Build-up is the process whereby pollutants accumulate on the landscape during dry weather conditions. The number of dry days before a storm determines the degree of accumulation of pollutants on surfaces (Tsihrintzis and Hamid, 1997). However this accumulation is not straightforward and several factors influence the accumulation and compactness of pollutants on a surface including anthropogenic activity on different types of land use. Changes in land use ultimately reflect changes in water resources “because water quality is so clearly impacted by people’s use of resources and because human well-being is so clearly linked to the availability of clean water” (Wear *et al*., 1998: 619).

Different land uses influence the types of pollutants and different quantities of pollutants that accumulate on the landscape. The main sources of pollution in South African rivers come from industrial effluents, domestic and commercial sewage, acid mine drainage, agricultural runoff, and litter (DEAT, 1999). Similarly pollution sources in the City of Cape Town relate to the dominant economic activities in the region namely industry, real estate, construction, tourism and agriculture (RHP, 2005).

In urban catchments land use is not the only determinant of pollution. Urban factors such as increased imperviousness and the rate of runoff play a role in the pollutant accumulation and transportation. Urban development results in a hardening of surfaces and an increase in the percentage and extent of impervious areas (Simpson and Stone, 1988). In urban areas, surface hardening results in higher runoff rates and a change in the peak flow rate. High peak flows of runoff influence the wash-off of nutrients and sediments from surfaces as there is a greater volume and intensity of water washing over the landscape. Chiew *et al.* (1997) add that the rate of redistribution or removal of pollutants is also influenced by factors such as traffic or construction activities.

Numerous studies have been conducted on the relationship between land use and water quality such as Tsihrintzis and Hamid (1997), Wang (2001), Grobicki (2001) and Mtetwa *et al.* (2003). For instance, Wang (2001) measured the spatial relationship between land use and water quality in a watershed in Ohio, USA. The study found that there was significantly lower water quality downstream of urban land areas compared to non-urban areas. In two South African studies, one by Grobicki (2001) and another by Mtetwa *et al.* (2003), it was shown that surrounding land uses had a direct effect on the water quality in rivers. Mtetwa *et al.* (2003) conducted a study in a semi-arid rural catchment where the main land use was agricultural. Grobicki's (2001) study was based in Cape Town in an urban catchment that assessed how informal settlements impacted on water quality. These studies reinforce earlier discussions on the anthropogenic influence on land and consequent impact on the quality of the receiving waters. Tsihrintzis and Hamid (1997) state that land use is one of the most important factors for determining the NPS pollutant load in runoff. Davies and Day (1998) and RHP (2005) add that the state of a river often mirrors the landscape in the catchment.

In essence the complex nature of natural systems found in rivers and catchments is indicative of the need for a holistic approach to monitoring. The challenge is to find monitoring tools that can be used to evaluate processes that occur on land and in water as an inter-related system (Jakeman and Letcher, 2003). The literature suggests that the answer may lie in models which may prove to be tools for stormwater management (Chiew *et al.*, 1997; Obropta and Kardos, 2007). However the reliability associated with a models output is linked to the quality of the data used.

2.2. MODELS AS TOOLS FOR STORMWATER MONITORING

Conventional monitoring approaches for collecting water quality data involve assessing chemical concentrations in stormwater using field-based sampling techniques. This conventional approach is often inappropriate in an African context (Ongley, 1999). Ongley identifies neglect, chronic underfunding and a lack of focus as the reasons for inadequate national water quality monitoring programmes in Africa. In general, models are developed to address research questions where field data is lacking. In this section the strengths and weaknesses of stormwater monitoring programmes will be discussed and compared to the role that models could play in integrated stormwater management.

2.2.1. Stormwater monitoring programs

Some researchers argue that the main goal of stormwater monitoring programmes should be to identify high risk discharges, determine total maximum daily loads (TMDL) and reduce stormwater pollution (Thomas, 1993; Lee *et al.,* 2007). Thomas (1993) conducted a stormwater monitoring programme in Atlanta and the study informed decision making about the prioritisation of pollutants. The study also identified different types of land uses from which the pollutants were generated. As a result various development strategies to control pollutants could be devised.

Stormwater samples are obtained using field-based methods of grab sampling and/or flow weighted composite methods. Grab samples often do not provide enough precise information for decision making (Lee *et al.*, 2007). In addition field-based methods are time consuming and are hugely demanding on human and financial resources (Freni *et al.*, 2008). In an evaluation of the effectiveness of the stormwater monitoring programmes in the United States, it was concluded that grab samples had more variability than samples that were measured using a flow weighted approach (Lee *et al.*, 2007). Grab sampling has to be well timed to firstly reduce the bias caused by the first flush effect and secondly to ensure coordinated monitoring across study sites and therefore the reliability of comparisons. Flow weighted composite sampling is based on long term monitoring over a range of flows in order to obtain an EMC value that can be associated with each land use type in a study area. Therefore, according to Lee *et al.*, (2007) a flow weighted composite sampling is universally recognised as a better approach for stormwater monitoring.

South Africa does not have a national storm event monitoring program although several regional and catchment studies have been conducted. Any data from storm event monitoring in specific catchments or development sites are also not easily accessible in the public domain for the City of Cape Town. Consequently there is scant evidence about the causes of high discharge and acceptable pollutant loads in runoff from regional stormwater monitoring programmes. A review of the literature on urban runoff indicates that many small monitoring studies share a common focus in their efforts to determine the sources/causes of pollution. According to Heath *et al.* (2009) South Africa has devoted attention to quantifying NPS pollution and identifying ways to control pollution at source. Heath *et al.* (2009) support the use of models to determine sources of NPS pollution. They refer to a project funded by the Water Resource Commission (WRC) in which modelling and experimentation techniques were used to assess NPS pollution from mining, industrial and power generation sectors. This was a ground breaking project that resulted in an improved understanding of how source control of NPS pollution could be used to manage pollution impacts in South Africa. The example given by Heath *et al*. (2009) demonstrates that modelling can be used to provide the information required for managing water quality. The implementation of models as a tool worldwide recognises that models present a rapid and less resource intensive way in which to monitor the state of water resources in situations when field-based approaches cannot be applied.

2.2.2. Stormwater modelling

An evaluation by the United States Office of Technology Assessment (US OTA), described in Bobba *et al.* (1999), describes different approaches to the analysis of water quality. It was found that models were the best alternative to field-based techniques for analysing complex resource problems. Based on these research results Bobba *et al.* (1999) suggest that models can be beneficial for decision making about water resources. Models can be described as simplified representations of a complex reality (Allen and Lu, 2003). They are tools that improve the understanding of relationships between land use and water quality. They integrate conceptual theorems about this relationship and in some cases they incorporate Geographical Information Systems (GIS) to display and analyse data (Vivoni and Richards, 2005). According to Allen and Lu (2003) it is the complex nature of urban land use systems that has made an integrated approach appropriate and necessary for model design.

The traditional command and control style approach to the management of natural resources has been replaced by an integrated approach. This paradigm shift has been supported by advances in GIS technology. GIS has made it practical to consider spatial detail in the assessment of resources (Theron *et al.*, 2006; Wegener, 1995). Complex ecosystem process can be simulated through the use of GIS and models. Pullar and Springer (2000: 452) state that models that are combined with GIS "provide a tool to run a simulation and to interpret the results in a spatial context". Meyer *et al.* (1993: 207) add that the "joint application of GIS with physically based models allows for the development of geographic or spatial decision support systems." GIS based models enable decision making processes to work with the spatial implications of managing natural resources (Refsgaard and Knudsen, 1996).

2.3. TYPES OF MODELS

According to Bobba *et al.* (1999), the development of models is guided by the need to develop models that either improves the understanding of system dynamics or that can be utilised to control the response of a system. Depending on whether the focus is on source control or system understanding, the nature of the data required by the model will differ. Bobba *et al.* (1999) emphasise that system dynamic models are more complex than models used for controlling system response. As such, the former type of model requires more extensive data sets.

According to Constanza *et al.* (1993: 547) three criteria inform model selection:

- Realism -ability to simulate system behaviour in a quantitatively realistic way
- Precision -ability to simulate system behaviour in a quantitatively precise way
- Generality - representing a broad range of systems' behaviour within the same model.

Constanza *et al.* (1993), state that these three criteria cannot be simultaneously met through the application of one model and modellers must choose which criteria they want to emphasize at the cost of one or both of the other criteria. It is for this reason that Constanza *et al.* (1993) describe models as abstract representations of a complex reality analogous to maps and whose usefulness is best determined by their ability to solve problems. This is supported by Bobba *et al.* (1999: 26) who describe models as an "abstraction or simplification of the prototype system."

There are a diversity of model classifications discussed in the literature and as such it is not feasible to discuss them all. The essential difference in the modelling approaches is the amount of data required, the information that can be obtained from the model, the sophistication of the analysis performed and the simulation period (Zoppou, 2001). Hydrologic models, hydraulic models and water quality models are three commonly used classifications for categorising stormwater management models.

2.3.1. Hydrologic models

Hydrologic models simulate rainfall-runoff processes in order to generate information on runoff characteristics. Hydrologic models can be differentiated into three groups based on how processes and space are represented in the model. These areas of focus include the nature of the input and output data, the temporal trends being evaluated and the spatial trends being evaluated. These model types are discussed briefly below:

- **Deterministic and stochastic models** are differentiated from other hydrologic models by the nature of the input data used and the resulting output. “In a deterministic model all the variables are known with certainty therefore the model will always produce identical results for the same input parameters” (Zoppou, 1999: 4) and they attempt to describe processes using physical laws or principles. According to Zoppou (1999) a stochastic model will always produce a different model response because random values from a distribution have been applied as inputs. These models assume that processes or variables are governed by laws of chance, or that one can use probabilistic laws or principles to explain them.
- **Continuous and single event models:** Models used to consider individual rainfall events or consider periods within a rainfall event are known as single event time step models. Single event models according to Zoppou (2001: 199) are “short term models used for classifying a few or individual storm events.” Alternatively, continuous event mean models simulate a catchments overall water balance over long time periods.
- **Lumped and distributed models** are defined by the way in which the model treats spatial variability (Zoppou, 1999: 5). Lumped models use spatially averaged parameters. They also conduct computations over the whole catchment region. Distributed models on the other hand are based on the division of the landscape into smaller more functional land units. Table 1 draws on information gathered from

Pullar and Springer (2000)[a] and Carpenter and Georgakakos (2006)[b] and illustrates the differences between lumped and distributed models.

Table 1 Comparison of Lumped and Distributed model approaches

Lumped models	**Distributed models**
• Do not make predictions for specific sites[a] i.e. low resolution[b] • Model becomes less accurate and informative as the variation within the catchment increases[a]	• Good at detecting local effects and anomalies i.e. high resolution[b] • Complex operation processes, requiring large volumes of data to describe variation in the landscape[a] • Incorporate a variety of spatially varying land characteristics[b]

2.3.2. Hydraulic models

Hydraulic models use a known flow volume to provide information about flow characteristics such as direction, pressure and velocity. These types of models have different characteristics based on the way in which they:

- simulate flow direction i.e. one dimensional or multi dimensional
- simulate velocity i.e. unchanging velocity or velocity changing with time
- calculate pressure of flow i.e. uniform or non uniform flow pressure.

2.3.3. Water quality models

Water quality models simulate the various processes and interactions of stormwater pollution such as build up, wash-off and impact processes and therefore these models share the same characteristics of hydrologic and hydraulic models. Korfmacher (1998) describes water quality models as tools used to determine the nature and amount of effluent discharged by a point source of pollution. These models describe variations in water quality of which pollution is one aspect. This may require gross assumptions to be made in order to model pollutant accumulations and the eventual impacts.

2.3.4. Model complexity

There are numerous classifications which have been applied to describe models based on model complexity. For this study, the definition of model complexity' was best represented as the "extent to which a model attempts to represent the many and diverse processes that affect the response of runoff to rainfall" (Hughes, 2004: 638).At the broadest level models can be categorised as either simple or complex.

The terms 'simple' and 'complex' differ from the everyday understanding of these terms. Simple models are based on mathematical algorithms that attempt to be representative of the broad hydrological processes observed in reality, such as the generation of runoff from impervious surfaces (Zoppou, 1999). They combine basic algorithms that mathematically describe the different processes occurring in the ecosystem in order to make pollutant load estimates.

Complex models have numerous parameters. They attempt to explicitly represent the individual processes of interception, infiltration, soil water drainage, evapo-transpiration and ground water movement (Hughes, 2004: 639). This generally requires more complex mathematical equations for the estimation of loads. However the nature of complex models implies a need for more data requirements which leads to a feedback loop where more complex models require more data (Sivakumar, 2008).

Determining whether to apply a simple or complex model should be informed by the technical needs of the problem being assessed, and secondly, the inherent complexity of the problem being studied. These criteria are elaborated by the CRC (2005) in a report that outlines the considerations used in selecting a model as being dependent on:

- data requirements;
- expertise requirements; and
- resource requirements of the study.

The necessary conditions for the selection of a simple model versus a complex model for assessments are outlined in Table 2. Simple models are usually applied to a single area but they can be made more complex by disaggregating the total area to be modelled into smaller sub-areas (Hughes, 2004). Schueler (1987) and Chandler (1994) suggest that these areas should be no greater than 260 hectares (approximately 640 acres). The temporal modelling capabilities of simple models are often limited to monthly and annual load estimates which can be problematic when a shorter duration is required (USEPA, 1992). This makes the output from simple models very broad and generic.

Most models being operated in South Africa are of the complex type (Hughes, 2004) and there are few examples where simple models have been applied to assess land use-water quality relationships. On the other hand complex models can be used for the simulation of limited time intervals (Hughes, 2004). Complex models can be applied to large and more multifaceted catchments because they involve detailed modelling processes which are better representative of the processes they are simulating (USEPA, 1992). As such, complex models require very comprehensive data sets that inform the different ecosystem processes they mimic mathematically. In situations where reliable data is a limiting factor, a simple model would be more appropriate than a complex one.

The United States Office of Technology Assessment (US OTA) conducted a comparison of models of different complexity which was evaluated by Bobba *et al.* (1999). In the US OTA study it was found that less data intensive (simple) models performed as well as or even better than more complex models. These findings were supported by Chandler (1994) who compared a complex distributed model (SWMM) to a simple model and found that the simple model performed as well (i.e. within the same level of acceptability or reliability) as the more complex model. Bobba *et al.* (1999) suggest that there is no reason to apply complex models when simple models can be used to adequately to address the research question (Obropta and Kardos, 2007). Table 2 is adapted from Chandler (1996). It summarises the conditions under which complex and simple models can be applied based on work by Schueler, (1987) and Chandler (1994).

Table 2 Conditions for the appropriate application of simple and complex models to estimate pollutant loads.

Model	When to apply	When not to apply
Simple	• Small urban watersheds (< 260 ha) • Only stormwater runoff and pollutant load estimates are desired • Need for quick and reasonable load estimates • Only percent imperviousness and runoff concentrations are available • Only planning level estimates are needed	• Baseflow runoff pollutant loads are required • Large watersheds (> 260 ha) • Non urban land uses (e.g. construction sites, industrial areas, rural development (agricultural uses), as reliable “C “ values are unavailable • Ambiguity about watershed’s percent imperviousness
Complex	• Large and complex watersheds • Desire for: - A time history of runoff flow rate and pollutant concentrations; - Definition of channel segments, bridges, culverts etc., subject to erosion; - Determination of maximum water elevations (for identifying floodplains); and - Hourly or daily load inputs to lake, river, or estuary water quality model	• Limited by time • Limited by funds • High accuracy needed for dissolved pollutant parameters • Uncertain whether complex model can provide more accurate information than a simple model

2.4. APPLICATION OF MODELS

A number of broad issues in stormwater management are outlined by Lee *et al.* (2007); that of the determination of sources of high discharge, determination of daily acceptable limits and an evaluation of whether management strategies contribute to the reduction of pollutant loads. Modelling techniques can be used to address these issues as outlined by Aryal *et al.* (2009: 72) in a comment that "the basic components of an urban stormwater model are rainfall runoff modelling, pollutant build-up and decay and transport modelling."

High discharge of pollutants can result in impacts on the receiving water body. Deviations from this desired state are not always noticeable immediately upon impact of pollution instead it may take a series of impacts or long duration of time before a concentration is reached that is outside the normal range for that system. Shock loadings of pollutants to a river system result in dramatic changes to the systems which can become permanent if they occur multiple times in a year (Tsihrintzis and Hamid, 1997). Models can be used as predictive tools for proactive management of pollutants by highlighting how land use change will influence the quality of stormwater runoff.

The South African Water Quality Guidelines (DWA, 1996) define what constitutes "acceptable" or "unacceptable" water quality. These guidelines are not static and vary for the different water uses such as domestic or agricultural uses. For stormwater guidelines the potential users of water should be identified and a set of objectives defined for the reduction of pollution in stormwater to meet the standard necessary for the stormwater to support its users. According to Schoeman *et al.* (n.d) a move by South Africa to produce NPS discharge quality guidelines would not be without precedent. Once stormwater guidelines have been defined management strategies can be developed that ensure that these standards are met.

The final goal in stormwater monitoring is to evaluate the management strategies used to reduce pollutant loads. These management strategies are based on the principles of Water Sensitive Urban Design (WSUD). WSUD relates to the interaction between urban built form and the integrated management of the urban water cycle (Wong, 2007). Wong discusses the management of the urban water cycle and includes objectives for water conservation, pollution control of waste water, and stormwater and mitigation of the effect of increased flow as a result of urbanization of catchments. Sustainable Urban Drainage Systems (SUDS) is a branch of WSUD concerned with the implementation of stormwater management measures that attempt to maintain natural flow processes (D'Arcy and Frost, 2001). Examples of SUDS techniques include man-made wetlands and retention ponds. These sustainable technologies provide mechanisms to help reduce pollutant loads in rivers as well as to minimise the discharge from polluting material (Rauch *et al.,* 2005). One of the main priorities in stormwater management is to evaluate whether techniques are working to reduce loads and to what level of effectiveness they work (Lee *et al.,* 2007).

2.5. MODELLING – WHAT STILL NEEDS TO BE OVERCOME

The application of models is often constrained by the availability of data for the modelling process. As such " the potential role of modelling itself has been questioned in recent times, with decision makers viewing models as potential 'black boxes' which cannot be fully trusted" (Giupponi and Sgobbi, 2008). Data availability is a common challenge for developing and developed countries because water quality data is either badly recorded and stored or not monitored at all (Ongley, 1999). The availability of good data is instrumental in the modelling process and especially so when the precision of the model output is paramount. The more detailed the modelling process the greater the associated data requirements. Not only are data requirements dependent on the nature of the model but they are dependent on the nature of the question being posed.

Korfmacher (1998) states that in many cases the model selected for analysis is the most complex model. There is a perception that complex models are more credible than simple models even when applied to general screening assessments. As a result simple models are perceived as having a low level of credibility and thus the validity of the results from these models is questionable. Several studies have been conducted whose outcome favoured the use of simple models over complex ones, depending on the nature of the research question (Chandler, 1994; Bobba *et al.,* 1999). Due to the fact that simple models do not necessarily factor in calibration these tools are also viewed more critically by decision makers.

Although models address one problem of information generation, there still exists a key concern around the credibility of the output information. According to Chandler (1994) the accuracy of data entered into models influences model validity. The credibility of a model is questioned when the data utilised in modelling is not known to be reliable. Therefore some testing of the model results against known data is required. Model testing comprises of two steps: calibration and validation. These stages in modelling rely on the user having collected or obtained field monitored data on the parameters under evaluation. The calibration process requires data sets for the same space and time as what is being modelled, whereas for validation data sets need to be from a different time period than those used for calibration (Korfmacher, 1998). The US EPA (2001) outlines that the usefulness of any model is dependent on the testing process applied to that model.

Where modelling is used in state agencies, modellers tend to stick to the models that they are familiar with rather than conducting research on all available models (Korfmacher, 1998).The role of both simple and complex models in stormwater management finds support in the literature. The main challenge identified in the application of models is to ensure that there is credible data available for modelling. Some view models as essential tools in stormwater management because of their predictive capabilities whilst for others, models and especially simple models are still not accepted tools for stormwater management.

CHAPTER 3

Methodology

3.1. STUDY DEFINITION

The objectives of the study outlined in chapter 1 are to:

- Demonstrate the use of the BASINS model to simulate and analyse the relationship between water quality (TP and TSS concentrations in runoff) and different land uses in the catchment.
- Assess the validity of the models estimations of pollution against pollution values measured using field based techniques in order to determine the potential of the model as a reliable tool for stormwater monitoring.
- Evaluate the judgement of industry professionals on the potential use of the BASINS PLOAD model in the CoCT.

The chapter describes the study area and the steps taken in the selection of a model from the modules available within the BASINS system; the BASINS system design; and extensions within this system. The rationale for the selection of the PLOAD extension will be discussed in a later section which outlines the model design, theory, algorithms and data requirements. The final section of the chapter deals with the application of the model, including a discussion on the study site chosen, the modelling process, and the validation and assessment processes applied to the estimates made in PLOAD.

3.2. STUDY AREA SELECTION

This study was conducted in the Cape Metropolitan Area (CMA) located in the Western Cape Province of South Africa. The study catchment was chosen which would include representation of each of the many different land uses in the CMA. The second criterion used in site selection was the availability of data for modelling.

3.2.1. The Kuils River Catchment

The headwaters of the Kuils River arise in foothills of the Tygerberg Hills from where the river flows through a myriad of land uses and eventually enters the sea at Macassar on the False Bay coastline. Categorised as a second order river, it is the largest river draining this

Figure 3 (a-d) Sections of the Kuils River a) Middle reaches of the Kuils River with urban open spaces in the foreground and high density and informal housing in the background; b and c) Near the confluence of the Eerste-Kuils River, where the river forms a series of water pockets and where small streams are polluted from the surrounding land use which includes runoff from informal settlements and urban open land; d) the effects of eutrophication are evident in the accumulation of green algal matter on rocks and the odd colouring in the soils on the banks of the river (see b).

catchment. Historically this was a seasonal river that drained a catchment of approximately 240 km^2 and the river once meandered through a series of sandy dunes draining into pools known as “kuils”. Subsequent to extensive urban development in the area, the seasonal and perennial wetlands of the area were altered. This is demonstrated in Figure 3(a) where a section of the Kuils River can be seen in the foreground and in the distance the informal settlement area of Khayelitsha can be seen. Such examples of development have resulted in unstable wetland pockets forming in the middle reaches of the catchment in the area now known as the Cape Flats as illustrated in Figure 3(c).

Land use in the Kuils River catchment is diverse. Topo-cadastrial data, obtained from the Department of Land Affairs, identified fourteen different land use types in the Kuils River catchment. The main land uses are residential, rural and agricultural land use, urban open space and undeveloped land. The diversity of land uses in this catchment made it a favourable choice for this study because it allowed for an analysis of the pollutant loads from different land uses. Figures 3(b-d) illustrate the impacts of pollution on this river system. These images demonstrate impacts of pollution such as discolouration of soil and eutrophication. It is noted that pollution may not be the sole cause for the impacts described here, however other causes can only be determined through more detailed study.

There are four waste water treatment works (WWTW’s) located along the Kuils River, namely Bellville, Scottsdene, Macassar and Zandvliet. Many of these treatment works are operated above the design capacity which has resulted in pollution of the river system as confirmed in studies by Parsons and Taljard (2000). Data from these treatment centres showed that in 2009 the Bellville and Scottsdene WWTWs were respectively releasing 33mg/l and 60mg/l TP. This exceeded the discharge limit of suspended solids set at 18mg/l in the DWA water quality guidelines. The average TP output observed from the four WWTW sites was 4.3mg/l. Although no limit was set for ortho-phosphate for these specific centres the national discharge limit for TP entering water bodies was set at 1mg/l in the Government Gazette (1984).

The pollutant loads discharged from WWTWs in the catchment contribute to the poor water quality conditions of the in-stream water quality in the Kuils River. More attention has been devoted to assessing the impact of point source pollution over assessing NPS pollution. This is shown by the vast literature that is focused on the former source of pollution. The availability of data on pollutant discharge from these treatment centres was useful for rationalising why pollutants in stormwater runoff should be monitored. The association of trends observed in in-stream pollutant loads with discharge trends from WWTWs is discussed in greater detail in Chapter 4.

Figure 4 Sites along the river in the upper Kuils River sub-catchment

Figure 5 The middle reaches of the Kuils River catchment - a large section of this part of the river has been canalised

Figure 6 Eerste Kuils River confluence during low flow months.

Figures 4-6 illustrate different sections of the Kuils River. The upper section of the river lies within a low density residential area. At the location where the image shown in Figure 4 was captured there is an open area of low grassland that extends approximately 100m on either side of the river. Further downstream of the river, some canalisation has occurred as shown in Figure 5. In the middle reaches of the river there is minimal water flow as is characteristic of the early summer period during when the image was taken. Figure 6 illustrates the confluence of the Eerste and Kuils Rivers. In this image the Kuils River can be seen as the small stream of water in the foreground that joins a larger more abundant water source that is the Eerste River.

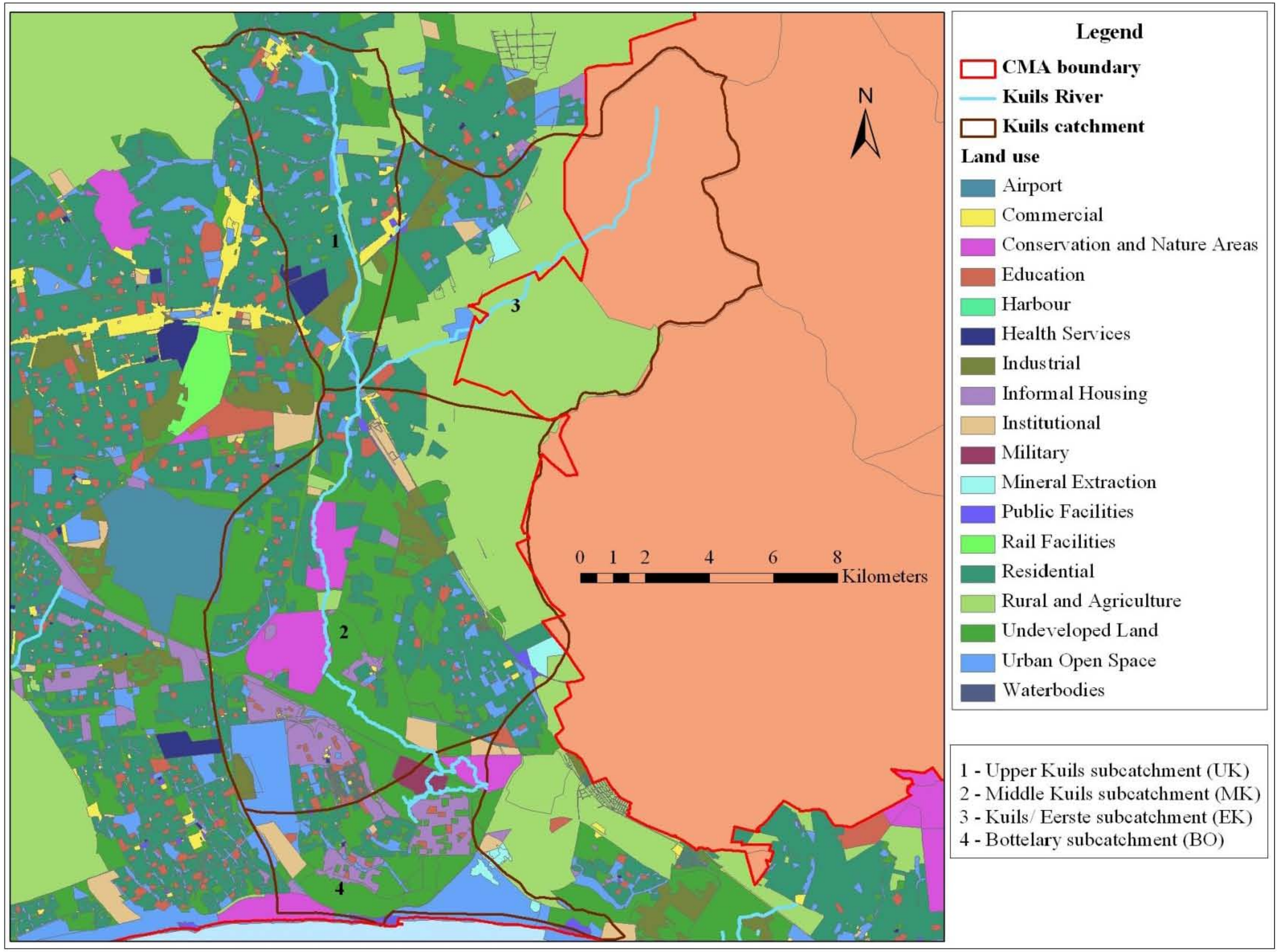

Figure 7 Kuils River catchment land use with sub-catchment boundaries

3.2.1.1. Stormwater and runoff pollution in the Kuils River catchment

Informal settlements are common features in large metropolitan cities in South Africa. According to DWA (2001), pollution from informal settlements represents the greatest threat to water quality conditions of surface waters. This is supported by the findings from stormwater monitoring projects conducted in informal settlements located along the Kuils River such as in Kalkfontein (Bila and Pithey, 2004). Informal settlements comprise approximately 4% of the land use area in the Kuils River catchment. Most of the informal land use is found in the lower reaches of the catchment (sub-catchments MK and EK in Figure 7). Informal land use has been reported to be contributing a large proportion of the pollutant loads transported in runoff (Wimberley and Coleman, 1993). The Kuils River catchment includes areas with and without informal land use.

3.2.2. Catchment delineation

The study catchment was delineated manually according to the monitoring zones identified in a report on the state of rivers in the greater Cape Town region (RHP, 2005). Contour lines (50m) and a 10m DEMs were used to guide the delineation process using the BASINS system tools. The BASINS system gives the user a choice between manual delineation and an automatic delineation. Manual delineation was applied in this study because the gradient was relatively uniform but also because it was impossible to determine sub-catchment boundaries at the resolution of the available DEMs.

Manual delineation involved using contour lines and knowledge of the systems in the study area to determine the most suitable sub-catchment boundaries. The catchment was divided into four regions: Upper Kuils (UK); Bottelary (BO); Middle Kuils (MK); and the Eerste-Kuils (EK) at the lower end of the river where the Kuils and Eerste Rivers meet. These sub-catchments are illustrated in Figure 7.

3.3. BASINS SYSTEM DESCRIPTION

“BASINS” is an acronym for Better Assessment Science Integrating Point and Non-Point Sources. This framework houses several modules that range in complexity and applicability in one single platform so as to achieve rapid assessments. The BASINS system has not been widely used in South Africa although there were some attempts to learn and implement the system during the U.S.–South Africa bi-national training programme in 2001. The participants in this initial study visit have since left the country or the Department of Water Affairs. As such the BASINS system was never integrated into the South African model tool kit.

The BASINS system is available from the United States Environmental Protection Agency (USEPA) website. Unlike earlier versions, the BASINS v4.0 system uses an open source GIS system thereby providing a complete modelling system that is freely accessible. The system contains models that have been widely used and accepted in modelling literature. These models include PLOAD, SWMM, HSPF, SWAT and AQUATOX, and are referred to as extensions throughout this review as they form part of the BASINS system and are not being applied in their 'stand alone' contexts. The following descriptions are based on the EPA description of these modules in the BASINS 4.0 user manual:

> **PLOAD** is a NPS pollution module in the BASINS framework that is used to calculate pollutant loads for watersheds by estimating NPS pollution on an annual average basis.
> **SWMM** is a dynamic rainfall-runoff simulation model used for single event or long term (continuous) simulation of runoff quantity and quality from primarily urban areas.
> **HSPF** simulates the hydrologic and associated water quality processes on pervious and impervious land surfaces and in streams and well-mixed impoundments. This is the main water quality modelling system in BASINS. This model can be used to estimate loadings from both point and non point sources.
> **SWAT** is a physically based watershed scale model designed to predict the impacts of land use on water quality by modelling sediment and chemical yields in large complex watersheds over long periods of time. AGWA is a GIS based system capable of conducting all phases of watershed modelling for the SWAT model.
> **AQUATOX** is a simulation model for the estimation of the assimilative capabilities of a river system by modelling the fate of pollutants such as nutrients and chemicals, and also modelling the effects these pollutants might have on aquatic fauna and flora.

3.3.1 BASINS system credibility

In a study by Tong *et al.* (2002) the authors found the BASINS system to be a useful and reliable tool for characterising water quality conditions in diverse watersheds and at different scales. The authors came to this conclusion after using BASINS to conduct a study on the effect of land use on water quality in the Little Miami River Basin in Ohio, USA. Whittemore *et al.* (2000) concur with these findings, based on their review of the second version of this system and recognised that BASINS is an excellent tool for comprehensive assessments and modelling. Endreny (2002) who conducted a review of BASINS v.3 noted that this system has a user friendly interface and concluded that it provides a useful tool for hydrologists.

Initial reservations at the start of this study were that this system was created for studies on catchments in developed countries and during analysis the software could make general assumptions about the landscape or data that could ultimately bias the results. However, as found in Endreny's (2002) review of BASINS, this system allows for user input data outside of the data provided by the EPA thereby making it applicable to international studies. The author does note that external data sources outside those provided by the EPA may not easily integrate into the BASINS system.

The extensions found within the BASINS framework have been developed by the EPA. Manuals, case studies and technical notes are freely available for these extensions from the USEPA website. Additionally training on the use of the BASINS system is provided through live classes and downloadable exercises to assist system users.

3.4. MODEL SELECTION

The extension chosen to address the study aim was selected from those available in the BASINS system because the system offered models with a wide range of complexity. The BASINS extensions were reviewed to determine the simplest model that would address the immediate study objectives. The BASINS extensions were assessed using the following criteria: relevance; credibility; usability; and utility.

The PLOAD model is a simple model suitable for the assessments conducted in urban contexts. The model determines gross estimates of pollutant loads in runoff at the catchment scale and can be used to estimate loads of both biological and chemical pollutants. Therefore this BASINS system could be a suitable tool to address the first objective of this study - to estimate TP and TSS loads in runoff. The PLOAD extension supports the use of load estimations based on the rainfall-runoff characteristics of the landscape. In the PLOAD extension, runoff generation and land use coverage are key determinants of the model estimates. This extension can also be used to determine the impacts of point sources and bank erosion as well as the estimated reduction as a result of the implementation of best management practices (BMPs). Given the limited data availability in the selected study site, this simple model was more suitable than the more complex model options which would have extensive data requirements.

PLOAD has been widely reviewed by several authors (Reginato and Piechota, 2004; Syed and Jodoin, 2006). These studies recognise the credibility of PLOAD in load estimation studies. The PLOAD model is based on two widely known algorithms: Schueler's (1987) simple method; and the export coefficient method. Both of these algorithms are well documented in the literature and are used to form the basis of some complex models such as SWMM.

The integration of the PLOAD model into the BASINS system improves the utility of the application. BASINS is based on non-proprietary software so that this model can be used by small research groups or individuals at relatively no cost. This system has an online user group that allows quick access to modellers and other researchers using the BASINS system. This is a further reason for choosing the BASINS PLOAD extension.

3.5. PLOAD MODEL DESIGN

PLOAD is a simplified GIS based model that estimates user defined NPS pollution for specified pollutants on an annual average basis. According to the BASINS user manual (Edwards and Miller, 2001) this model was designed to be a screening tool that can be applied to National Pollutant Discharge Elimination System (NPDES), stormwater, watershed management and reservoir protection projects.

The modelling process involves three processing steps: (1) identifying watershed and land use data; (2) defining the pollution loading method; and (3) calculating pollutant loads. These three steps will be discussed with reference to how they were applied to the Kuils River catchment area and are illustrated in Figure 8.

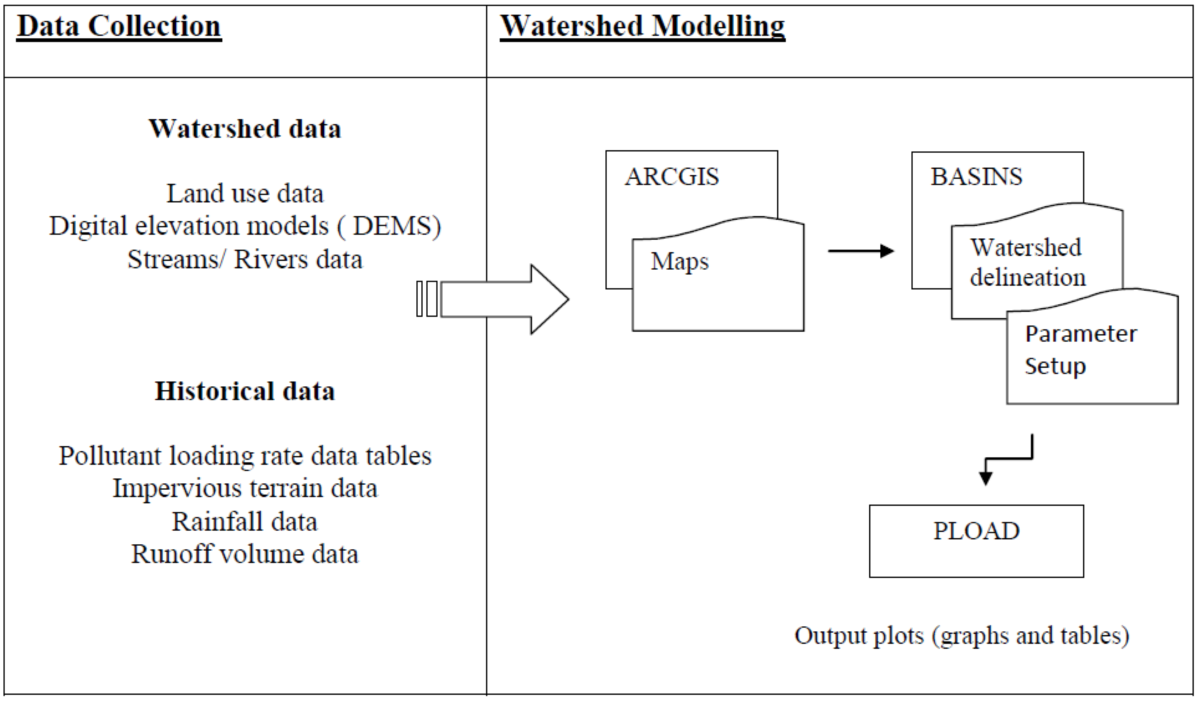

Figure 8 Data collection and water quality modelling processes using BASINS and PLOAD

3.5.1. Data identification

Data requirements differ from model to model. The 'simple method' of pollutant load calculation requires data on land use, rainfall, Event Mean Concentration (EMC) values and impervious coverage.

1. ***Data required for both calculation methods***

The 2001 catchment boundary shapefile for the CoCT Municipality boundary was obtained from the Chief Directorate: National Geospatial Information Department of Surveys and Mapping, Department of Rural Development and Land Reform in Cape Town. The shapefile contained quarternary level catchments which were later delineated into sub-catchments for the purposes of this thesis as described in section 3.2.2 of this chapter.

The general land use shapefile for the CMA was collected for the study sites from the CoCT Municipality. The catchments of interest and the land use within these catchments were delineated in BASINS and saved as separate shapefiles. This delineation enabled the model to be replicated to improve the validity of the results and for comparisons of the pollutant loads entering differing regions of the river as runoff.

2. *Data required for "Simple" Calculation method*

The simple method requires EMC data for each land use in the study area. EMCs are pollutant rates for urban land use types (Edwards and Miller, 2001). Butcher (2003) elaborates on this by describing EMCs as the representative value of the net runoff contributions from both pervious and impervious surfaces in a given area during a wash-off event.

According to Burton and Pitt (2001), EMCs should be estimated from at least three sampling events, but at least twenty-five samples of rainfall events are required to estimate the EMC value within an error of 25% or less. This rigorous analysis is not always feasible when concentration values are collected manually because rainfall events can occur at unexpected times. The manual collection procedure is also a highly labour intensive. In the Kuils River catchment, most months in 2009 exhibited between two to three rainfall events, although a much higher frequency of rainfall events was observed in June. Therefore to collect data for this study with a high level of reliability would require several years of observation of EMC values. Due to this limitation EMC data was obtained through a review of the literature.

EMC data for the study catchment was obtained from a report by Thomas *et al.* (2006) in which NPS runoff was estimated in the Kuils River catchment. As the land use shapefile used by Thomas *et al.* (2009) used a different classification scheme from the land use file used in this study, not all the data for the different land use types could be obtained from the EMC list created by Thomas *et al.* (2009). The land uses whose data was inferred are marked with an asterisk symbol in Table 3. The reliability of the EMC data obtained from the Thomas *et al*., (2009) study could only be determined by comparisons with EMC values determined for similar land uses in other studies. EMC values are required for many models. Therefore the development of a database for South Africa is an area of future research that would improve the reliability of modelling practices. The missing EMC values had to be interpreted from international literature. These values were taken from authors such as Edwards and Miller (2001), and Raird *et al.* (1996). The resulting EMC table (Table 3) that was converted to *.dbf* format was used to replace the default "emcgiras" table in the BASINS PLOAD program files. As a result there was some error associated with the EMC values used in this study as the data were not developed specifically for the Kuils River catchment. Furthermore the techniques used to develop those values may not have been consistent across all the studies from which the data was drawn. The degree of error associated with these values could not be quantified.

Table 3 EMC and impervious percentage data

Land use	**EMC**		**Impervious coverage (%)**
	TP (mg/l)	**TSS (mg/l)**	
*Airport	0.1	26	60
Commercial	0.31	112.18	80
Conservation and Nature areas	0.25	196.17	20
Education	0.16	108	60
Health services	0.16	108	50
Industrial	2.13	192.63	80
Informal housing	3.53	321	74
Institutional	0.16	108	60
Military	0.24	70.56	60
*Mineral extraction	0.14	2	40
Public facilities	0.24	70.56	50
Residential	0.29	40.63	51
Rural and Agricultural	3.78	234.5	20
Undeveloped land	0.03	68	20
Urban open space	0.03	68	20

Impervious coverage data are needed in the model to simulate the runoff process. This data were unavailable for the Western Cape region and as such inferences were made from the literature. The land uses, where data was inferred, are marked with an asterisk symbol in Table 3. It was difficult to apply these values with much certainty as impervious cover is influenced by differences in land uses, soils and geology. The studies used to infer these impervious values shown in Table 3 included work by Chormanski *et al.* (2008) who conducted a study in Brussels to determine the impact of different methods of estimating impervious surface on the prediction of peak discharge, and Francey *et al.*(2010) who conducted a study to collect stormwater data for Australian catchments and the PLOAD v.3 users manual (Edwards and Miller, 2001). The percentage impervious cover values used for the purposes of this study are illustrated in Table 3.The impervious data used in this study were known to have weaknesses associated in the application of international values in a local context.

Precipitation data needed for this study were obtained from South African Weather Service (SAWS) data files for the Cape Town International Airport Weather Station (Appendix A). Daily rainfall records were averaged to obtain the monthly rainfall for the Kuils River catchment. This meterological data was used to calculate the ratio of storms producing runoff otherwise known as the ‘runoff factor’. This ratio is defined as the percentage of rainfall that generates runoff. There is a lot of uncertainty associated with the selection of this factor (Reginato and Piechota, 2004). This uncertainty is due to the fact that the runoff coefficient is not a static factor and could change for each individual rainfall event in accordance with factors such as the level of development and soil compactness amongst others. For the purposes of this study, a value of 0.2 was used based on studies by Eady (2009), who conducted a study in the Mgeni River catchment in South Africa, and Scott *et al.*(1996).

3.5.2. Defining pollution loading method

One of two algorithms can be used in the calculation of pollutant loads in PLOAD: the export coefficient method; and the simple method. The export coefficient method is less data intensive (requiring export coefficient data and meteorological data) than the simple method approach (requiring meteorological data, land use data, percentage impervious surface, and event mean concentration data).

The simple method was selected for calculating pollutant loads in this study based on an assessment of the available data and requirements of both PLOAD algorithms. Although the simple method required more data it is suitable for the analysis of urban catchments and can be used to investigate impacts of point sources of pollution and BMP. The export coefficient method is best applied to larger catchments exhibiting agricultural or undeveloped land uses and is less suitable than the two algorithms for assessing the peri-urban context that this study seeks to evaluate.

3.5.3. The simple method

The simple method (Schueler, 1987) requires data on EMC and impervious nature of the land use in the catchment. Estimations of chemical pollutant loads are calculated in the model as a product of the runoff and pollutant concentration. Runoff from each land use is calculated using Equation (1) and (2).

$$\mathbf{R = P^{*}\, P_j{}^{*}R_{vu}} \quad \text{..........} \quad (1)$$

Where: R = Annual runoff (inches)
P= Annual rainfall (inches)
P_j= Fraction of annual rainfall events that produce runoff
R_{vu} = Runoff coefficient

The runoff coefficient is the ratio between flow and rainfall volume (Longobardi *et al.*, 2003). The calculation is based on the percent impervious land surface for a specific land use. This dependence of the runoff ratio on the percent impermeable area is documented by Schueler (1987). Therefore impervious cover can be assumed to be a reasonable predictor of the R_{vu}. Equation (2) which was used for this calculation is shown below:

$$\mathbf{R_{vu}= 0.05 + (0.009 * I_u)} \quad \text{..........} \quad (2)$$

Where: R_{vu}= runoff coefficient for land use type u, $\text{inches}_{run}/\text{inches}_{rain}$
I_u= Percent Imperviousness

Pollutant loadings are then calculated using the equation:

$$\mathbf{L_p= 0.226^{*}\, R^{*}\, C_u{}^{*}\, A_u} \quad \text{..........} \quad (3)$$

Where: L_p= Pollutant load, lbs
R = Runoff (inches)
C_u= Event Mean Concentration for land use type u, milligrams/litre
A_u = Area of land use type u, acres
0.226[1] = Unit conversion factor

The loading values produced by this equation were given in pounds per acre and converted to metric units in the analysis.

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[1] 0.226 = conversion factor derived from 2.72/12;
where 12 = conversion factor (inches/foot) and 2.72 = conversion factor (pounds/acre-foot-ppm)

3.5.3.1. Limitations of the simple method

The simple method provides estimates of pollutant loads generated by storm-flow and does not take into consideration factors such as baseflow or dry weather pollutant load generation in the catchment. Baseflow is the contribution of groundwater to the stream flow. According to the New York Department of Environmental Affairs (2001) baseflow usually constitutes only a small fraction of the total pollutant loads in runoff from urban areas therefore it can be ignored at the scale of a development site, but may be significant at the catchment scale.

Although PLOAD links land use to the pollutant load that is estimated in the runoff, it does not give an output that highlights the load associated with each land use. In addition, the user does not have an easy option or tool available that allows for the calibration of the model outputs.

3.5.3.2. Optional simulations using the PLOAD Model extension in BASINS

The PLOAD extension gives the user an option to simulate impacts caused by point sources of pollution, BMPs and bank erosion. In this way the user can evaluate the impacts of these factors on the loading output. This serves as a useful tool for users who would want to assess pre- and post-management loads in catchments or whose study sites exhibit characteristics of bank instability or modification. The impact of point sources, BMPs and bank erosion were not taken into account during the modelling process for this study because the data for these analyses was not readily available and would require time and funding that was outside the scope of this study.

3.6. MODEL CALIBRATION

Model calibration is widely considered to be an important stage in the model testing process (Reckhow and Chapra, 1983). The absence of this stage in a modelling exercise, according to Scholten *et al.* (2000), can result in uncertainties. Hall *et al.* (2004 in Pappenberger and Beven, 2006) state that in cases where adjustments were not made for uncertainty in the model, the results should be treated as probabilistic or possibilistic rather than as deterministic. However, in a study by Refsgaard and Knudsen (1996) of hydrological models the authors showed support for the capabilities of 28 hydrological models tested in the absence of site calibration and with limited validation. The model applied in this study was developed for stormwater monitoring in the United States, therefore calibration of this model was required to reduce any bias that might be associated with the model output.

For this study a calibration technique was adapted from Reginato and Piechota (2004) as no measured monthly runoff loads in the study catchment could be obtained. Reginato and Piechota postulate that the runoff coefficient calculated in Equation (2) is not always representative of the amount of rainfall that is converted into runoff and it is the runoff coefficient that should be calibrated. Monitoring data on known runoff values was used to calculate an adjustment factor for the runoff volume calculated using the PLOAD model. The calibration approach adjusted for errors in the runoff generation process.

The runoff coefficient (fraction of rainfall converted into runoff volume) is calibrated by using historically monitored rainfall and runoff data. As no sites currently exist for monitoring runoff quality along the Kuils River, data had to be obtained from the nearest monitoring site at Klein Welmoed (Figure 9) on the Eerste River. The Kuils River catchment is a tributary of the Eerste River and therefore data from the site in the latter sub-catchment was the closest data set to the unknown data for the Kuils River.

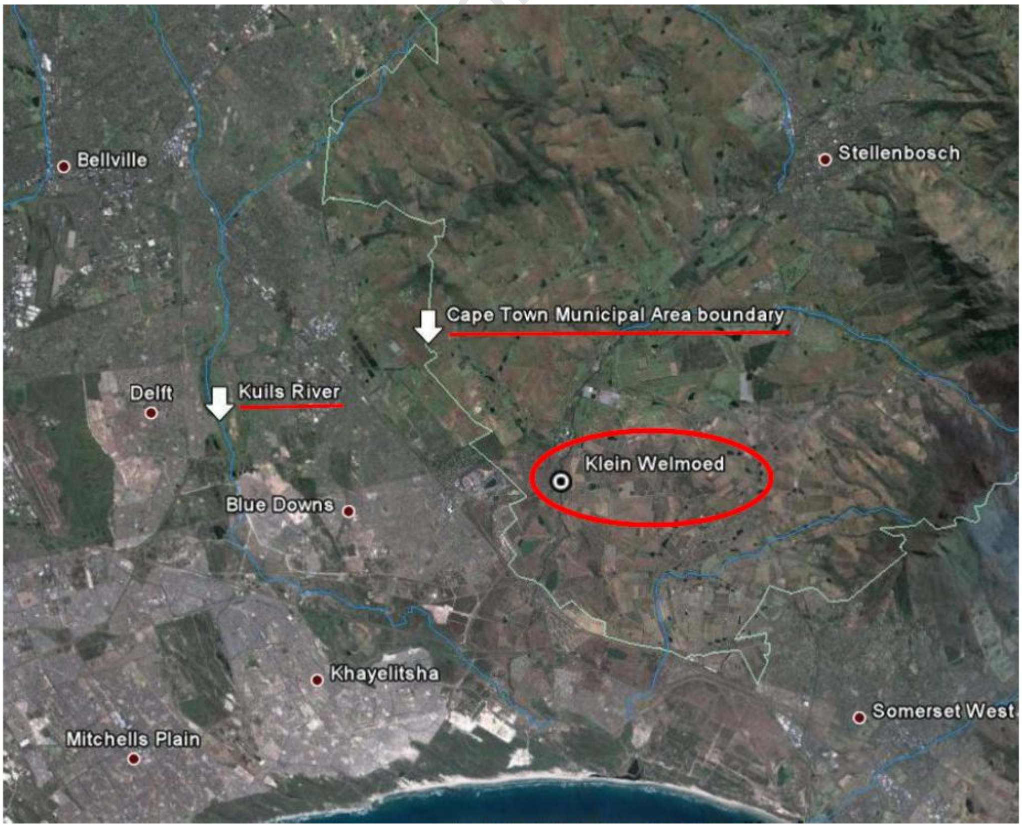


Figure 9 Location of the monitoring station on the Eerste River at Klein Welmoed

Klein Welmoed was selected as a proxy site based on the similarity of land use types and rainfall patterns that the site exhibited to the study area. Rainfall patterns can be constant across a large area therefore finding a site with similar rainfall to the study area should have posed an easier task than finding a site whose land use patterns matched the study site. However discrepancies in rainfall data revealed that sites within the Kuils River catchment, within close proximity of each other, did not have similar precipitation values. In considering the runoff generation process, it was more appropriate to consider how land use types affect runoff generation than to focus on how different rainfall distributions over one land use type changes pollutant loads in runoff. A site that was surrounded by similar land use types would act as a better proxy than one whose rainfall pattern was similar and yet the surrounding land use differed. The proxy site chosen for this study was the closest site that exhibited a similar land use distribution.

For the calibration process monthly data on the volume of runoff data from Klein Welmoed was obtained from the Department of Water Affairs (DWA). The DWA data was provided in cubic metres per second and converted to mega litres per day for the purposes of calibration. The location of the Klein Welmoed station is shown in Figure 9. The calculations used in calibration are outlined in Appendix B. Equation (2) was used to compare observed stormwater volume (V_m) to the stormwater volume (V_c) so that PLOAD could be calibrated from the runoff volume. An adjustment factor (A_f) was calculated using the equation:

$$A_f = V_m/V_c$$

The observed runoff was divided by the calculated runoff (calculated using Equations (1) and (2) of the PLOAD model) to determine an adjustment factor for each month. The adjustment factor is the fraction by which the model incorrectly estimated the actual volume of runoff generated in the landscape. The adjustment factor was calculated for a whole catchment scale because runoff data were not available at the sub-catchment level. A monthly adjustment factor was calculated to account for the changes in runoff volume due to seasonality. The significance of the calibration process is outlined in Chapter 5.

3.6.1. Development of a calibrated model of PLOAD

PLOAD can be adapted to include calibration and pollution estimations at the land use scale. An automated version of the PLOAD model was developed for this study which included a function to calibrate the model. The calibrated model multiplied the adjustment factor (input by the user) against the runoff volume calculated in the model as outlined in the section above. This model is referred to throughout this study as PLOADcal, so as to reduce the confusion between discussions on the original model and the automated version.

The PLOADcal model was written in visual basic to run the "simple method" algorithm for the Kuils River study. PLOADcal applies the same mathematical techniques as those used in PLOAD in order to make load calculations. The PLOADcal model estimates loads for each individual land use type and gives an output of the load in pounds for that particular land use. The total load for each land use in the sub-catchment represents the sub-catchment load. The model was developed specifically for this study using data for the Kuils River catchment. The PLOADcal model does not have a GIS component, therefore the model process is much more time consuming than the original PLOAD model because land uses had to be evaluated individually.

The PLOADcal model served several functions in this study. It was used as a tool to review the model design as described in section 3.7.1. It also served as a tool for the calibration of PLOAD simulations and it allowed for the individual land use contributions to pollution loads in sub-catchments to be determined (Section 3.8).

3.7. POLLUTANT LOAD ESTIMATIONS

Pollutant loads of TP and TSS were estimated for each sub-catchment for the year 2009. Annual and monthly load estimates were modelled for each of the four sub-catchment regions to determine pollution loads over a long time period as well as the seasonal trends in pollution loads.

The PLOAD model estimates the load per sub-catchment unit and the load per acre for each sub-catchment unit. Although the PLOAD model estimates loads for each land use, and then uses the sum of these to determine the loads in each sub-catchment, it is not programmed to give a load output from each individual land use. In addition, the algorithms used in calculation of loads cannot be calibrated within the BASINS PLOAD extension. Using the information gathered on the errors in the model to develop an automated version of PLOAD, the contribution of each type of land use to the total pollution loads in the sub-catchments was determined. This automated model (PLOADcal) described in Section 3.6.1, was used to determine the relative contribution of each land use to the sub-catchment load. The land uses that should be managed as priority areas in each sub-catchment were identified through this process.

3.8. MODEL VALIDATION

Estimations from the model were tested for normality in order to determine a suitable statistical test. A rank correlation analysis was found to be the most suitable approach because the data had a skewed distribution as detailed in section 4.3. Estimations were statistically compared with known in-stream pollutant loads to determine the degree of association between pollutant trends in-stream and in runoff. This approach was used because there were no data on pollutant concentrations in runoff from the study catchment. Since pollutants in runoff enter river systems and influence the concentrations of pollutants in in-stream waters, it was determined that if NPS pollution is a significant contributor to pollution in receiving waters then there should be some observable trend between in-stream concentrations and changes in runoff concentrations. In-stream water quality data was available for the Kuils River catchment from nineteen monitoring sites scattered throughout the length of the river. The data from these sites were collected by the CoCT municipality.

The statistical analysis used did not account for factors such as baseflow, temperature, groundwater flow or discharge from WWTWs in the analysis of in-stream trends. These factors are some of the main variables that contribute to the changes in in-stream water quality. The lack of data available restricted an analysis of the contribution of these variables and the runoff estimates of the in-stream conditions. Due to data constraints, a qualitative approach was used to assess the potential use of the model and the limitations of the model - which would reduce its perceived credibility and reliability.

3.9. MODEL ASSESSMENT

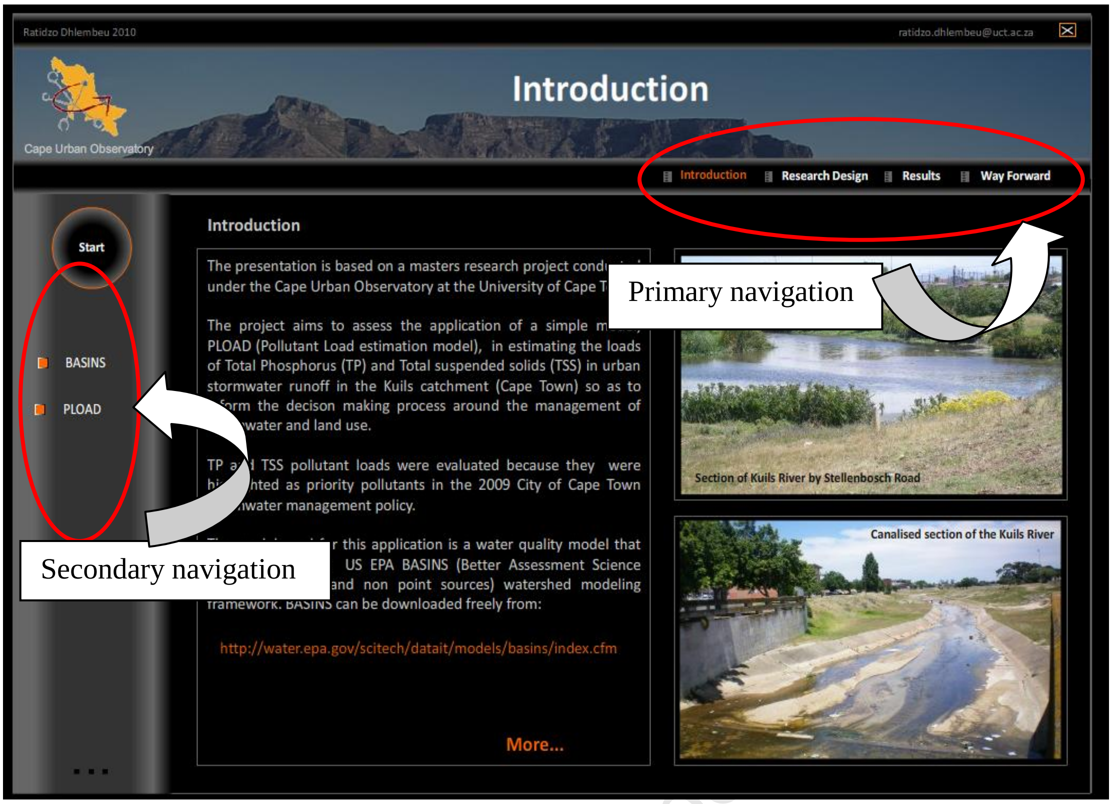
3.9.1. Assessment of the PLOAD model

Young (2006) found that the PLOAD model ignores relatively small areas of land during the simulation process such that estimations made using this model are slightly lower than the results they obtained from an automated version of the PLOAD model. The author postulated that the error occurred in the creation of the intersected land use and sub-catchments spatial layer. This was the only account of this modelling error in PLOAD observed in the literature. A similar approach to the one used by Young (2006) was used to evaluate the PLOAD model in this study. The PLOAD model estimates were compared with the results from the PLOADcal model as the latter model did not include a spatial component.

The PLOADcal model (Section 3.6.1) was used to estimate the annual pollutant load observed from the four sub-catchments. These results were compared with the results from the same simulation conducted using the original BASINS PLOAD. The differences in the estimations made by the two model versions were used to determine whether the PLOAD model was making significant errors in calculating the pollution loads which would compromise the validity of the use of this model.

3.9.2. Assessment of the model applicability to inform decision making

The opinion of five professionals working in the field of stormwater management was elicited as a qualitative means of evaluating the suitability of the PLOAD model. A fifteen minute presentation (Appendix D), outlining the modelling process, was created and distributed to these professionals. The presentation was designed using an interactive interface consisting of primary and secondary navigation tabs as shown in Figure10.



Introduction

The presentation is based on a masters research project cond under the Cape Urban Observatory at the University of Cape T

The project aims to assess the application of a simple m PLOAD (Pollutant Load estimation model), in estimating the loads of Total Phosphorus (TP) and Total suspended solids (TSS) in urban stormwater runoff in the Kuils catchment (Cape Town) so as to form the decison making process around the management of water and land use.

TP a d TSS pollutant loads were evaluated because they were hi hted as priority pollutants in the 2009 City of Cape Town water management policy.

r this application is a water quality model that US EPA BASINS (Better Assessment Science and non point sources) watershed modeling framework. BASINS can be downloaded freely from:

http://water.epa.gov/scitech/datait/models/basins/index.cfm

More...

Figure 10 Example of the presentation interface

The primary navigation tabs were located at the top right hand side of the presentation screen. Users could select these tabs to read through a general outline of the modelling process and the results. Those users who were interested in more detail than the information provided in the primary interface could utilise the secondary navigation tool on the left hand side of the presentation screen. Links were provided to relevant URLs and draft chapters of the thesis for more detailed descriptions of the study. Other features of the presentation included an audio-visual demonstration on the use of the PLOAD model in BASINS and links to some of the data files used. At the end of the presentation, participants were requested to fill a survey document that was attached as a link in the presentation. A survey (Appendix E) included with the presentation was used to gain feedback on the participants experience with stormwater models, the perceived strengths and weaknesses of the PLOAD model and the value of the model output in informing the goals of stormwater management raised in the CoCT stormwater policy. The responses were integrated into the final discussion of the model process and outputs that make up Chapters 4 and 5 of this thesis.

The five professionals who participated in the survey were all employees of the City of Cape Town Municipality’s Catchments, Stormwater and River Management Branch of the Roads and Stormwater Department. The respondents were Messrs Nico Meyer, Rod Arnold, Barry Wood, and Abdulla Parker, and Ms Candice Haskins. These practitioners have been involved in stormwater management in the City over several years. Their experience in the stormwater industry makes these practitioners opinions invaluable in assessing the potential application of the PLOAD model.

CHAPTER 4

Results of PLOAD modelling process

4.0. INTRODUCTION

In this study TP and TSS in runoff were estimated at both monthly and annual intervals for four sub-catchments of the Kuils River (Upper Kuils, Bottelary, Middle Kuils, and Eerste-Kuils). The pollutant loads generated from each land use in the four sub-catchments were also determined using an automated version of PLOAD described in Chapter 3. This chapter will review the model output for annual, monthly and land use pollutant estimates.

4.1. MODEL CALIBRATION

The calibration of PLOAD used the adjusted runoff volume to match the actual runoff volume observed in the landscape as closely as possible. To determine the adjustment factor the observed runoff data were divided by the calculated runoff volume estimates. The adjustment factor was calculated at the catchment scale because runoff data was unavailable at a sub-catchment level. The adjustment factor was calculated for each month to account for the changes in runoff volume due to seasonality. The results of this calibration are shown in Table 4.

Monthly runoff data was obtained from the Department of Water Affairs for the Eerste River at Klein Welmoed. The monthly runoff volume was calculated by the model using the equation below (Equation 2 of the simple method):

$$R = P * P_J * R_{VU} \quad \text{..........}(2)$$

The runoff volume generated in each sub-catchment during storm events was calculated on a monthly basis. Adjustment factors were calculated for each month of the year in 2009 using data from Klein Welmoed as a proxy for the Kuils River catchment.

Table 4 Adjustment factors used in the calibration of the runoff volume calculated in PLOAD

Month	**A_f**
JAN	4.09
FEB	0.17
MAR	3.97
APR	0.14
MAY	0.19
JUN	0.96
JUL	0.46
AUG	0.46
SEPT	0.55
OCT	1.14
NOV	0.70
DEC	0.81

The adjustment factor is the order of magnitude by which the observed runoff volume exceeds the calculated runoff value. There is no observable difference between the two values when the adjustment factor is equal to 1. In comparison to the other months, the runoff calculated for the months of January (A_f= 4.09) and March (A_f = 3.97) were significantly lower than the observed runoff for those months. In the months of February (A_f = 0.17) and April (A_f = 0.13) an opposite trend was displayed, with the observed runoff being significantly lower than the calculated runoff in comparison with other months.

The adjustment factors calculated for this study were based on the assumption that the study site experiences consistent rainfall. As A_f was applied across a whole catchment this meant that the value calculated for each month was a generic value for catchment. Given the data limitations of this study the calibration approach used was very crude. A detailed account of the calculation of these adjustment values is given in Appendix B.

4.2. POLLUTANT LOAD ESTIMATIONS

The Department of Water Affairs and Forestry (1996) proposed an ideal discharge limit for phosphate of 0.1 mg/l. Phosphate concentrations above this limit could result in the eutrophication of waters. This concurs with Oberholster and Ashton (2008) who also recommended that effluent concentration of < 0.1 mg/l was required to minimise the effects of eutrophication.

The WWTW discharge limit for suspended solids outlined in the South African National Water Act (1997) water quality guidelines is 18 mg/l. This limit for all discharges of suspended solids from WWTW was changed from the previous limit of 25 mg/l. The target water quality range for suspended solids in aquatic systems is < 100 mg/l (DWAF, 1996). This range applies to all aquatic systems but water quality should remain within a 15% deviation of the norm for that specific water source.

4.2.2. Annual pollutant concentration estimations

The results of the annual concentration estimates indicate that pollution loads are lowest in the sub-catchment surrounding the headwaters of the Kuils River. In this region of the river the land use activity is predominantly residential, urban open space, undeveloped land as well as some areas of rural-agricultural land use. The land use distribution map is shown in Figure 11. TP and TSS load estimates for the UK sub-catchment were the lowest of all the sub-catchments. The estimate for TP in this sub-catchment was 0.04 mg/l while the TSS estimate made for this sub-catchment was 5.1 mg/l. The estimates for these pollutants were much lower than the discharge limit (0.1 mg/l and 18 mg/l respectively) defined by the DWA.

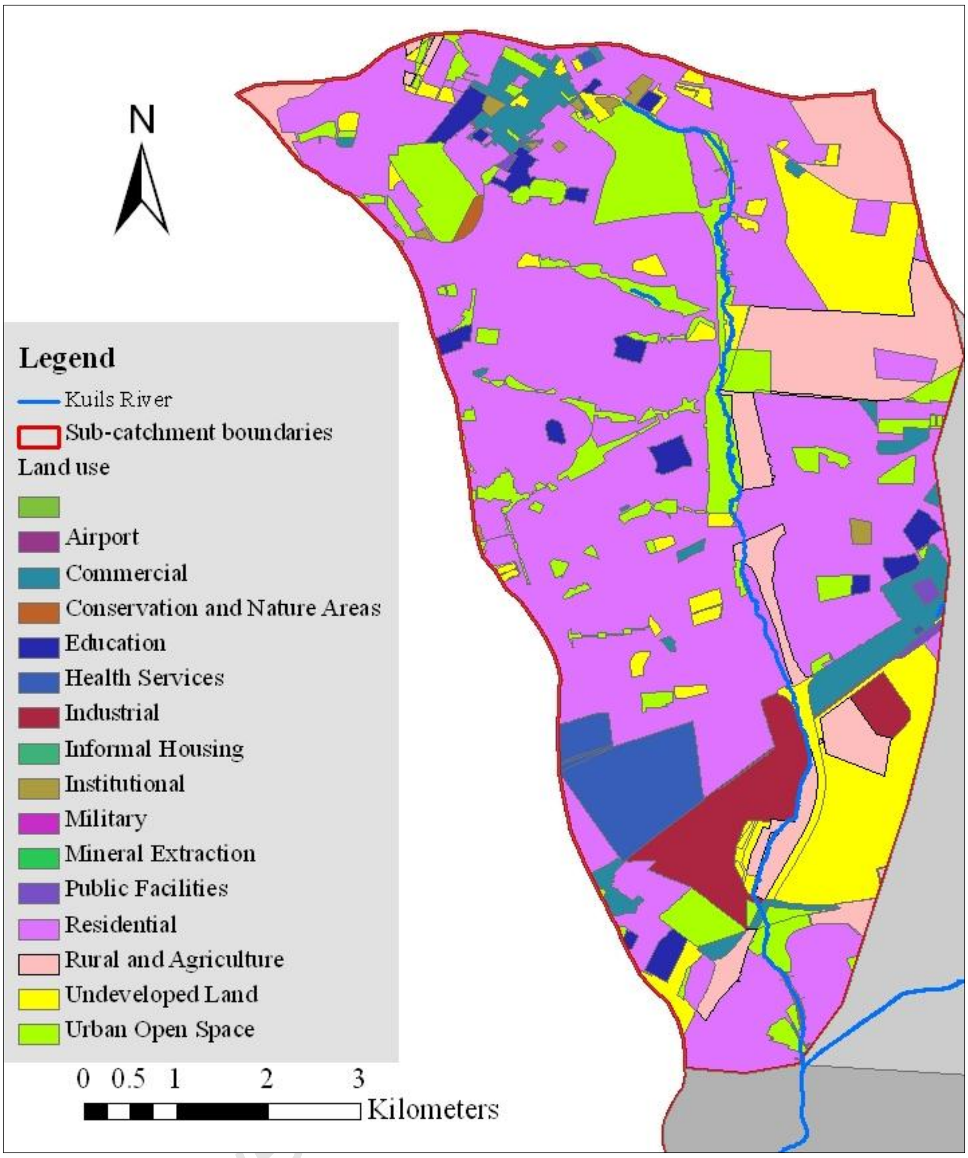


Figure 11 Land use in the Upper Kuils (UK) sub-catchment

The BO sub-catchment was estimated to have the highest loads of TP and TSS. This trend was probably a result of the fact that land use in the sub-catchment was predominantly rural-agriculture. The estimated pollutant concentration for TP was 0.12 mg/l and 7.8 mg/l for TSS. TP loads estimated for this sub-catchment were above the discharge limits whereas TSS loads were significantly below the limit of 100 mg/l. Management intervention to reduce the concentration of TP in runoff would be paramount in reducing the risk of effects such as eutrophication in the Bottelary River which is a tributary of the Kuils River. Water extracted from BO is used in agricultural activities which form the main land use in the catchment (Figure 12). Therefore poor water quality conditions will have major implications for users of water, especially for those users in the agricultural industry as this is in one of the major economic activities in the CMA (River Health Programme, 2005).

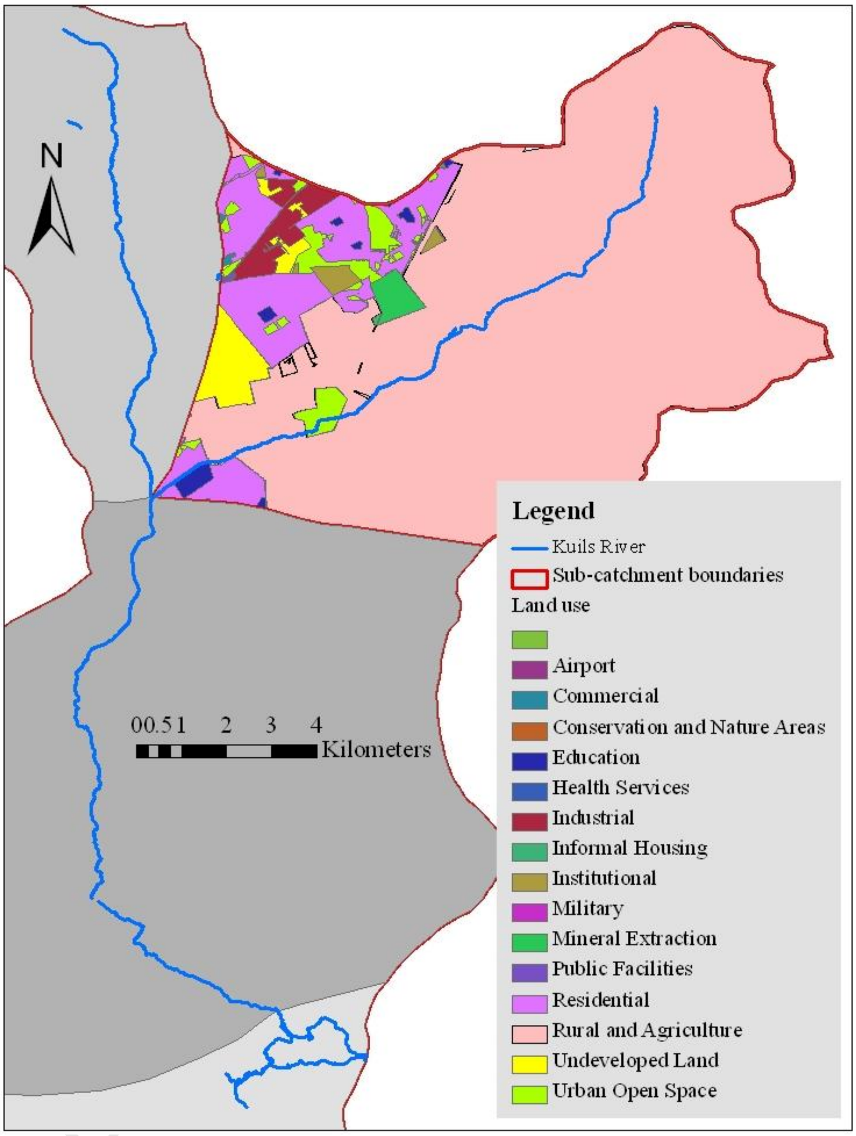


Figure 12 Land use in the Bottelary (BO) sub-catchment

The MK sub-catchment is located below the confluence of the UK and BO sub-catchments. This region had the second highest estimated concentration for TP with an estimated gross annual concentration for this sub-catchment of 0.06 mg/l. The estimated TSS load was 6.6 mg/l which was the second highest TSS load observed from all the sub-catchments. The land use in this catchment is predominantly a combination of undeveloped land, residential and rural-agricultural land use as shown in Figure 13. These were land uses that had some of the highest event mean concentration values for TP and TSS yet the loads estimated for this sub-catchment were not significant when compared to discharge limits defined by the DWA. This was probably due to the fact that the land uses areas were small and the pollutants sourced from these land uses did not cumulatively exceed the discharge limits.

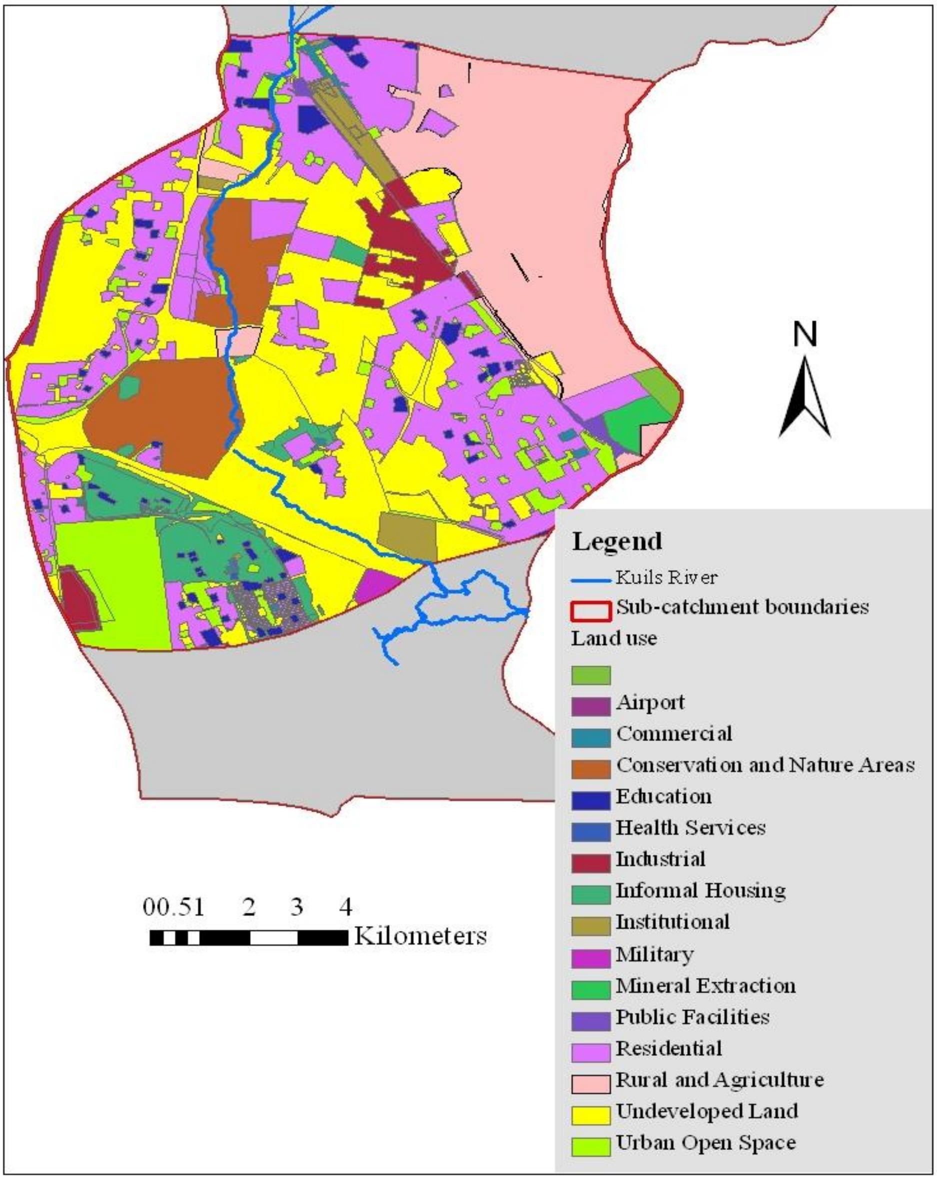


Figure 13 Land use in the middle Kuils (MK) sub-catchment

The EK sub-catchment which had a high presence of undeveloped land, urban open space and informal housing had an estimated TP concentration of 0.06 mg/l. The estimated TSS concentration exceeded all other catchments with a value of 8.1 mg/l. This sub-catchment exhibits very similar land use types to the MK sub-catchment therefore initial expectations were that the average annual pollutant concentrations would be similar for these two sub-catchments. The land uses in this sub-catchment are shown in Figure14. The loads estimated in the EK were below the discharge limits defined by the DWA for both TP and TSS therefore pollution generated on an annual basis from this catchment did not identify a need for an intervention.

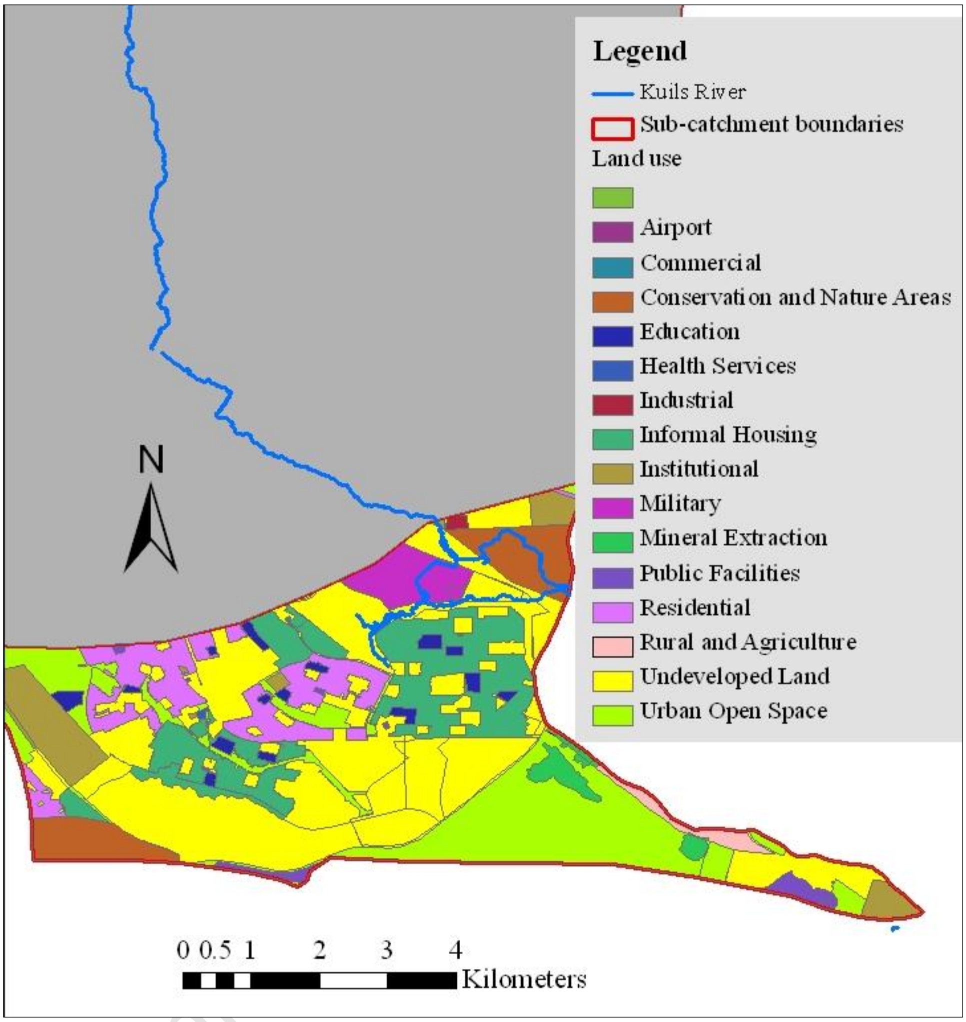


Figure 14 Land use in the Eerste-Kuils sub-catchment

A graphic presentation of the annual analysis is shown in Figures 15 and 16. These maps illustrate the annual pollutant loading outlined in the sections above; the sub-catchment with the highest TP concentration in runoff is the BO sub-catchment which is closely followed by the EK and MK sub-catchments which had the same pollutant concentration. For TSS the highest load was observed in the EK sub-catchment followed by the BO sub-catchment.

Based on the annual estimates, none of the sub-catchments exhibited a TSS load that exceeded the assigned discharge limit for this pollutant. TP load in the BO sub-catchment were 0.02 mg/l higher than the discharge limit for this nutrient. The impact of TP loads higher than 0.1 mg/l could be eutrophication of the river draining this catchment.

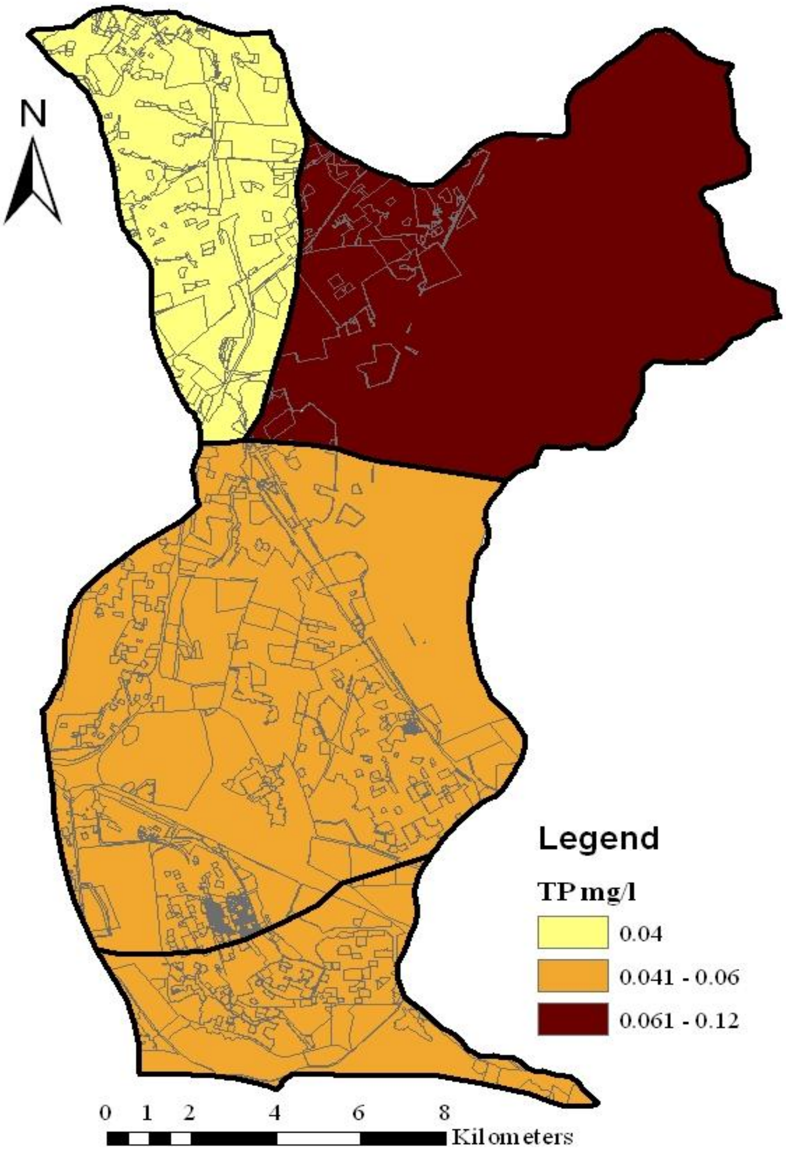


Figure 15Annual TP load estimates

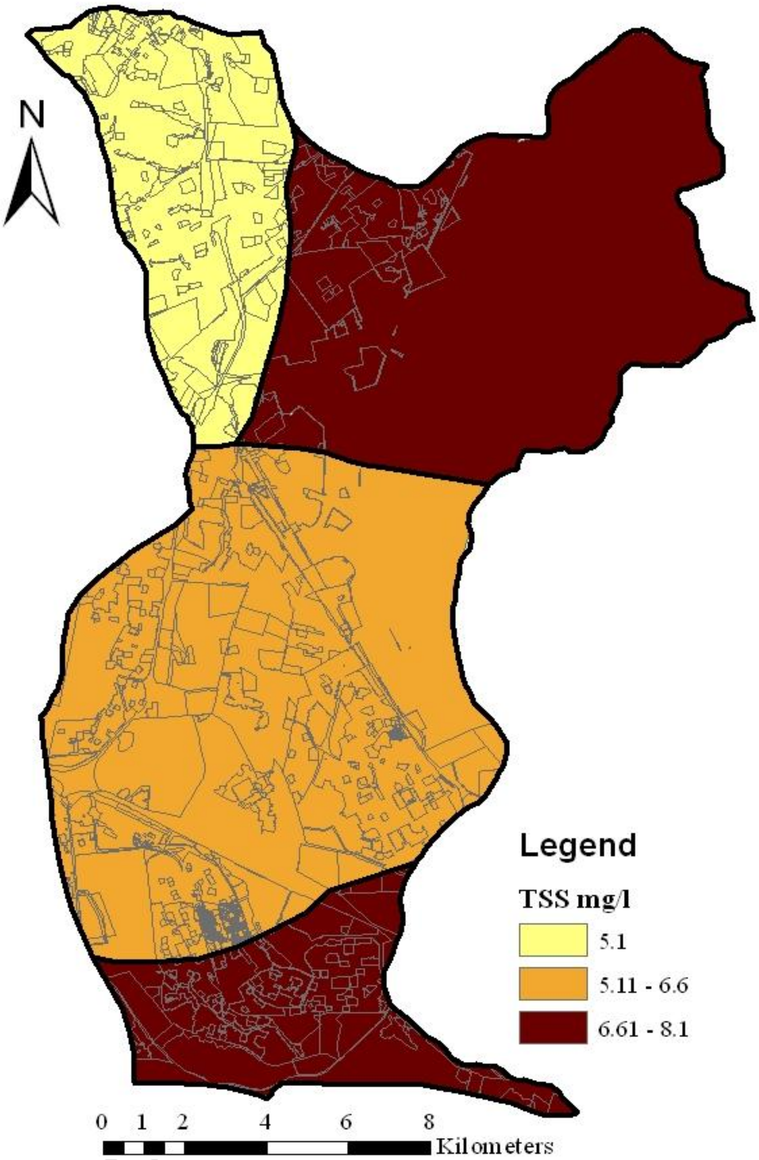


Figure 16Annual TSS concentration estimates

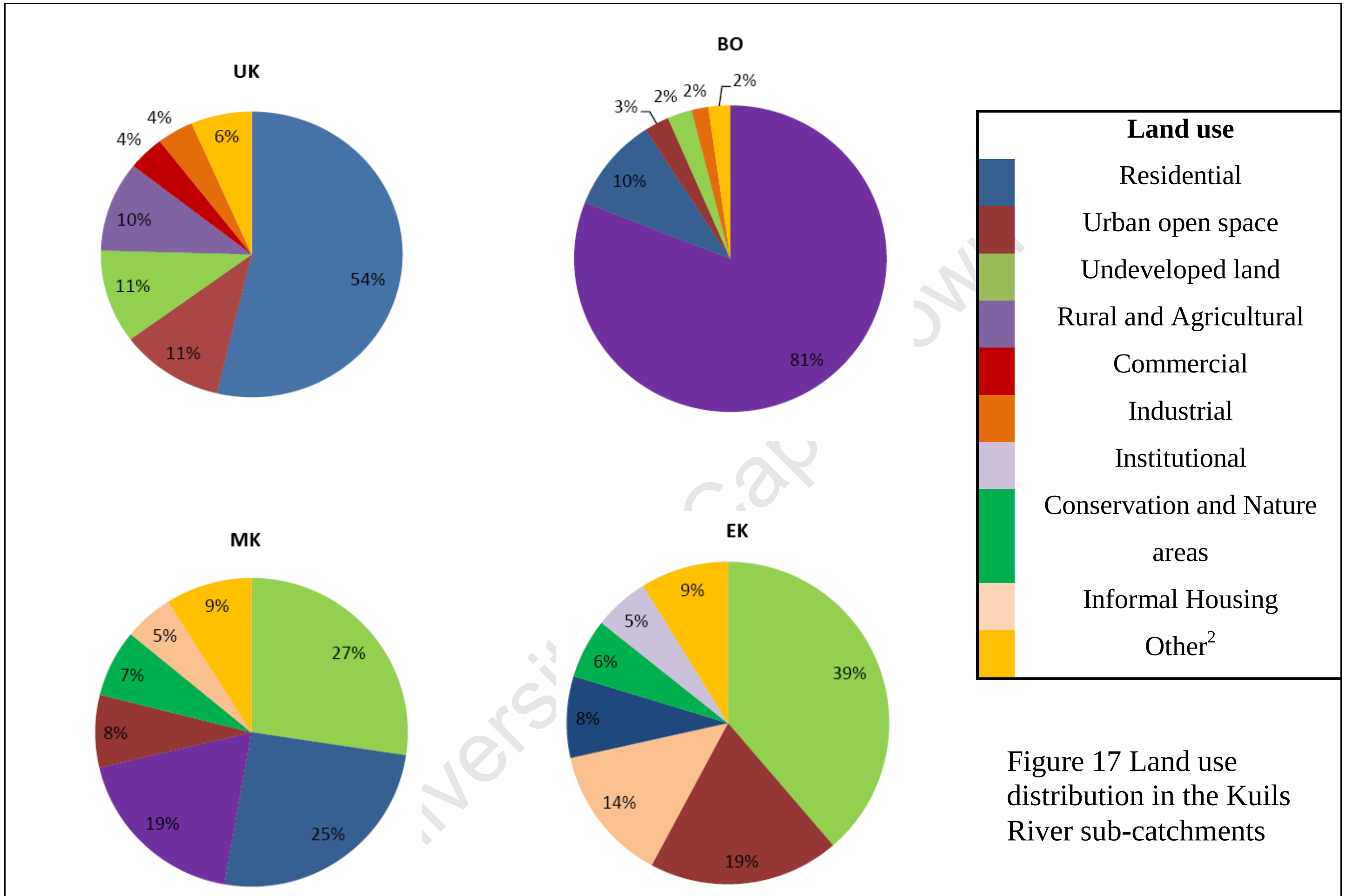


Figure 17 Land use distribution in the Kuils River sub-catchments

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[2] Other land uses denotes land uses that were not within the top five or six largest land uses in a given sub-catchment. These smaller land uses are not the same for all of the catchments. The land uses that constitute this "other" category generally include Institutional, mineral extraction, military, health services, commercial, public facilities and education.

4.2.3. Monthly load estimations

Three seasonal periods are discussed as there is no obvious autumn season in South Africa – summer, winter and spring. The monthly load estimates were used to determine the seasonal trends observed in pollutant concentrations. The highest pollutant loads were anticipated during the winter months when rainfall was at a peak (64 – 108.4 mm for 2009) resulting in a higher runoff.

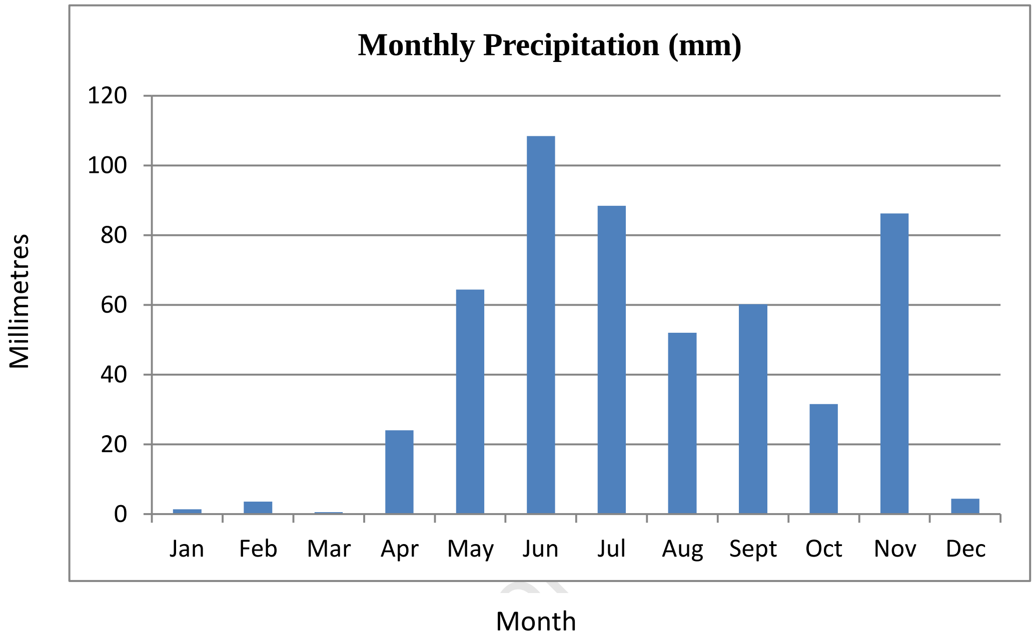


Figure 18 Monthly precipitation levels in the Kuils River catchment (data from SAWS 2009 database)

4.2.3.1. Estimated TP concentrations

The estimated TP concentrations for the UK sub-catchment (Figure 19) revealed that concentrations of <0.001 mg/l were observed in the months of December and January through to March. Estimated pollutant concentrations increase with increasing rainfall. As such the highest TP concentration for this sub-catchment was observed in the month of June (0.018 mg/l) for the UK sub-catchment.

This same seasonal trend was observed in the BO sub-catchment where the highest pollutant concentration occurred in June (0.025 mg/l) while the lowest estimated concentrations were observed from the three months of February through to April (0.001 mg/l). However in this sub-catchment, the pollutant concentrations estimated for each month where higher than those estimated for the other sub-catchments. These findings correspond with the results from annual concentration assessments.

The MK and EK sub-catchments exhibited the same estimates of pollutant concentrations with deviations of ≤0.001 mg/l. The highest pollutant concentration for these sub-catchments was estimated for the month of July (0.01 mg/l) and the month of June with an estimated load of 0.009 mg/l.

4.2.3.2. Estimated TSS concentrations

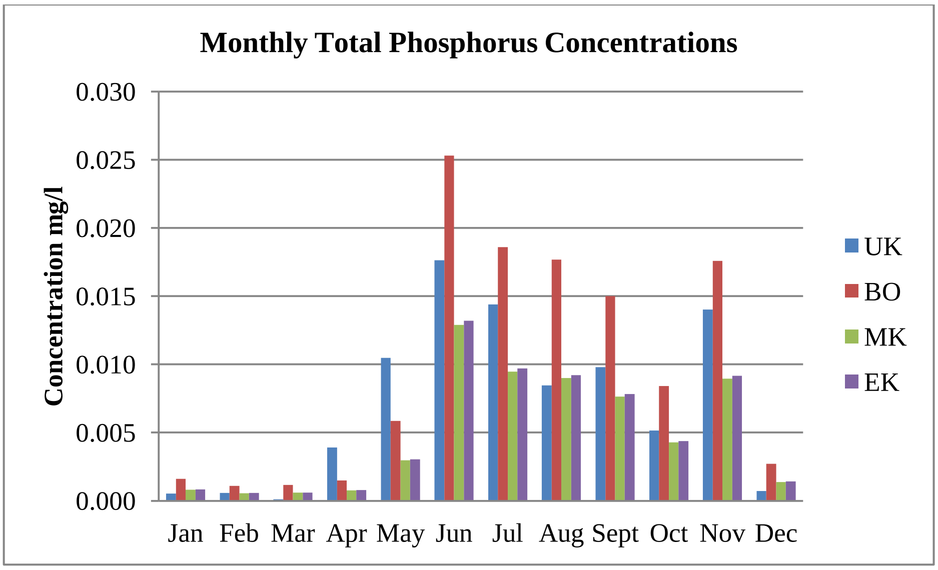
A graph of the TSS concentrations for the four sub-catchments is shown in Figure 19. Similar to estimations of TP, the TSS concentrations for the UK were lower than the estimated concentrations in the other three sub-catchments. The highest estimated concentration for this pollutant occurred in June (1.11 mg/l). The lowest estimates were obtained in the summer months of January through to April when concentrations were < 0.07 mg/l.

In the BO, the highest concentration estimate (1.69 mg/l) was observed in the month of June. The lowest concentrations in the BO sub-catchment were estimated for the months of February and March (0.07 and 0.08 mg/l respectively), which corresponded with the trends from other sub-catchments where summer had the lowest generation of pollutants. Estimates of TSS differed in the MK and EK sub-catchments. In the MK the highest TSS estimate was 1.44 mg/l whereas the load for EK was 1.76 mg/l for the month of June.

Monthly estimates of TSS in sub-catchments revealed that pollutant concentrations varied between 0.07 mg/l and 1.76 mg/l. The highest monthly TSS concentrations were observed from the EK sub-catchment with the month of June showing the highest TSS estimate of 1.76 mg/l. The trend also shows that the lowest concentrations were not necessarily always observed in the months with the lowest rainfall. The lowest rainfall was observed in the month of March (0.6 mm) and the estimated concentrations in this month were higher in all sub-catchments than for February when the observed mean monthly rainfall was 3.6 mm. In December the same amount of rainfall was experienced as for February, yet estimations in the former month were higher than the latter. It was also evident from a comparison of the estimates of TP and TSS concentrations in runoff that the MK and EK sub-catchments which exhibited the same land use types also shared the same values for TP estimates and yet differed for the TSS estimates. Detailed tables outlining the estimate values obtained for each month are given in Appendix C.

Figures 19 shows that TP pollution for the BO sub-catchment requires attention as it exhibits the highest estimated concentrations for TP followed by the UK sub-catchment. The BO and EK sub-catchments are both significant contributors to high pollution loads. The graphics also illustrate that pollutant loading in runoff follows a seasonal trend with the months of June, July, August and November being prime months in which efforts should be directed towards reducing loads as this is period when pollution is highest.

In the summer months (January to May; and December) very little runoff was generated and the estimated pollutant concentrations were low (TP < 0.3 mg/l and TSS < 1.8 mg/l). The highest concentration for both TP and TSS occurred during the winter months (June to August). The spring months (September to November) showed concentrations that were the second highest to the winter observations. Tables outlining the monthly pollutant concentration estimates are given in Appendix C as it would be too cumbersome to discuss every result obtained from this modelling process.



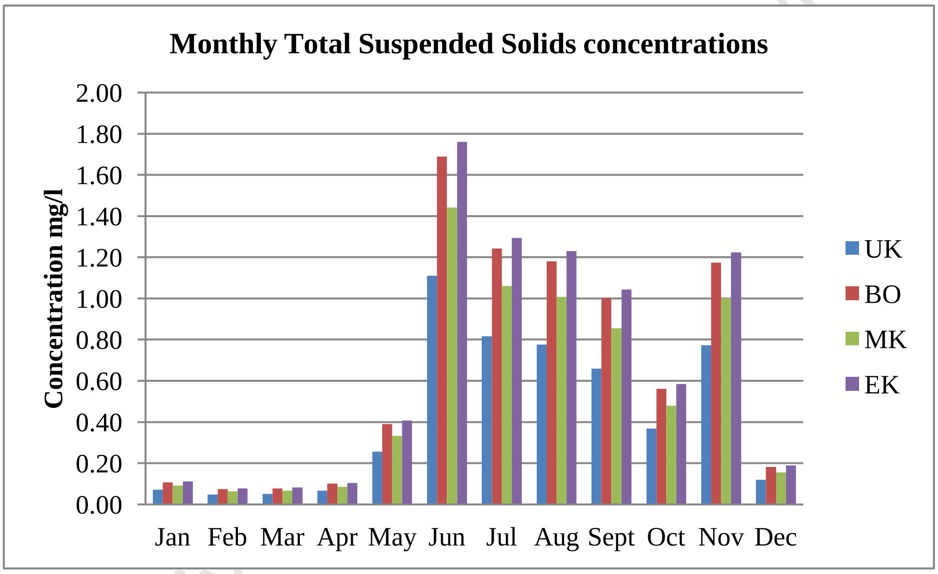


Figure 19 Monthly TP and TSS concentration estimates in the Kuils River sub-catchments

4.2.4. Assessment of land use contribution to loads

An analysis of the contribution of land use to the pollutant concentrations from sub-catchments will identify to the extent to which or whether land is a determining factor in the generation of pollutant concentrations. Arguably it is this type of analysis that could be used to inform the implementation of strategies to minimise pollutants in stormwater.

Although PLOAD is designed to identify the connection between land use and the expected generation of pollutants, but the output cannot provide estimated values for each of the individual land use types. Therefore the automated model (PLOADcal) was used to determine the contribution from individual land use areas. This model included coding for only the simple method algorithm as this was the estimation method applied in this study. PLOADcal mimics the PLOAD modelling process and uses the same input and output values as those used in the original PLOAD. The final model output from the PLOADcal is a load estimation given in lbs/year only. This output was mapped using ARCGIS because the PLOADcal model did not include a component for spatial analysis.

Figure 20 is a land use map of the Kuils River catchment. The graphic outlines the main land uses and their distribution in the sub-catchments. From the graphic, it can be seen that rural-agricultural, residential and undeveloped land uses cover most of the catchment.

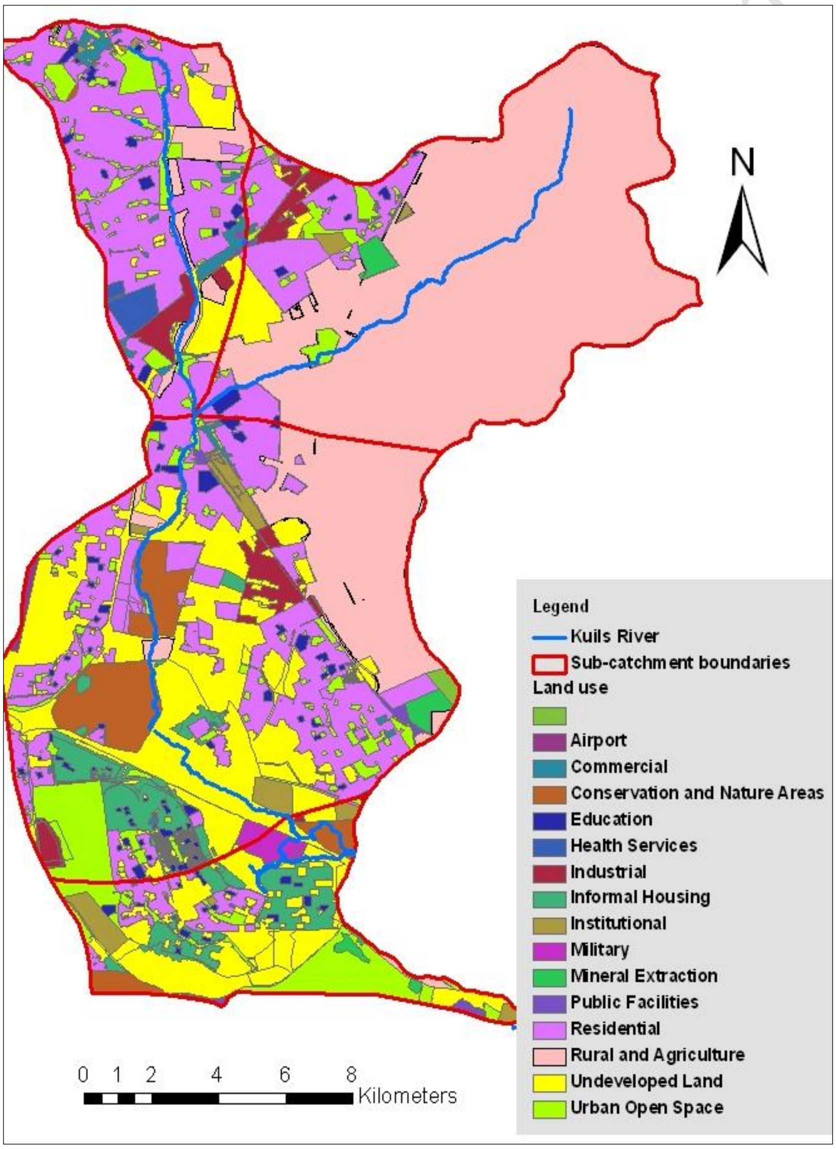


Figure 20 Land use distribution in the Kuils River Catchment

4.2.4.1. Land use contributions to TP loads

In the UK sub-catchment the highest loads were observed from rural-agricultural (380.79 kg/year), residential land use (31.98 kg/yr) and industrial land uses (274.97 kg/yr). The BO sub-catchment had high TP load estimates from rural–agricultural (6,379.73 kg/yr) and industrial land use (258.87 kg/yr). The three land uses with the highest loads in the MK were rural-agricultural (1,841.99 kg/yr), informal housing (1,474.67 kg/yr), industrial and residential land use (475.5 and 429.37 kg/yr). The EK sub-catchment which exhibited fourteen of the land uses only had one land use that generated a load over 453.59kg/yr. This land use was informal housing and the estimated loads from was 1,126.36 kg/yr. All the other land uses in the sub-catchment were between 2.27 kg/yr and 39.24 kg/yr.

The estimated TP concentrations from these sub-catchments were converted to a concentration value in mg/l to discount the influence that area has on the generated loads. The highest concentrations of TP were estimated from industrial (0.25mg/l) and informal housing (0.39mg/l). Land uses such as residential land use, which was identified as having the second highest load in the UK sub-catchment, had an estimated concentration of 0.023 mg/l. In the BO sub-catchment informal housing had a TP load value of 4.40 kg/yr which was significantly lower than the load of 6,379.32 kg/yr that was estimated for rural–agricultural land uses in that sub-catchment. This trend was similar for land uses in the MK and EK sub-catchment where the estimated load from industrial and informal land uses was high but the associated concentrations from these land uses was very low.

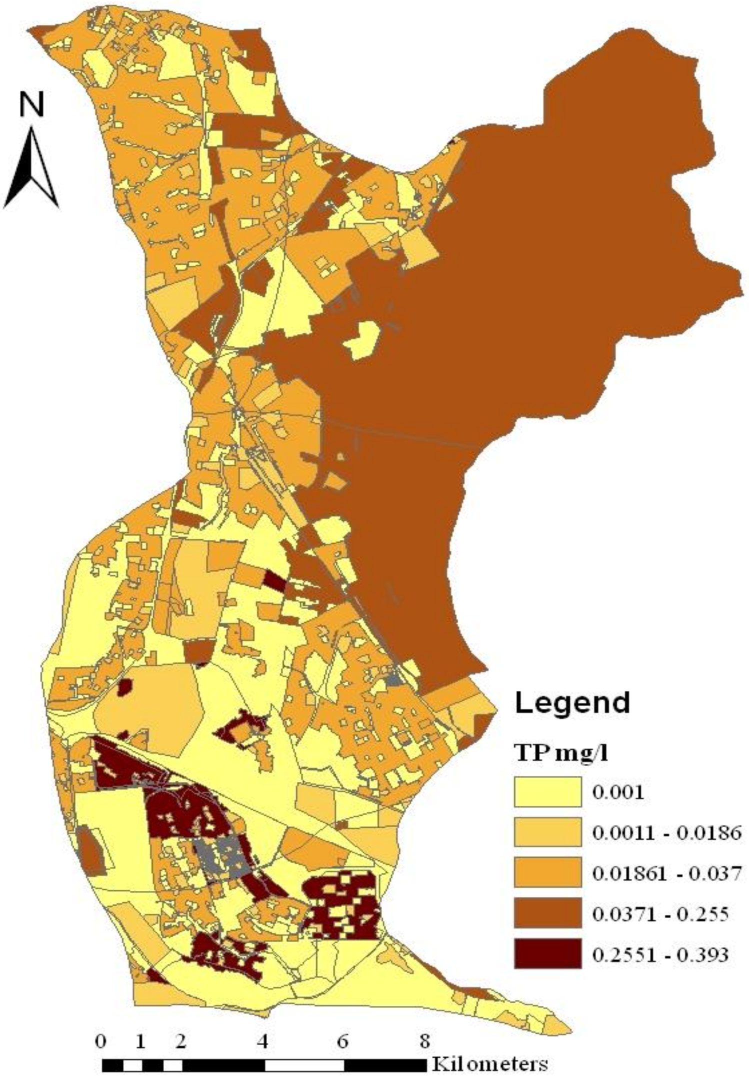


Figure 21 TP (mg/l) concentrations in different land use types

4.2.4.2. Land use contributions to TSS loads

In the UK sub-catchment the highest loads were observed from industrial land uses (24,868.20 kg/yr), rural-agricultural (23,622.27 kg/yr) and commercial land use (14,574.56 kg/yr). The BO sub-catchment was estimated to have similar land use types contributing to the highest TSS loads. The three land uses with the highest loads were rural-agricultural, industrial and residential land use and the load values obtained were 395,780.84 kg/yr, 23,410.95 kg/yr and 18,684.88 kg/yr respectively. In the MK sub-catchment several land uses where noted as contributing to high TSS loads in the sub-catchment. This sub-catchment exhibited all the land use types evaluated in this study. Of these fifteen land uses, four within the MK sub-catchment had loads higher than 45,359.24 kg/yr and these were namely informal housing (133,722.75 kg/yr), rural-agricultural (113,940.86 kg/yr), residential

(59,985.55 kg/yr) and undeveloped land (48,883.47 kg/yr). The EK sub-catchment only one land use type with a load above 45,359.24kg/yr (informal land use 102,146.51 kg/yr) was found. The next highest loads were exhibited from undeveloped land (19,648.93 kg/yr), institutional (11,432.12kg/yr) and urban open space (9,718.28 kg/yr).

Pollutant loads estimated in these sub-catchments were converted to a concentration value in mg/l to discount the influence that area had on the generated loads. This revealed that the highest concentrations of TSS were not necessarily associated with the land uses that had the highest loads. In the UK sub-catchment the concentrations from industrial land use (23mg/l) and commercial land use (13.4 mg/l) were the highest. Although the second highest load had been recorded from rural and agricultural land uses, this land use only contributed a pollutant concentration of 8.3 mg/l which was a lower value to what had been observed for some of the other land uses with lower loads e.g. institutional land use (load – 1,301.08 kg/yr and concentration - 9.89 mg/l).

In the BO, MK and EK sub-catchments a similar trend was found to that of the UK. The land uses contributing to the highest loads in the former three sub-catchments did not necessarily exhibit the highest concentration estimates. The land uses with the highest contribution to TSS concentration were industrial and informal housing land uses. The respective concentrations for these land uses were 23 mg/l and 35.7 mg/l. The land use that had been anticipated to be a high discharge source, rural-agricultural land use exhibited a high load in each sub-catchment but the TSS concentration from this land use was estimated at only 8.37 mg/l. These results are illustrated in Figure 22.

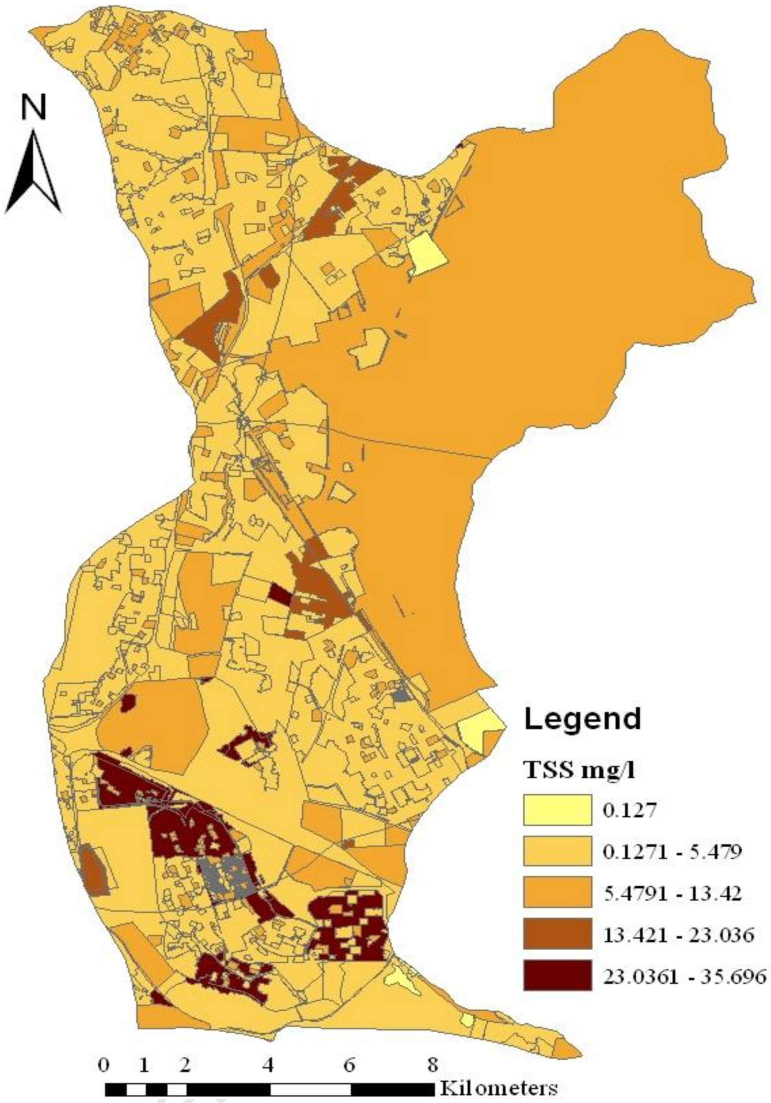


Figure 22 TSS (mg/l) concentration in different land use types

4.3. MODEL VALIDATION

Typically model validation involves comparing monthly model estimates to known loads obtained through field based investigations of the site. The constraints associated with data availability meant that a validation approach had to be developed which would allow for some comparison of the model outputs with known in-stream water quality data. The water quality monitoring data available in the catchment were in-stream pollutant concentrations which were obtained from the CoCT and pollutant discharge limits from WWTWs. This data was used in the validation of the model.

A Speaman's Rank correlation analysis was selected to validate the modelling results. The Spearman Rank correlation technique was selected after the model estimations were tested for normality and were found to have a skewed distribution. Furthermore it was acknowledged that the study would not be able to determine causation (that is, to determine that poor runoff water quality could be attributed to poor in-stream water quality), however we could verify whether increases in runoff pollution correlated with increases in in-stream pollutant loads.

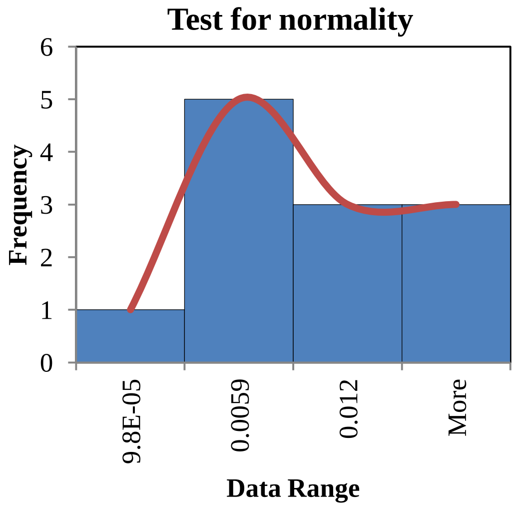


Figure 23 Example of the histogram plot used to test data for normality

Monthly pollutant estimates made using the PLOAD model were ranked in order of the month with the lowest to the highest estimated pollution load. Similarly data obtained from field based monitoring techniques over a 12 month period were ranked according to the amount of pollution observed that month. The ranks of the two data sets were analysed using Spearman rank correlation. This procedure was repeated using PLOAD model estimations and data collected on point source pollution from WWTW. This was done to determine whether there was a more significant correlation between nonpoint source pollution and in-stream pollutant concentration or point source pollution and in-stream pollutant concentrations. WWTWs along the Kuils River are shown in Figure 24. There are four waste water treatment plants in the catchment. The UK sub-catchment is the only sub-catchment that does not have a WWTW within its boundaries whilst the EK sub-catchment has two WWTW. Therefore in the BO, MK and EK sub-catchments a monthly average was taken of TP and TSS concentrations discharged from the treatment centre(s). This value was correlated (using a rank correlation) with the in-stream concentrations to assess if there was a strong association between these two values. In the EK sub-catchment where there are two

WWTWs, the monthly averages from each centre (Macassar and Zandvliet) were compared with the observations made of the in-stream concentrations. Rewrite for better clarity

An assessment was made to determine whether the contribution from non-point sources was significant compared to the loads from point sources that were discharged into the Kuils River. The analysis will determine whether the pollutant concentrations estimated in runoff loads follow a similar trend to that observed in in-stream conditions.

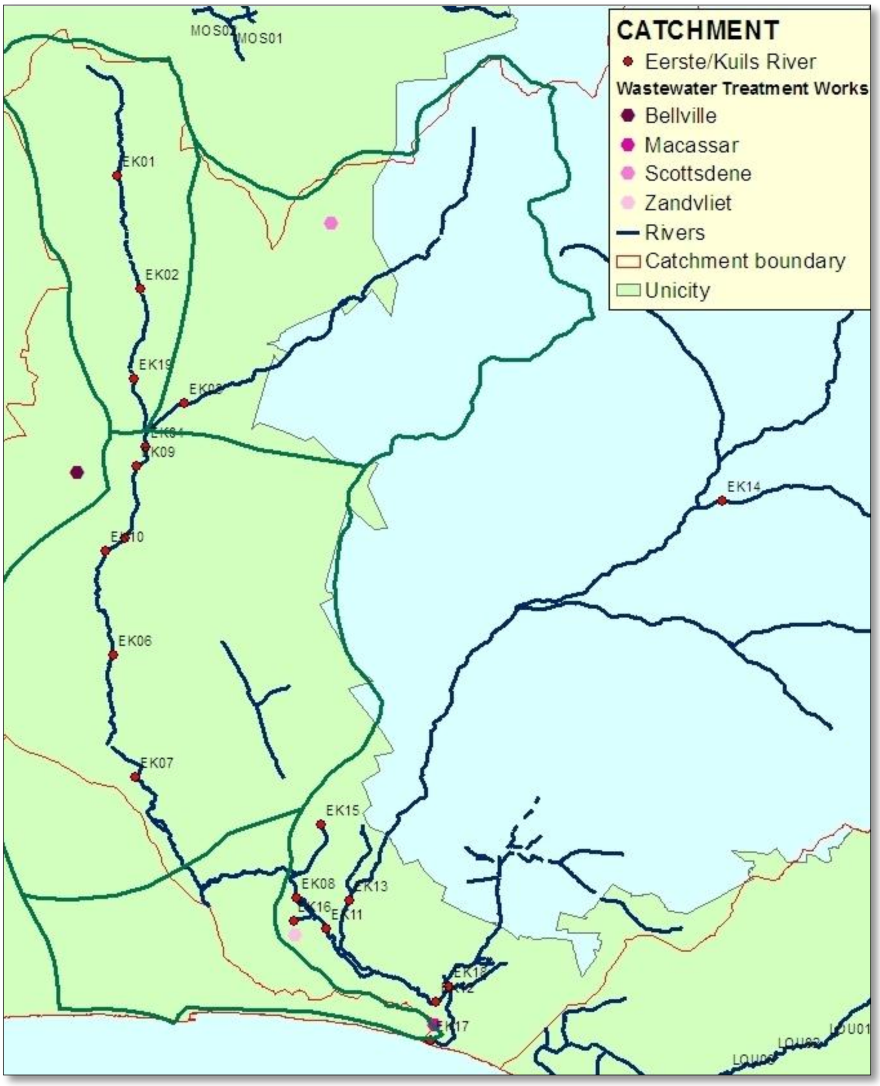


Figure 24 Location of Waste Water Treatment works and in-stream monitoring points along the Kuils River (Source: City of Cape Town, 2010)

The red dots in Figure 24 symbolise the in-stream monitoring points along the river. There are nineteen sites along the length of the Kuils River. To obtain a gross estimate of the in-stream concentrations of the sections of river in each of the sub-catchments, the monitoring points in each sub-catchment were identified and an average concentration from these sites was used for comparison with model estimates for this study.

4.3.1. Statistical analysis

Spearman Rank correlation analysis was used to compare in-stream loads to the estimations from the modelling process and also to observed concentrations from WWTWs in the sub-catchment. The significance of the correlation coefficient was based on the hypothesis:

- H_0 = in-stream concentrations and the concentrations estimated in the modelling process were independent
- H_1 = in-stream concentrations and the concentrations estimated in the modelling process were positively/negatively correlated

4.3.1.1. Comparison between in-stream concentrations and PLOAD estimates

A comparison between in-stream pollutant concentrations and the concentration estimates made by the model revealed a strong negative correlation between the TP trends for the UK, MK and EK sub-catchments. The correlation coefficient is represented by $r_{S.}$ The r_S value for the UK, MK and EK sub-catchments were -0.73, -0.82 and -0.92 respectively. The runoff coefficient was significant at $\alpha = 0.05$ therefore it could be assumed that the r_s values for these sub-catchments was valid. These r_s values signify a strong negative association between in-stream and model estimates. A negative association shows that the concentrations of TP in runoff increase while in-stream concentrations decrease. This trend could be attributed to diffusion. The BO sub-catchment was the only site observed to have a weak positive correlation with $r_S = 0.35$ significant at $\alpha = 0.05$. Therefore the TP trends in runoff from the BO sub-catchment have a very weak association with observed in-stream trends. This association revealed that as runoff concentrations increased so the concentrations of pollutants increased but this was only a slightly notable trend in this sub-catchment. More site specific data on runoff volume and precipitation in sub-catchment could have improved the result. Figure 25 shows rank correlation analysis. These graphs were created by plotting ranked in-stream concentrations against the ranked of pollution runoff.

TP (mg/l)

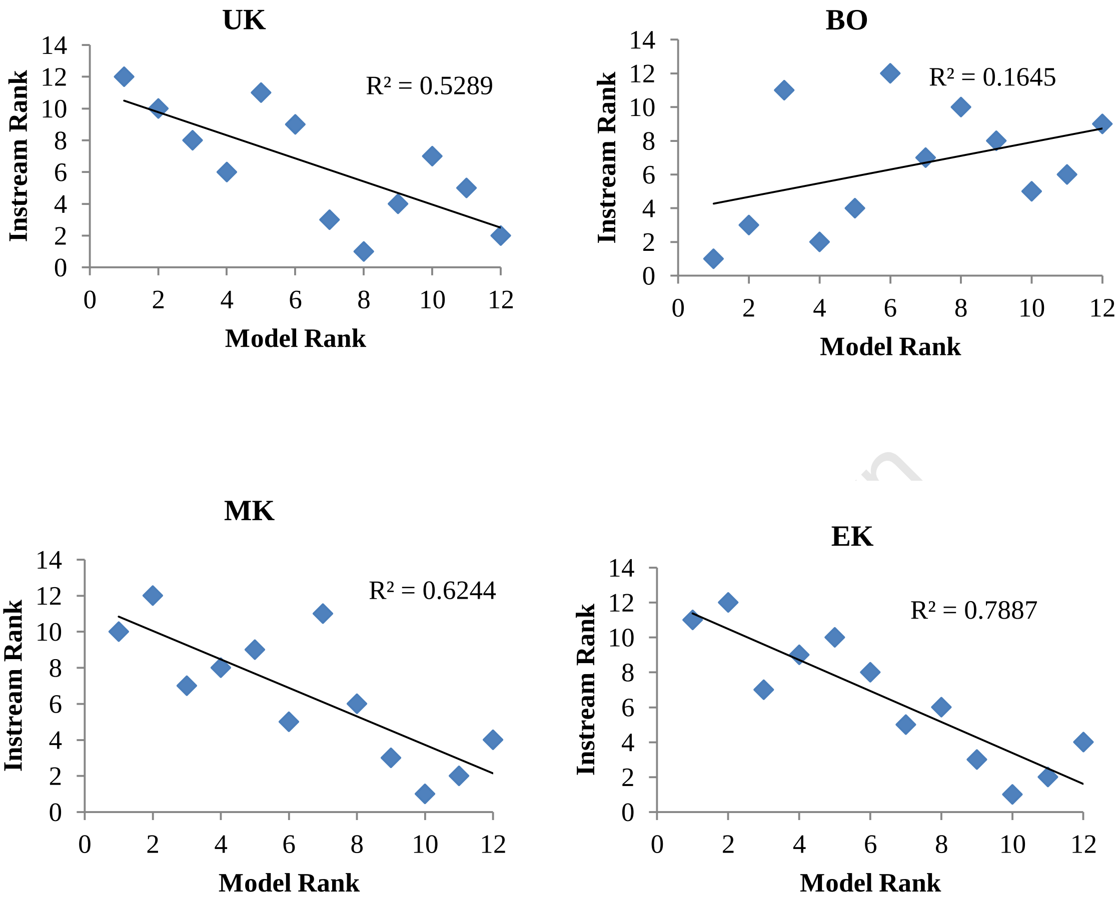


Figure 25 Graphical representations of the rank correlation between in-stream TP concentrations and model TP estimates

In an analysis of the TSS concentrations, the r_s values for the UK and MK sub-catchment demonstrated a very weak negative correlation (-0.1) and a weak positive correlation (0.459) respectively. Therefore the conclusion can be drawn that in-stream TSS concentrations in the UK and MK sub-catchments do not demonstrate a trend that is statistically correlated to the concentrations transported by runoff into rivers. An analysis of the TSS trends revealed a strong negative relationship between in-stream concentrations and the estimated concentrations in the EK sub-catchment (-0.63). A comparison of the trends in the MK sub-catchment also revealed a strong negative correlation (-0.74). The results for both these sub-catchments at $\alpha = 0.05$ were significant therefore we reject the null hypothesis which states that these two variables are independent. Therefore as the runoff concentrations for TSS increase in the EK and MK sub-catchment, the concentrations in-stream decrease. The results of this analysis, which has been outlined above, are given in Figure 26.

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TSS (mg/l)

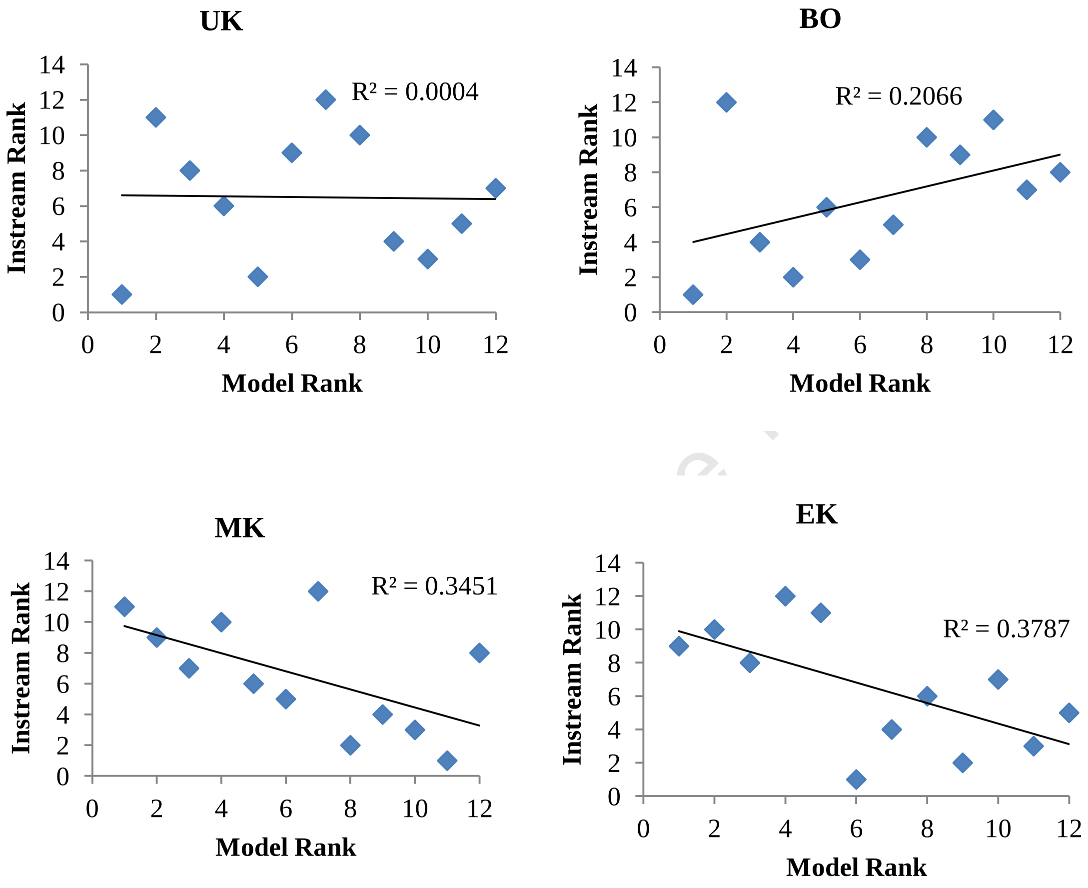

Figure 26 Graphical representations of the rank correlation between in-stream TSS concentrations and model TSS estimates

The trends observed from the correlation between in-stream loads and model estimates followed an inverse pattern for the UK, MK and EK sub-catchments. In the BO sub-catchment the trend was positively correlated with in-stream trends. The discharge from WWTW in the sub-catchments was then analysed using the same rank correlation technique to determine what influence point source pollution had on in-stream water quality trends and the associated implications of this for the validation approach used in this study. This comparison between WWTW and in-stream loads is discussed below.

4.3.1.2. Comparison between in-stream concentrations and WWTW

A comparison between in-stream concentrations and the observed concentrations from WWTWs revealed that for TP only the trends in the EK sub-catchment were correlated with the trends from WWTW. The EK sub-catchment has two WWTW centres (Zandvleit and Macassar). Each centre was compared individually against the in-stream concentrations. The former site had an r_s value of 0.65 whereas a comparison with Macassar revealed an r_s value of 0.67. These coefficient values were statistically significant $\alpha = 0.05$ therefore leading to the conclusion that there is a positive association between the concentrations observed from WWTWs in the EK sub-catchment and the in-stream TP concentrations.

The UK sub-catchment does not have a WWTW within its boundaries and therefore this sub-catchment was not included in this analysis. However concentrations from the BO and MK sub-catchments which have the Scottsdene and Bellville WWTW respectively were not significantly correlated with the observed in-stream concentrations. The r_s value in sub-catchment BO was -0.37 and in the MK this value was 0.53. Both of these r_s values did not statistically infer a strong relationship between the variables under examination. The correlation coefficients were confirmed by an examination of the critical values at $\alpha = 0.05$. As such it was not possible to reject the null hypothesis which states that the trends were independent.

TP (mg/l)

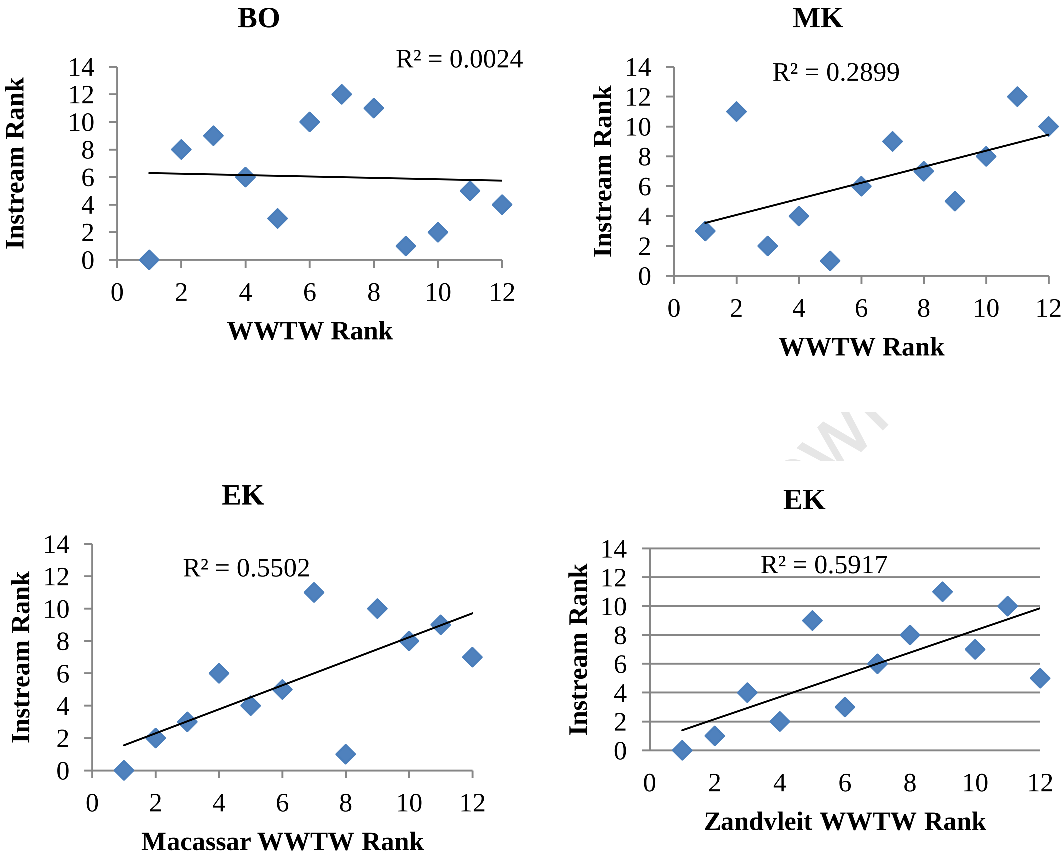

Figure 27 Graphical representations of the rank correlation between in-stream TP concentrations and TP observations from WWTW

A correlation between TSS concentrations in-stream and WWTW data correlated positively in the BO (r_s = 0.54) and EK (Macassar, r_s = 0.57) although these correlations were not ‘strong’. Weak negative correlations between in-stream and WWTW variables were observed in the MK and EK (r_s = -0.32 and Zandvleit, r_s = -0.47 respectively). The critical values associated with the correlation coefficients were significant at α = 0.05 therefore the null hypothesis which states that the two variables are independent could be rejected at this level of significance.

TSS (mg/l)

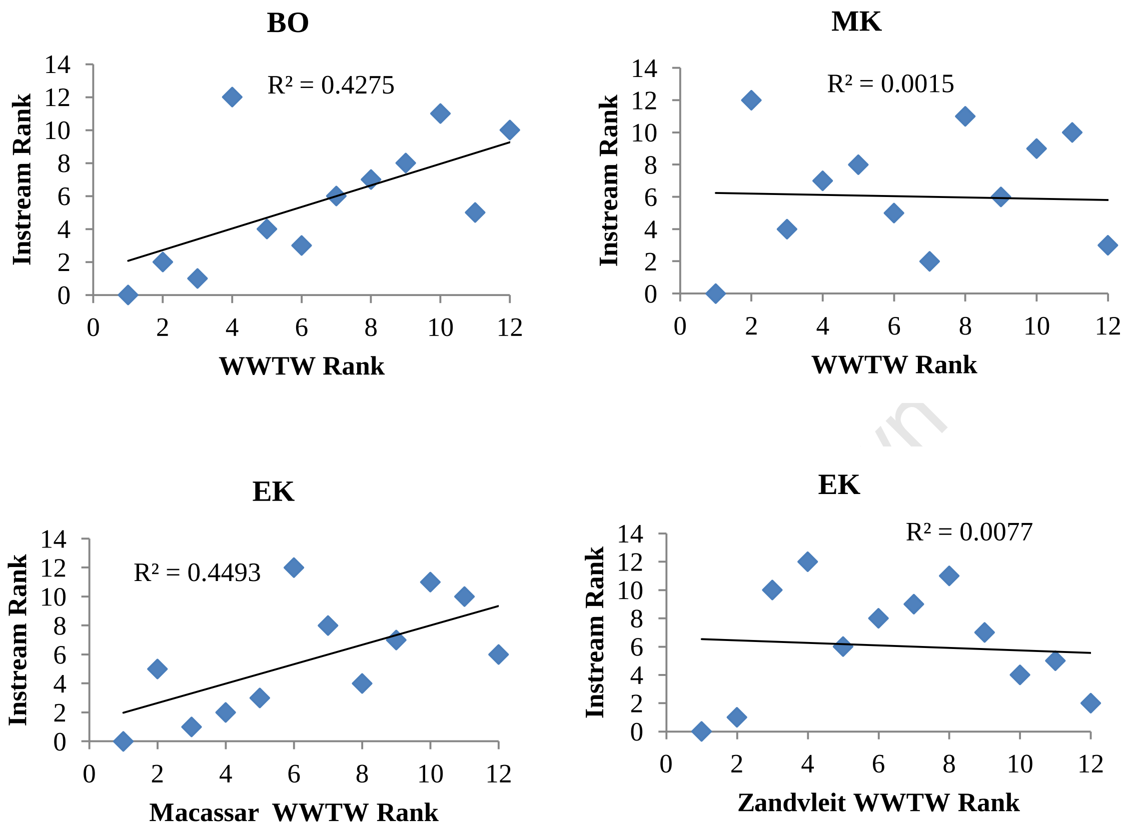

Figure 28 Graphical representations of the rank correlation between in-stream TSS concentrations and TSS observations from WWTW

An analysis of the association between in-stream pollutant trends and the trends in runoff showed that all, except for the BO sub-catchment, had a negative association for TP and TSS. Results for the BO sub-catchment could be influenced by dilution and dispersion. However this would need to be confirmed using precipitation data specific to each of the sub-catchment.

A correlation analysis of the trend from WWTWs and in-stream concentrations in the MK and EK sub-catchments showed a positive association. In the BO sub-catchment the association was weak with a negative correlation. This is explained by the analysis of in-stream and runoff trends which demonstrated a strong positive association with each other. An analysis of the BO and EK (Macassar) WWTWs showed a positive correlation with respect to the in-stream trends. In the MK and EK (Zandvleit) the observed trend showed a weak correlation. The finding implies that NPS runoff in the BO sub-catchment had a significant impact on the quality of receiving waters than the impact from PS pollution.

The statistical validation outlined above was imperfect because it could not be used to confirm the results of the modelling process. Only an association between the in-stream pollutant loads and the runoff pollutant loads could be determined. The validation approach was therefore not conclusive enough to confirm the model output. Since the aim of the study was to test the potential use of the PLOAD model it was important to compliment the effort to improving validation by eliciting the judgement of industry professionals on the potential use of PLOAD. The results of the qualitative assessment are discussed in Chapter 5.

4.4. TEST OF THE PLOAD MODEL DESIGN

In a research project (Young, 2006) that aimed to adapt an automated tool to assess PLOAD, the author found that the PLOAD model ignores relatively small areas of land during the simulation process. As a result, the estimations made using this model were lower than the results they obtained from the application of an automated version of the PLOAD model developed for their project. This account was the only one that identified a possible modelling error in PLOAD. Based on Young's review (2006), a similar approach to evaluating the PLOAD model was used to evaluate the model design in this study. The estimates from the PLOAD model were compared with the results of an automated model (PLOADcal) that was developed for comparison with the original model.

The PLOADcal model was written in visual basic to run the "simple method" algorithm for the Kuils River study. PLOADcal served as a calculator applying the same mathematical techniques as those used in PLOAD in order to make load calculations. The PLOADcal model estimates loads for each individual land use type and gives an output of the load in pounds for that particular land use. For a sub-catchment evaluation the total of the loads for each land use in the sub-catchment would equal the sub-catchment load.

An assessment of the PLOAD model estimates of loads in the Kuils catchment showed that the land area over which the model made load (or concentration) estimates was less than the known area of the catchments. Therefore it could be concluded that the PLOAD model was discounting areas of land use during the calculation of pollutant concentrations as was observed in the study by Young (2006). Table 5 illustrates a comparison between the calculations made using an uncalibrated PLOAD model and the uncalibrated PLOADcal model for each sub-catchment over the period of one year. The results show a slight discrepancy between the PLOAD and PLOADcal estimations. More specifically this comparison revealed that the areas that were discounted did not significantly affect load estimations at a sub-catchment scale. However at the land use level this discrepancy could result in major errors in the reporting of land use contribution to loads because evaluations of individual land uses would be at a fine scale compared to the scale of the available data.

Table 5 Comparison of PLOAD and PLOADcal model estimations

Sub-catchment	**PLOAD uncalibrated load estimate (kg/year)**		**PLOADcal uncalibrated load estimate (kg/year)**		**Percent difference**	
	TP	**TSS**	**TP**	**TSS**	**TP**	**TSS**
UK	1,066.40	134,046.07	1,067.21	141,181.58	0.08	5.1
BO	6,809.78	451,106.23	6,797.34	453,769.72	-0.18	0.59
MK	4,361.74	474,852.70	4,371.22	487,460.75	0.22	2.6
EK	1,267.80	159,868.18	1,273.08	169,272.24	0.4	5.5

Estimates of the percent difference between the two simulations of TP loads (Table 5) were below the 1% value. Therefore there was no significant difference between PLOAD and PLOADcal estimates for this parameter. In the four sub-catchments the percent difference in TP estimates ranged from 0.22 to0.4%. The percent difference in the BO sub-catchment was a negative value which was indicative that in the modelling instance for TP in the BO sub-catchment the PLOAD model overestimated the area of the BO sub-catchment.

Estimates of the percent difference between the two simulations of TSS loads (Table 5) were between 0.59 and 5.5%. The UK and EK sub-catchments exhibited the largest percentage difference (approximately 5%) between the PLOAD and PLOADcal estimates for TSS. The BO sub-catchment had the least observed difference (0.59%) while the MK sub-catchment had a 2.6% difference between model estimates.

The source of error associated with the estimates made by the PLOAD model is not known. It can only be assumed to be as a result of some error in the establishment of the intersection layer of catchment and land use shapefiles during modelling (Young, 2006). This might explain why the error percentages were different from one simulation to next and also different for load estimations on the same sub-catchment.

CHAPTER 5

Potential use of PLOAD for stormwater management in the CMA

5.0. INTRODUCTION

The PLOAD model has been used in number of international studies such as Syed and Jodoin (2006), and Reginato and Piechota (2004). These authors applied the PLOAD model in a study of the Black, Belle and Pine River Basins in Michigan and in a river basin in Miami. These studies recognised that the model has potential for assessing NPS pollution in urban runoff. In the Kuils River catchment, the model was applied to a scenario where data availability was a limiting factor. According to Ongley (1999) a common challenge in developing and developed countries is that water quality data is either badly recorded and stored or not monitored at all. The CMA is no exception and is one reason why it was decided to evaluate whether the PLOAD model would be a useful tool for stormwater management in the CMA.

The lack of historical data meant that the accuracy/reliability of the modelling results had to be tested using a combination of quantitative and qualitative techniques. The quantitative validation approach was discussed in Chapters 3 and 4 which outline the use of statistical comparisons of the model simulations against known data. The qualitative approach to model validation was conducted to achieve the third objective of the study. A survey was used to assess the perceptions of the use and function of PLOAD by professionals in stormwater management in the local authority.

The survey was designed to focus on the respondents' perceptions about the strengths and weaknesses of the PLOAD model (model evaluation) and the perceived value of the model output in informing decision making in stormwater management. In this chapter the responses from the survey will be discussed in line with the findings outlined in Chapter 4 and related literature.

5.1. STORMWATER MONITORING IN THE CMA

The City's stormwater by-law deals in part with the protection of stormwater systems from degradation or pollution. As such the stormwater policy was designed to support this by-law by improving the quality of stormwater runoff, controlling the quantity and rate of stormwater runoff, and encouraging natural ground water recharge. As noted in the literature review, NPS runoff is difficult to monitor. Traditional stormwater monitoring approaches, which involve field based analysis techniques, have several shortcomings in that they are time consuming and resource intensive. However data obtained from such projects is invaluable in guiding modelling processes. The advantage of models is that they can be used to predict pollutant trends which allows for a proactive approach to management.

The literature on storm water modelling suggests that models provide the best alternative to field based techniques for analysing complex resource problems. The City of Cape Town has used the Storm Water Management Model (SWMM) to model runoff quality and quantity. SWMM is a dynamic rainfall-runoff model that can be applied to single event or continuous simulation of runoff quality and quantity (Rossman *et al.,* 2005). The SWMM model is used to assess rainfall-runoff processes in selected sites in the CMA. As a complex model, SWMM requires intensive data sets on hydrology and flow in the catchment. This data are not available for all the catchments in the CMA. In this study several data sets had to be inferred from the literature in order to complete the input requirements. The application of the SWMM model whose data requirements are much more extensive than PLOAD imposes huge costs in the collection and compilation of data.

The PLOAD model used in this study was used to determine sources of high discharge. The results of the analysis of the Kuils River catchment identified the BO sub-catchment as a priority area for controlling TP pollutant concentrations in runoff. The other sub-catchments did not demonstrate pollutant discharge at a concentration that exceeded the associated discharge limits for TP and TSS. At a land use scale the impacts of informal land use, industrial and rural-agricultural land use was of concern in all the sub-catchments. The estimated TP and TSS concentrations from these land uses exceeded the discharge limits. The ability of the PLOAD model to assess land use contributions to pollutant loads was noted by several of the respondents. A land use analysis would enable the managers to "*determine* *which land uses to prioritise in the catchment"* (Respondent 2).The result obtained from the PLOAD model enables managers to identify areas of high discharge.

The main shortcoming of the study findings was that the PLOAD model output could not be validated because of a lack of empirical data that could be used for a comparison. According to Chandler (1994), the validity of any models result is directly related to the accuracy and variability of the information entered into the model programme and the way that the model is designed to manipulate that data.

The validation approach used in this study involved the use of a trend analysis to determine the association between estimates from the model and pollution impacts observed in-stream. The trends did not follow a pattern that could easily be determined. However, it was generally observed that if trends in runoff were strongly associated with trends in-stream, then there was a small association between WWTW trends and in-stream trends in the corresponding sub-catchment. The simple method provides estimates of pollutant loads generated by storm-flow and does not take into consideration factors such as baseflow or dry weather pollutant load generation in the catchment. Baseflow is the contribution of groundwater to the stream flow. According to the New York Department of Environmental Affairs (2001) baseflow usually constitutes only a small fraction of the total pollutant loads in runoff from urban areas and can be ignored at the site scale but may be significant at the catchment scale. Another example of a factor that may influence the association between pollutant loads in-stream and those in runoff is temperature. Temperature plays a role in processes associated with the breaking down of TP for use by aquatic organisms. The velocity of a river will also influence whether TSS remains in suspension or is deposited. These natural processes are not simulated by PLOAD and represent only a few of the explanations around variations in the degree of association between in-stream loads and the estimates made through modelling.

Another stormwater management goal is to determine the daily acceptable load limits in runoff. The CoCT stormwater policy does not highlight a need for TMDL development. Instead the policy highlights a need to reduce pollutant concentration of TP and TSS by 45% and 80% respectively. The participants in the survey suggested that the PLOAD model would be adequate to measure progress towards meeting certain targets. PLOAD can be used in the analysis of the percent of reduction in the pollutant loads.

The focus of stormwater management in the City according to a comment is on the implementation and monitoring of management strategies: "*the model confirms what we actually know regarding broad pollution sources so in that sense it is not 'new' information. What we actually need is practical ways of abating pollution*" (Respondent 1). Steps towards abatement could be achieved by prioritising and identifying where abatement measures could be implemented, e.g. informal housing, rural-agricultural and industrial land uses were identified as the priority land uses for management. Informal land use was highlighted by the participants as an important influence on water quality that requires further evaluation. "*Pollutant loading from informal settlements is one huge area of concern for us so possibly the model does assist with further illustrating and quantifying the extent of this problem"* (Respondent 1).

The first objective of this study was to demonstrate the use of the model to simulate and analyse the relationship between water quality (TP and TSS concentrations in runoff) and different land uses in the catchment. The PLOAD model was demonstrated as being adequate in simulating pollutant loads as outlined by the results described in Chapter 4 and the comments made by the survey respondents that will be elaborated on throughout this chapter.

5.2. MODEL EVALUATION

Model evaluation in this study refers to an assessment of the strengths and weaknesses of the model and the modelling processes as they relate to the study of the Kuils River catchment. This was informed by queries that were raised during the conceptualisation of the methods that would be used to address the aim of the study. One of the queries raised during the model selection process (described in Chapter 3) was whether PLOAD would make general assumptions about the study area since it was developed in the United States where the landscape differs markedly to that of the CMA. The literature suggested that the model would not bias the location in which it was applied (Endreny, 2002). This evaluation would help identify any possible errors associated with the models origin of development. The three areas that were considered in this evaluation process were the strengths and shortcomings associated with the model algorithms, data inputs and the model design.

5.2.1. Model algorithms

The simple method approach uses three algorithms, the first calculates the runoff coefficient and the runoff generated in the landscape and the final equation estimates the load as a product of runoff, area and the pollutant event mean concentrations. The equations simplify the complex relationships involved in rainfall-runoff processes. The equation applied in the calculation of runoff is a very basic mathematical description of the rainfall-runoff generation process. Runoff generated in the landscape is dependent on the soils, topography, impervious coverage and land use in an area. These values may not be consistent across a given land use type therefore there will always be some uncertainty associated with modelling processes because most models assume that variables remain constant across a given land use.

In recognition of the shortcomings that might be associated with Schueler's runoff equation, a calibration technique was used to compensate for errors made in the simplification of the runoff generation process. Without a reliable runoff data series from the Kuils River for calibration, a proxy site approach was used. The nearest site (Klein Welmoed) with monitored data on runoff volumes was used as a proxy site for calibration of the runoff equation. The use of a proxy site to calibrate the model was useful in one instance because it reduced the error associated with the modelling process. On the other hand it introduced a new level of complexity to the modelling process because a site had to be found that would exhibit the same characteristics as the Kuils River catchment. In this study, an evaluation of the percent difference between the observed and calculated runoff from Klein Welmoed showed a difference in values that ranged between 20.6% and 87.2% (percent values obtained by calculating percent difference values between observed and calculated runoff volume – see section 4.4). This variation shows a large discrepancy in percent difference values. This difference between observed and calculated runoff volumes is associated with the simplicity of the runoff calculation process in Equation 2. It can be concluded that the runoff calculation in PLOAD is not very precise and would therefore affect the reliability of the obtained results. The importance of the calibration process is demonstrated by these findings.

Simple models are often applied in situations that are limited by the availability of data and when calibration is not always conducted on these models. Comments made in the survey highlighted the importance of calibration and the reliability of data (Respondent 2 and 4). The participants acknowledged that stormwater modelling is based on 'crude' assumptions and processes but the value of a basic calibration technique, such as the one applied in this study, improved the reliability of results (Respondent 4).

The PLOAD equation (Equation 3), which was used to calculate the loads of the pollutants, could not be evaluated due to a lack of empirical data on loads in the catchment or any surrounding catchments. Equations (2) and (3) form part of Scheuler's (1987) method for pollutant estimation, has been used in studies by Reginato and Piechota (2004) and Syed and Jodoin (2006).

The algorithms in PLOAD were simple and the use of data that had so many uncertainties led to a reduced accuracy in the output from these equations. The algorithms used in PLOAD are very generic. The increased generality of the model reduces the model precision.

5.2.2. Data inputs

As noted in the earlier sections, the data obtained for this study was a limiting factor in the estimation of pollutant loads in runoff. Many of the data constraints influencing this project were discussed in the methodology chapter (Chapter 3) of this study. These included the lack of historical runoff data for model calibration, insufficient data on event mean concentrations and impervious land coverage. These data challenges have affected the quality of the results obtained from the modelling process but are not unique to this study.

The data applied in this study was very broad in that it was not specific for sub-catchments or land use types. Due to the size of the catchment and discrepancies in the way rainfall is recorded between sites, rainfall in one part of the catchment might differ from the amount of rainfall observed in another part. At the land use scale, the data used in analysis should preferably have been specific to that area. In the study however, the value of observed rainfall was kept constant for each sub-catchment because there were limited rainfall gauges available across different parts of the catchment. Similarly, in the calculation of the calibration factor, only one proxy site was used which resulted in a loss of accuracy because it had to be assumed "*that the correction factor determined by calibration is the same for all sub-catchments*" (Respondent 4).

The perception from one of the participants was the need for credible data to be used in modelling: "*...land use is a key component in modelling so if it [land use data] is outdated or not at a fine enough scale, then the resolution and accuracy of the model may be problematic. However use of models is always based on 'assumptions' and often associated with information gaps (otherwise we would not need models)*" (Respondent 1).

The role of detailed modelling tools like SWMM cannot be undervalued in stormwater management. However, the fact that simple models are less data intensive than more complex models should make them a more appropriate choice for use in broad assessments of diffuse water sources (Korfmacher, 1998).

5.2.3. Model design

The model design refers to how the model links spatial and non-spatial data together in order to estimate pollutant concentrations. The output generated by the PLOAD model was compared to an automated model created to run the same algorithms as PLOAD without the spatial component. It was found that the model would slightly overestimate or underestimate small areas of the catchment. The difference between the two values was less than five percent for each simulation. An evaluation of the cause of error requires a more detailed analysis than the scope of the study allowed.

The analysis of the model design is discussed in Section 4.4. A test of the model design revealed that the error made by the model was relatively insignificant. Although this demonstrated a weakness in the model design it was not significant enough to conclude that the model results where unreliable.

5.3. PERCEPTIONS OF THE USE OF THE PLOAD MODEL

The role of models in stormwater management has been met by different responses in the literature. Models are only representations of reality and cannot exactly depict the reality of the situations observed in the environment has resulted in some reservation concerning the use of models as monitoring tools. The potential role for models in reducing the time frames for data analysis and in reducing the cost associated with continuous field based monitoring are two positive aspects of using models that has been demonstrated by this study. The findings have also identified the priority issues in the management of stormwater pollutants.

One of the survey questions asked the respondents to identify what they perceived to be the capabilities and benefits of the PLOAD model. The following list summarises the comments made by all the respondents:

- *The model can be used for the assessment of pollutant loading from different areas within a catchment area.*
- *The model can be used for comparison of different strategies, e.g. source reduction or regional BMPs, to reduce pollutant loads (monthly or annual) discharging into receiving waters.*
- *The model can be used to spatially (GIS) depict pollutant loading from different areas.*
- *The model can be used to depict the influence of land use on runoff quality*

The use of the model in the above mentioned capacities highlights that practitioners acknowledge the potential role of models. This section seeks to discuss the respondent's perceptions on whether the above capabilities are suitable to stormwater monitoring objectives in the CoCT.

5.3.1. Assessment of pollutant loading from different areas within a catchment area

The model was applied to simulate pollutant generation from different areas. This is one of the objectives of stormwater monitoring. The participants suggested that the model was a useful for assessing pollutant loads from different management areas. In their response to question 5, simplicity and the minimal data requirements associated with the use of the model were factors that the participants highlighted positively. "*Subject to the limitations above, the model can be used as a crude planning tool for preparing (mainly distributed) pollution abatement plans at a catchment level... the ability for the model to indicate the relative contributions of pollutant loads for different sub-catchments would be of assistance in planning and prioritising regional runoff treatment facilities"* (Respondent 4).

The main issues that were highlighted through this survey were that there was an appreciation for the PLOAD model as a tool for broad pollution assessments; its simplicity and minimal data requirements meant that personnel not usually involved in modelling felt they could easily interpret and apply the model themselves. Despite these opinions there was still a general sense of "why use PLOAD when we have SWMM?" This was demonstrated in comments such as: "*the model is unlikely to yield reliable hydrological results when compared to a specialised model such as SWMM"* (Respondent 3). The SWMM model is more detailed than PLOAD but the data requirements for this model are significantly more extensive. After numerous efforts to obtain data for this study, the modelling exercise was constrained by a lack of reliable data. Respondent 3 did not have a strong modelling background but even those respondents who did were still hesitant about using a model like PLOAD which made numerous generalisations.

The survey did not seem to incite a keen interest from the participants. Of those participants who had modelling experience, none of them appeared to find more merit in the model than it being a simple tool whose capabilities were overshadowed by models such as SWMM. "*Whilst SWMM modelling of the pollutant wash-off process is equally crude in that it also uses EMCs or export coefficients, as a planning tool it would appear to have the following advantages over PLOAD:*

- *The runoff component can be far more reliably modelled and calibrated and impacts of changes in runoff better assessed;*
- *Continuous modelling will produce concentrations and loads during low-flows;*
- *Variables such as frequency of street sweeping can be introduced;*
- *It is the standard runoff modelling tool for Cape Town so it is natural that it be used for runoff quality as well."*

(Respondent 4)

5.3.2. Comparison of different management strategies

In the survey participants were asked what the perceived limitations of the model were and they highlighted the fact that the model was "*limited for more detailed planning"* (Respondent 3).The application of the model to evaluate complex catchments would therefore be questioned because of its limitation in detailed modelling. There was a sense from some of the comments that the PLOAD model did not seem to be able to achieve the same level of credibility as the SWMM model when applied to BMP evaluations.

Participants highlighted concerns about the accuracy of the model output. A comment made by one of the participants was that *"the pollutant loads calculated by the model are only* *indicative of what is potentially the spatial variation of pollutants over the catchment, because of the crudeness inherent in the model"* (Respondent 4). This suggested that there were concerns about the model output being misinterpreted because of its generality. The survey comment is in line with comments made by Korfmacher (1998) that there is a perception that complex models are more credible than simple model outputs.

5.3.3. Spatial (GIS) depiction of pollutants loading from different areas

The graphical display from the model was considered to be one of the strengths of the model. One of the participants commented that "*models generally can be inaccessible in terms of complexity and understanding to many people. It is helpful to have the spatial outputs as well as a string of numbers and graphs which probably also comprise much of the output"* (Respondent 1).Respondent 1 did not have a strong background in modelling. The study demonstrated the use of a model that was simple to understand and use. Therefore the graphical output would allow for information about the model to be conveyed and understood quicklyfor a user in the position of respondent 1. The graphical output also allows for decision makers to quickly pinpoint areas that should be prioritised in resource management.

5.3.4. Depiction of the influence of land use on runoff quality

Land uses such as informal settlements have been an area of concern for the stormwater management department (Respondent 1) because they have identified the potential impact of this land use in contributing to pollutant loads. Baker, (2003) identifies some reproducible trends from studies. One of the trends observed by Baker (2003) is that agricultural land use determines nutrient concentration in rivers. This statement supports findings made in this study that agricultural land use contributes to high pollutant loads. By linking land use to pollution generation the model should be able to guide resource managers in their prioritization of management areas. This ability to prioritise management areas was only indicated by two of the respondents. In one comment, Respondent 4 wrote: "*I consider the PLOAD model would be an adequate tool for many preliminary planning exercises."* Respondent 2 commented that "*the model will enable the CoCT to respond to the areas where the source of pollution takes place and as such prioritise valuable limited resources to address pollution management."*

The overall perspective from the resource managers was that the PLOAD model has several strengths and potential applications. However the respondents also felt that the model has several shortcomings that would deter them from using the model. These deterrents are however not a limitation of the PLOAD model design or the model process. Rather it is issues of data credibility and a general perception that the output from models is uncertain that limits the use of models.

Of those individuals that contributed comments to the survey, Respondents 1 and 3 had the least modelling experience. Both of these practitioners had positive perceptions of the application of the model. However Respondent 1 was more critical of the generalisations made by the model and the impact that data constraints had on the reliability of the modelling results demonstrated. Respondent 4, who had the greatest modelling experience of the group, did not demonstrate a strong sense that the PLOAD model would be used in the CoCT other than in basic screening or planning level assessments. The common opinion of the respondents is that the model has potential as a basic screening model and for guiding management priorities. However the simplicity (in terms of application and data constraints) of model was only appealing to those respondents who did not have a strong modelling background and therefore appreciated the simplicity associated with the model's application.

CHAPTER 6

Conclusions and Recommendations

6.1. INTRODUCTION

The aim of this project is to test the use of a model in simulating pollutant loads of total phosphorus (TP) and total suspended solids (TSS) in diffuse storm event runoff from urban land uses. This chapter will summarise the main finding associated with addressing the aim of the research. Firstly, each of the objectives will be discussed in context to show how they were achieved. These objectives are given in bold text. This will be followed by a section highlighting the main conclusions and finally a section which highlights the recommendations for future research studies.

Demonstrate the use of the model to simulate and analyse the relationship between water quality (TP and TSS concentrations in runoff) and different land uses in the catchment.

A comparison of the annual estimated TP and TSS concentrations in runoff revealed that the BO sub-catchment (0.12 mg/l) was the only sub-catchment that contributed to TP concentrations that exceeded the discharge quality guidelines for this pollutant (<0.1 mg/l). The TSS concentration generated in the sub-catchments did not exceed the discharge limit of 18mg/l outlined in the national discharge guidelines for water quality (DWAF, 1996). This finding indicates that the CoCT stormwater management policy that aims to reduce TP and TSS loads may not be channelled at the correct pollutants of concern in catchments. This generic focus on these pollutants may not be suitable for all catchments. A model like PLOAD would be a valuable tool in determining which pollutants to prioritise in individual catchments because the model can be applied very quickly and with minimal data availability. This type of information could guide the application of more detailed modelling analysis in the CMA.

The results of monthly load estimates revealed that pollutant concentrations were highest in the winter months and more specifically in the month of June. The BO sub-catchment was the study site with the highest estimated concentrations of TP whilst for TSS estimates both the BO and EK sub-catchments made significant contributions to the estimated loads. Therefore these sites represent areas that should be targeted for mitigation of pollution. The EMC values associated with the predominant land use types in this sub-catchment in conjunction with the location of the MK sub-catchment led to initial assumptions that this sub-catchment would demonstrate the highest loads of pollution generation.

An examination of the land use in these sub-catchments revealed that for TP concentrations, industrial and informal housing land uses generated the highest pollutant concentrations with rural agricultural land uses demonstrating significant contributions albeit lower than the former two land uses. Informal housing and industrial land uses were also found to generate the highest concentrations of TSS. These land uses present the key/priority land uses in the catchment in understanding the concentrations of a pollutant generated from different land use types. An estimation of the pollutant load generated in sub-catchments highlights which land uses to prioritise in management. In all of the sub-catchments except the EK sub-catchment, the highest loads for TSS and TP were from rural–agricultural land use which is in line with the initial expectation of the study. In the EK sub-catchment informal housing and undeveloped land generated the highest loads of TP and TSS respectively.

Assess the validity of the model results against known values

The results of the Spearman rank correlations reveal that the trends estimated for pollutant loads generated in sub-catchments are generally negatively associated with the trends observed in in-stream loads. In some cases the relationship between the two variables was very weak but it could not statistically be determined that the observed in-stream trends were independent from model estimates of loads in runoff. A rank correlation between in-stream concentrations and the concentrations discharged from WWTW revealed a similar weak correlation for most of the comparisons. However when the in-stream-WWTWs association was weak, there was a higher association between in-stream-model estimates. Therefore it can be concluded that high runoff pollutant loads contribute significantly to the poor water quality in rivers as do point sources of pollution.

The validation approach could not be used to prove the reliability of the model results but the trend analysis did provide useful insight into the importance of monitoring non point source pollution sources.

Elicit the judgement of industry professionals on the potential application of the model

The practitioners who were asked to respond to a survey on the PLOAD model had differing views on the potential application of the model. There were those who appreciated the simplicity associated with the model in terms of its data requirements, application and interpretation. These views were offered by those practitioners who had limited experience in the modelling. However this group of practitioners was also more critical of the impact the uncertainties associated with the data applied in this study. The more experienced practitioners highlighted concern over the generic nature of the modelling process in PLOAD. There was a feeling that the model would not be robust enough for stormwater monitoring in the CoCT. Overall both experienced and inexperienced practitioners noted the usefulness of the model in making broad screening assessments and guiding the prioritisation of key areas of concern.

6.2. CONCLUSIONS

The Kuils River was a suitable study site for the assessment of stormwater pollutant concentrations of total phosphorus and total suspended solids. Not only did the catchment exhibit a variety of land uses but the basic data requirements for the PLOAD model could be met through literature reviews, SAWS data files and through assistance from the City of Cape Town Stormwater Catchment Stormwater and Roads Department. The catchment was representative of many peri-urban catchments which demonstrate land use activities such as informal housing and rural- agricultural land use. Therefore the challenges experienced with data collection and modelling would be similar to the challenges that would be experienced when the model is applied in a different catchment within the CMA.

Based on the findings summarised earlier it can be concluded that the PLOAD model can be used to monitor catchments in the CMA where the goal is to obtain gross load estimates of pollutants from diffuse sources. Through identifying priority areas, limited resources can be channelled to areas where they can be most effective in minimising pollutant impacts.

The study also shows that even simple modelling in the Kuils River catchment cannot be conducted reliably because more effort needs to be directed at building data repositories on event mean concentration from different land use types in the catchment and runoff volume generated in catchments/sub-catchments from rainfall events. An analysis of the data used in the study revealed that the calibration factor and the rainfall data were generic over a large area and therefore there was a lot of error associated with the model output. Without credible data the role of PLOAD as a stormwater tool in CMA cannot be proven or disproved. What this study can demonstrate is that credible data is required for modelling to be successful in the metropolitan.

Simple models may not currently represent tools that can be applied across the board in catchments in Cape Town right now but it certainly can become a tool for the future. If data repositories can be developed now, then this information can be used to calibrate future stormwater quality simulations conducted using models. This conclusion is supported by comments made by survey respondents who acknowledged the potential of PLOAD as a tool to address stormwater management objectives even though they showed some reservation for the models application across the board. Once credible data is available the perceived contribution that a simple model like PLOAD can make to stormwater management in the CMA might become less contentious.

In evaluating the application of the PLOAD model in an urban South African catchment it was identified that the PLOAD model has several shortcomings. Firstly the model applies very simple equations in order to simulate pollutant loads. This may impact on the credibility of the model as demonstrated in the responses received to the survey. An additional weakness of the model lies in the fact that it does not have an in-built function for calibration. Calibration is considered a key process in modelling and the absence of which may lead to much scepticism about the model output. Finally, as the model was developed overseas, the operating system does not allow the user to input data in Standard International (SI) unit format nor does it allow for an output in SI units. These factors inhibit its use as a global model because more effort is required by the user in order to confidently apply the model or report on the model outputs.

6.3. RECOMMENDATIONS

It can be concluded that the practical application of the PLOAD model was adequately demonstrated through the obtained results. However the perceived applicability of the model by stormwater resource specialists was not as tangible. The specialists responded positively to the use of the model for stormwater assessments in the CMA however they raised several concerns around the model's reliability as a tool for stormwater analysis. Based on these results the following recommendations can be made for future research studies:

- Develop a systematic data collection method and then re-test the pollutant loads in runoff using PLOAD; and
- Conduct a comparison of pollutant load in runoff across several catchments.

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Survey respondents

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APPENDICES

Appendix A: 2009 Rainfall data for the Kuils River Catchment

Date 2009	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1	0	0	0	0	0.8	0	0	0	9.6	0	0	0
2	0	0	0	0	0	3	1.4	0	0.2	0	0	0
3	0	0	0	0.4	0	1.4	0	0	1.4	0	0	0
4	0	0	0	0	0	6	0	11	0.2	0	0	0
5	0	0	0	0.2	0	22.6	0	5.2	0	0	3.4	0
6	0	0	0	0	0.4	0.6	0.2	0.6	9.2	0	0	0.4
7	0	0.4	0	0	1.6	0	0	0	10	3.2	44	3.6
8	0.8	0	0	0	0	0	0	0	4.4	0	15.8	0
9	0	0	0	0	0	0	0	0	0	0	0.4	0
10	0	0	0	0	0	0	1.2	1.8	2.4	0	19.2	0
11	0	0	0	0	0	0	2.2	9.2	0	20.2	1.2	0
12	0	0	0	0	0	0	55.2	2.2	0.4	2.4	1	0
13	0	0	0	0	0	16.6	4.8	0	1	0	1.2	0
14	0	0	0	0	11.6	0	2	0	2	0.8	0	0
15	0	0	0	0	18.4	13	0.2	0.2	0	2.2	0	0
16	0	0	0	0	11.2	0	0	0	1.6	0	0	0
17	0	0	0	0.4	0	0	0	0	0.6	0	0	0.4
18	0	1.8	0	0	0.4	0	0	20.8	0.2	0	0	0
19	0	0.4	0	4.8	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0.4	0	0	0	0

Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Annual**
21	0.2	1	0	0	0	0	1.4	0.6	0	0	0	0	
22	0.2	0	0	0	0	7	1.6	0	0	0	0	0	
23	0	0	0	3.6	0	17.2	0	0	0	0	0	0	
24	0	0	0	0.4	0	19	0	0	0	0	0	0	
25	0	0	0	12.8	0	2	0	0	17	1.8	0	0	
26	0	0	0	0.2	0	0	0	0	0	0.6	0	0	
27	0.2	0	0.6	0	1.4	0	0	0	0	0.4	0	0	
28	0	0	0	0.2	13	0	0	0	0	0	0	0	
29	0		0	0.4	4.4	0	0	0	0	0	0	0	
30	0		0	0.6	0.8	0	3.2	0	0	0	0	0	
31	0		0		0.4		15	0		0		0	
Average	0.05	0.13	0.02	0.80	2.08	3.61	2.85	1.68	2.01	1.02	2.87	0.14	43.77
TOTAL (mm)	**1.4**	**3.6**	**0.6**	**24**	**64.4**	**108.4**	**88.4**	**52**	**60.2**	**31.6**	**86.2**	**4.4**	**525.20**
Inches	0.06	0.14	0.02	0.94	2.54	4.27	3.48	2.05	2.37	1.24	3.39	0.17	20.68

*Data was obtained from the South African Weather Service database at Cape Town International Airport data station (0021178A3)

Appendix B: Calculation of adjustment factors for purposes of calibration

An adjustment factor was calculated in section of the chapter on research methods. Firstly the runoff estimated by the PLOAD model was calculated manually. The calculation was based on Equation 2 of the simple method.

$$\mathbf{R = P^{*}\, P_j{}^{*}R_{vu}} \text{...} (1)$$

Where: R = Annual runoff; P= Annual rainfall; P_j= Fraction of annual rainfall events that produce runoff; R_{vu} = Runoff coefficient

Rainfall (m)			0.0008	0.0132	0.0006	0.0222	0.0642	0.054
	Rvu		**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
Airport	0.59	0.2	0.0000944	0.001558	0.0000708	0.00262	0.007576	0.006372
Commercial	0.77	0.2	0.0001232	0.002033	0.0000924	0.003419	0.009887	0.008316
Conservation and Nature areas	0.23	0.2	0.0000368	0.000607	0.0000276	0.001021	0.002953	0.002484
Education	0.59	0.2	0.0000944	0.001558	0.0000708	0.00262	0.007576	0.006372
Health services	0.5	0.2	0.00008	0.00132	0.00006	0.00222	0.00642	0.0054
Industrial	0.77	0.2	0.0001232	0.002033	0.0000924	0.003419	0.009887	0.008316
Informal housing	0.716	0.2	0.00011456	0.00189	0.00008592	0.003179	0.009193	0.007733
Institutional	0.59	0.2	0.0000944	0.001558	0.0000708	0.00262	0.007576	0.006372
Military	0.59	0.2	0.0000944	0.001558	0.0000708	0.00262	0.007576	0.006372
Mineral extraction	0.41	0.2	0.0000656	0.001082	0.0000492	0.00182	0.005264	0.004428
Public facilities	0.5	0.2	0.00008	0.00132	0.00006	0.00222	0.00642	0.0054
Residential	0.509	0.2	0.00008144	0.001344	0.00006108	0.00226	0.006536	0.005497
Rural and Agricultural	0.23	0.2	0.0000368	0.000607	0.0000276	0.001021	0.002953	0.002484
Undeveloped land	0.23	0.2	0.0000368	0.000607	0.0000276	0.001021	0.002953	0.002484
Urban open space	0.23	0.2	0.0000368	0.000607	0.0000276	0.001021	0.002953	0.002484
Total calculated runoff			**0.0011928**	**0.019681**	**0.0008946**	**0.0331**	**0.095722**	**0.080514**

Rainfall (m)			0.0818	0.0784	0.0558	0.015	0.0512	0.0068	
	Rvu		**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**annual**
Airport	0.59	0.2	0.0096524	0.009251	0.0065844	0.00177	0.006042	0.000802	0.061974
Commercial	0.77	0.2	0.0125972	0.012074	0.0085932	0.00231	0.007885	0.001047	0.080881
Conservation and Nature areas	0.23	0.2	0.0037628	0.003606	0.0025668	0.00069	0.002355	0.000313	0.024159
Education	0.59	0.2	0.0096524	0.009251	0.0065844	0.00177	0.006042	0.000802	0.061974
Health services	0.5	0.2	0.00818	0.00784	0.00558	0.0015	0.00512	0.00068	0.05252
Industrial	0.77	0.2	0.0125972	0.012074	0.0085932	0.00231	0.007885	0.001047	0.080881
Informal housing	0.716	0.2	0.01171376	0.011227	0.00799056	0.002148	0.007332	0.000974	0.075209
Institutional	0.59	0.2	0.0096524	0.009251	0.0065844	0.00177	0.006042	0.000802	0.061974
Military	0.59	0.2	0.0096524	0.009251	0.0065844	0.00177	0.006042	0.000802	0.061974
Mineral extraction	0.41	0.2	0.0067076	0.006429	0.0045756	0.00123	0.004198	0.000558	0.043066
Public facilities	0.5	0.2	0.00818	0.00784	0.00558	0.0015	0.00512	0.00068	0.05252
Residential	0.509	0.2	0.00832724	0.007981	0.00568044	0.001527	0.005212	0.000692	0.053465
Rural and Agricultural	0.23	0.2	0.0037628	0.003606	0.0025668	0.00069	0.002355	0.000313	0.024159
Undeveloped land	0.23	0.2	0.0037628	0.003606	0.0025668	0.00069	0.002355	0.000313	0.024159
Urban open space	0.23	0.2	0.0037628	0.003606	0.0025668	0.00069	0.002355	0.000313	0.024159
Total calculated runoff (m)			**0.1219638**	**0.116894**	**0.0831978**	**0.022365**	**0.076339**	**0.010139**	**0.783073**

Runoff monitoring data was obtained from the DWA for Klein Welmoed in 2009. These monthly values were divided by the calculated runoff values to obtain an adjustment factor. The adjustment factor was used in calibration of the model estimates outlined in the results chapter.

Month	**Runoff (ML/day)**		
	Observed	**Calculated**	**Af**
JAN	42.68	10.43	4.09
FEB	32.40	190.49	0.17
MAR	31.02	7.82	3.97
APR	41.21	299.01	0.14
MAY	155.43	836.80	0.19
JUN	695.69	727.31	0.96
JUL	494.64	1066.20	0.46
AUG	470.02	1021.88	0.46
SEPT	411.78	751.55	0.55
OCT	223.08	195.51	1.14
NOV	482.63	689.60	0.70
DEC	72.23	88.63	0.81

Appendix C: Monthly pollutant load estimates for sub-catchments

TP mg/l	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
UK	0.001	0.001	0.000	0.004	0.010	0.018	0.014	0.008	0.010	0.005	0.014	0.001
BO	0.002	0.001	0.001	0.001	0.006	0.025	0.019	0.018	0.015	0.008	0.018	0.003
MK	0.001	0.001	0.001	0.001	0.003	0.013	0.009	0.009	0.008	0.004	0.009	0.001
EK	0.001	0.001	0.001	0.001	0.003	0.013	0.010	0.009	0.008	0.004	0.009	0.001

TSS mg/l	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
UK	0.07	0.05	0.05	0.07	0.26	1.11	0.82	0.78	0.66	0.37	0.77	0.12
BO	0.11	0.07	0.08	0.10	0.39	1.69	1.24	1.18	1.00	0.56	1.17	0.18
MK	0.09	0.06	0.07	0.09	0.33	1.44	1.06	1.01	0.85	0.48	1.00	0.15
EK	0.11	0.08	0.08	0.10	0.41	1.76	1.29	1.23	1.04	0.58	1.22	0.19

Appendix E: Survey responses

The survey comments received from the respondents are given in this appendix. These include the questions and associated responses. Each survey included the following introduction:

This survey will be used in as part of the results obtained in a Masters project conducted at the University of Cape Town. The survey questions relate to the presentation that was included with this document. Please complete questions in the provided spaces.

The survey comprises seven questions and will take approximately 10minutes to complete.

Once you have completed the survey please email the completed document to the researcher at ratidzo.dhlembeu@uct.ac.za

Please complete and forward responses by 28 January 2011

If you have any further queries about the presentation or the survey you can contact Ratidzo Dhlembeu at 021 650 4857

Please note: Although the survey is designed to be non-controversial, all responses given to this survey will be kept anonymous and will not be linked back to the respondent.

RESPONDENT 1 SURVEY COMMENTS

1. In your experience in stormwater management, what modelling applications have you been exposed to using? If so, please name them.

Only PCSWMM indirectly – colleagues use it. I have no training or direct experience with it

2. If you responded by naming modelling applications in #1, please answer the following:
   How have these models been used by the City? For instance, are they operated with the City’s department or is the operation outsourced? Please give a brief response about each model.

PCSWM is used in a lot of projects that are undertaken for CSRM by consultants. Mostly hydrologically modelling, floodlines, sizing of stormwater systems etc. very little in terms of water quality modelling at this stage

3. The City of Cape Town stormwater management policy outlines a need to reduce the pollution load generated by various urban developments. Thus far pollutants Total Phosphorus (TP) and Total Suspended Solids (TSS) have been targeted for general reduction.

   Did the PLOAD module appear to be helpful in meeting the objectives of the stormwater management policy with respect to modelling TP and TSS loads? Please clarify further.

The policy focuses on water quality and quantity improvement measures that should be implemented in developments i.e. at a much smaller scale than the PLOAD model operates at. The model shows the broad catchment areas that are contributing P and TSS. I guess if land use data existed at a finer scale and the “catchment” was broken into much smaller units (down to the level of a large development site), then the model might be useful in predicting anticipated pollution that is likely to be generated on the site.

I have not really had much modelling experience so am not really sure if the above comment in valid or not…

4. From what you observed in the presentation, what do you consider to be the capabilities of PLOAD? Please list one or more.

Currently we do not have much information regarding flow rates so are unable to calculate pollutant loads. The model could therefore assist in providing an estimate of the seasonal or annual loading contributed by different areas.

5. What do you consider to be the major strengths of PLOAD?

Visual spatial illustrations – models generally can be inaccessible in terms of complexity and understanding to many people. It is helpful to have the spatial outputs as well as a string of numbers and graphs which probably also comprise much of the output

6. What do you consider to be the major limitations of PLOAD

The model uses units such as pounds, acres etc which is not helpful in SA (probably not a major problem though / could be overcome)

Scale – especially if it is being suggested as a model to help with policy implementation

7. What concerns if any do you have about the use of the model in estimating the runoff coefficient and pollutant loads?

Not sure if the model was able to account for the contribution of load from the major sewage works in the catchment? It is surprising that high load from the Bottelary catchment and the middle Kuils was identified as due to agriculture and informal settlements. Maybe I missed it being mentioned but the WWTW are also possibly major contributors?

8. The model attempts to link between land use and pollutant loading. How and why might this be helpful to present practices in the City, if at all? For example, would this perhaps help to prioritise management issues in the City's catchments?

The model confirms what we actually know regarding broad pollution sources so in that sense it is not "new" information. What we actually need is practical ways of abating pollution – not always possible and actually often very expensive.

Pollutant loading from informal settlements is one huge area of concern for us so possibly the model does assist with further illustrating and quantifying the extent of this problem

9. Please use this space to add further comment.

General comment and no criticism to you since I know how you struggled to get good input data from us!

The output of any model and the information and decision support derived from the output is only as good as the quality of info that is put in. Land use is a key component so if it is outdated or not at a fine enough scale, then the resolution and accuracy of the model may be problematic. However use of models is always based on 'assumptions' and often associated with information gaps (otherwise we would not need models). The key is to apply our minds to what the output is saying to make sure it leads to sensible decision making.

It might also be helpful to put the river in as a layer on top of the Land use so that the map makes more sense? Also show the location of the major point sources i.e. the WWTWs

RESPONDENT 2 SURVEY COMMENT
1. In your experience in stormwater management, what modelling applications have you been exposed to using? If so, please name them.
PCSWMM, EPA Stormwater Modelling and Hecras modelling software.
2. If you responded by naming modelling applications in #1, please answer the following: How have these models been used by the City? For instance, are they operated with the City's department or is the operation outsourced? Please give a brief response about each model.
Operation is mainly outsourced and is used to calculate flows for developments and pollution loading of development proposals.
3. The City of Cape Town stormwater management policy outlines a need to reduce the pollution load generated by various urban developments. Thus far pollutants Total Phosphorus (TP) and Total Suspended Solids (TSS) have been targeted for general reduction. Did the PLOAD module appear to be helpful in meeting the objectives of the stormwater management policy with respect to modelling TP and TSS loads? Please clarify further.
The PLOAD module appears to be helpful as it is able to determine the local pollution loads (per sub-catchment). As this exercise determines the NPS load, the model will enable the CCT to respond to the areas where the source of pollution takes place and as such prioritise valuable limited resources to address pollution management.
4. From what you observed in the presentation, what do you consider to be the capabilities of PLOAD? Please list one or more.
Ascertaining NPS loads in sub-catchments with limited data availability. Decision making tool.
5. What do you consider to be the major strengths of PLOAD?
Speed of determining NPS loads. Simple to use.
6. What do you consider to be the major limitations of PLOAD
Not being able to determine point source pollution loads.
7. What concerns if any do you have about the use of the model in estimating the runoff coefficient and pollutant loads?

How accurate is this model? Need to be compared with other work undertaken.
8. The model attempts to link between land use and pollutant loading. How and why might this be helpful to present practices in the City, if at all? For example, would this perhaps help to prioritise management issues in the City’s catchments?
Once the accuracy of the model has been confirmed, can the model be used to assist the City to prioritise management issues in the city’s catchments. For example, is addressing pollution due to farming activities more urgent than for informal settlement etc.
9. Please use this space to add further comment.

RESPONDENT 3 SURVEY COMMENTS
1. In your experience in stormwater management, what modelling applications have you been exposed to using? If so, please name them.
SWMM, Stormwater (Illudas)
2. If you responded by naming modelling applications in #1, please answer the following: How have these models been used by the City? For instance, are they operated with the City's department or is the operation outsourced? Please give a brief response about each model.
Operated on outsourced basis with limited in-house capability
3. The City of Cape Town stormwater management policy outlines a need to reduce the pollution load generated by various urban developments. Thus far pollutants Total Phosphorus (TP) and Total Suspended Solids (TSS) have been targeted for general reduction. Did the PLOAD module appear to be helpful in meeting the objectives of the stormwater management policy with respect to modelling TP and TSS loads? Please clarify further.
The model does depict the influence of land use well. It's use at a more detailed development level in designing treatment facilities was not demonstrated
4. From what you observed in the presentation, what do you consider to be the capabilities of PLOAD? Please list one or more.
See above
5. What do you consider to be the major strengths of PLOAD?
Gives an overall view of catchment contributors and would be useful in catchment planning related work (viz. formulation of management plans)
6. What do you consider to be the major limitations of PLOAD
Possibly not detailed enough for evaluation of stormwater BPM's
7. What concerns if any do you have about the use of the model in estimating the runoff coefficient and pollutant loads?

Cannot comment. The model is unlikely to yield reliable hydrological results when compared to a specialised model such as SWMM
8. The model attempts to link between land use and pollutant loading. How and why might this be helpful to present practices in the City, if at all? For example, would this perhaps help to prioritise management issues in the City’s catchments?
See 5 above
9. Please use this space to add further comment.
Well done. An interesting project.

RESPONDENT 4 SURVEY COMMENTS

1. In your experience in stormwater management, what modelling applications have you been exposed to using? If so, please name them.

PCSWMM

2. If you responded by naming modelling applications in #1, please answer the following:
   How have these models been used by the City? For instance, are they operated with the City's department or is the operation outsourced? Please give a brief response about each model.

All stormwater runoff modelling on behalf of the City is done using any SWMM-based software so that to ensure consistency in the modelling and data format.

3. The City of Cape Town stormwater management policy outlines a need to reduce the pollution load generated by various urban developments. Thus far pollutants Total Phosphorus (TP) and Total Suspended Solids (TSS) have been targeted for general reduction.

   Did the PLOAD module appear to be helpful in meeting the objectives of the stormwater management policy with respect to modelling TP and TSS loads? Please clarify further.

The CCT policy requires treatment runoff on the development site or at regional treatment facilities. PLOAD is appears to be more suited to planning of regional facilities, as used in the Kuils River.

4. From what you observed in the presentation, what do you consider to be the capabilities of PLOAD? Please list one or more.

Assessment of pollutant loading from different areas within a catchment area.
Comparison of different strategies, e.g. source reduction or regional BMPs, to reduce pollutant loads (monthly or annual) discharging into receiving waters.
Spatial (GIS) depiction of pollutants loading from different areas.
Graphical depiction of pollution loads either from various catchment areas or on a time scale.

5. What do you consider to be the major strengths of PLOAD?

Simplicity and minimal data requirements.
Ability to carry out coarse calibration.
GIS & graphical display- useful for presentations

6. What do you consider to be the major limitations of PLOAD

Limited for more detailed planning as it does not appear to be able to give any indication of area requirements for BMPs?

7. What concerns if any do you have about the use of the model in estimating the runoff coefficient and pollutant loads?

Calibration of the runoff coefficient is only as good as the available observed runoff data. Furthermore the calibration methodology applied in the Kuils River project, although sound, assumes that the correction factor determined by calibration is the same for all sub-catchments. However it is nevertheless better than no calibration and, given the crudeness of the assumptions and parameters as well as of the underlying method of the entire model, it can be considered acceptable.

It needs to be clearly understood that the pollutant loads calculated are only indicative of what is potentially the spatial variation of pollutants over the catchment, because of the crudeness inherent in the model as mentioned in the paragraph above.

8. The model attempts to link between land use and pollutant loading. How and why might this be helpful to present practices in the City, if at all? For example, would this perhaps help to prioritise management issues in the City's catchments?

Subject to the limitations above, the model can be used as a crude planning tool for preparing (mainly distributed) pollution abatement plans at a catchment level. Whilst I have used the word "crude" this is merely a reflection of the general state of the art in runoff quality modelling, particularly where there is a severe lack of observed data, as in SA and not a reflection on the PLOAD model. I consider the PLOAD model would be an adequate tool for many preliminary planning exercises.

Clearly the ability for the model to indicate the relative contributions of pollutant loads for different sub-catchments would be of assistance in planning and prioritising regional runoff treatment facilities but it is not clear to me how other measures such as low impact development (mentioned somewhere) is modelled.
Since the CCT policy only requires runoff treatment in terms of % reduction targets, the PLOAD model would be generally adequate. If TMDLs were a requirement, the reliability of the modelled results could be seriously questioned without adequate observed data for calibration.

Whilst SWMM modelling of the pollutant washoff process is equally crude in that it also uses EMCs or export coefficients, as a planning tool it would appear to have the following advantages over PLOAD:

- The runoff component can be far more reliably modelled and calibrated and impacts of changes in runoff better assessed;
- Continuous modelling will produce concentrations and loads during low-flows;
- Variables such as frequency of street sweeping (amongst others?) can be introduced;
- It is the standard runoff modelling tool for Cape Town so it is natural that it be used

for runoff quality as well.

9. Please use this space to add further comment.

Clarity on how “low impact development” is modelled would be of interest, as this is one of the planning scenarios currently being looked at for new development areas in Cape Town.

The Kuils River project described has me confused as “loads” are referred to in many of the results (e.g. the annual trends) but the units shown are those of “concentration” (i.e. mg/l)

The 5th respondent communicated their views in a short email. The relevant section of this correspondence is shown in the text below. Names of the respondents and any persons they referred to have been removed from the text.

I cannot add anything of value. Neither can I add to what "RESPONDENT 4" replied in the survey questions.

I would like to make the following observation: We know that the Kuils River is highly polluted ant that the situation is worsened with the dumping of huge quantities of sewerage into the Kuils River as a result of malfunctioning of the Bellville WWTW. It would be of value to have an understanding of water usage in the Kuils River and what the effect of the polluted water is. How much water is used for irrigation, stock farming, recreation and other uses. These are the questions that a Reserve Study of the Kuils River should resolve.

From your observations I recommend that you very briefly address the usage of water and potential consequences.