THE IMPACTS OF FUTURE URBAN GROWTH ON STREAMFLOW IN THE MGENI CATCHMENT

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ABSTRACT

Natural vegetation has been converted to land uses, such as agriculture, commercial forestry and urban use, to meet increasing human demands for food, fuel and shelter. These land use changes modify the surface conditions of an area, resulting in changes in hydrological responses. Urban land use, in particular, has a significant impact on catchment hydrology as a result of the increased impervious areas such as concrete, tar and roofs. To assess the future hydrological impacts of urban land use, the scale and location of future urban areas must be considered. The objective of this study was to assess the hydrological responses to future urban growth in the Mgeni catchment, South Africa. An urban growth model was used to generate scenarios of plausible future urban growth and these scenarios were modelled using a hydrological model to determine the hydrological responses to urban growth.

The plausible future urban growth in the Mgeni catchment was modelled using the SLEUTH Urban Growth model (SLEUTH). The SLEUTH acronym stands for the input layers required for the model *viz*. **S**lope, **L**and use, **E**xcluded areas, **U**rban Extent, **T**ransport routes and **H**illshade. SLEUTH is able to provide the scale and location of future urban growth required to assess the hydrological impacts of future urban growth. The data requirements and modelling procedure for SLEUTH is relatively simply and therefore it is well suited to a South African context. SLEUTH was calibrated and applied to the Mgeni catchment to project future urban land use. When assessing the 95-100% probability class, the results revealed that the Henley, Pietermaritzburg and Durban areas would experience the highest urban growth in the Mgeni catchment by the year 2050. The outputs of the SLEUTH Model for the Mgeni catchment showed a number of similarities to another application of SLEUTH in Cape Town. These similarities indicate the SLEUTH performs in a similar way for the two South African cities. Therefore, it was concluded that the SLEUTH Model is suitable to account for urban growth in the Mgeni catchment, as required for use in hydrological impact studies.

The hydrological responses to urban growth in the Mgeni catchment were assessed using the ACRU model. The scenarios of plausible future urban growth generated by SLEUTH were overlaid with current land cover layers to generate maps of plausible future urban land use. The results showed extensive urban growth of >95% probability occurring in the Midmar, Albert Falls, Henley, Pietermaritzburg, Table Mountain, Inanda and Durban Water Management Areas (WMAs) by 2050. Increases in mean annual streamflows were observed in many of these areas; however the Henley, Pietermaritzburg and Table Mountain WMAs were shown to have greater increases in mean annual streamflow than the other areas that showed similar increases in urban growth, thus indicating that these WMAs could be particularly responsive to urban growth in the future. Furthermore, the results showed that the type of urban land use is important in determining the hydrological responses of urban land use, as the imperviousness differs between the different urban land uses.

Streamflow responses were shown to be influenced by the scale and location of urban growth in the Mgeni catchment and specific areas, such as the WMAs along the Msunduzi River, were identified as potentially responsive to urban growth. Summer streamflows were indicated as being more responsive to urban land use changes than winter streamflows and increases in streamflows due to urban growth start to over-ride the impacts of other land uses which have substantial impacts on hydrological responses such as commercial forestry, and commercial sugarcane by 2050, whereas in other areas increases were mitigated by the presence of major dams. Lastly, it was shown that the type of urban land use, such as built up urban areas when compared to informal urban areas for example, have a significant impact on streamflow responses. These results are useful as they can be used to inform both water resources planning as well as urban planning to ensure that South Africa’s valuable water resources are protected.

DECLARATION 1 – PLAGIARISM

I, *Benjamin Alan Mauck*, declare that

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

(ii) this thesis has not been submitted for any degree or examination at any other university;

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

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Prof. Graham P.W. Jewitt

DECLARATION 2 – PUBLICATIONS

DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part of and/or include research presented in this thesis (including publications submitted and published, giving details of the contributions of each author to the research and writing of each publication):

Publication 1 – Chapter 2 of this thesis
Mauck, B.A. and Warburton, M.L. 2012. Mapping areas of future urban growth in the Mgeni catchment. *Submitted to the Journal of Environmental Planning and Management*.

The analysis for this publication was conducted by B.A. Mauck with technical advice from M.L. Warburton. The publication was written in its entirety by B.A. Mauck and all figures, tables and graphs were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding interpretation was provided by M.L. Warburton.

Publication 2 – Chapter 3 of this thesis
Mauck, B.A. and Warburton, M.L. 2012. The impact of future urban growth on streamflow in the Mgeni catchment. *Submitted to WaterSA.*

Hydrological model configuration was undertaken by M.L. Warburton, while urban growth scenarios were compiled by B.A. Mauck. Analysis of the output from the hydrological modelling for the various urban growth scenarios was conducted by B.A. Mauck with technical advice from M.L. Warburton. The publication was written in its entirety by B.A. Mauck and all figures, tables and graphs were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding interpretation was provided by M.L. Warburton.

PREFACE

The work described in this thesis was carried out in the School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg under the supervision of Dr Michele Warburton and Professor Graham Jewitt. These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any other tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

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1. INTRODUCTION

Over the past 50 to 60 years significant land cover and land use changes have occurred worldwide (Lambin *et al*., 2001; Tang *et al*., 2005) and these trends are set to continue into the future (DeFries and Eshleman, 2004). Natural vegetation has been converted to land uses, such as agriculture, commercial forestry and urban land use to meet increasing human demands (DeFries and Eshleman, 2004; Tang *et al*., 2005). Land use changes modify the surface conditions of an area, resulting in changes in hydrological responses (Falkenmark *et al*., 1999; Costa *et al*., 2003; Legesse *et al*., 2003; DeFries and Eshleman, 2004). Urban land use in particular, has significant ramifications on catchment hydrology, as a result of the increased impervious areas associated with urban land use (Jenerette and Potere, 2010). The hydrological impacts of urban land use are well-documented, with research being focused primarily on streamflow, stormflow and the surface runoff generated from urban land use (Leopold, 1968; Hollis, 1975; Hall, 1984; Shaw, 1994; Ward and Robinson, 2000). However, more recent studies of the impacts of urban land use on groundwater (Lerner, 2002; Younger, 2007), total evaporation (Praskievicz and Chang, 2009), and changes in the urban climate (Bornstein and Lin, 2000; Collier, 2006) have provided insight into the impacts of urban land use on the entire hydrological cycle. However, there is a need to estimate both the scale and location of future urban areas, to assess the likely future hydrological impacts to allow for future water resources planning.

Urbanisation is a global phenomenon that is occurring at a rapid rate, primarily due to natural population increases and migration to urban areas (Hill and Lindner, 2010; Mishra *et al*., 2010). Increased urban population results in increased urban land use, therefore increasing impervious areas, such as concrete, tar and roofs, which alter the catchment's hydrological response. In the following section, the effects of land use, and the changes thereof on catchment hydrology, will be addressed.

1.1 The Effects of Land Use on Hydrological Responses

To understand the hydrological impacts of land use change, the terms 'land use' and 'land cover' must also be understood. Land cover is defined by Schulze (2004, pg 86) as "the biophysical state of the Earth's surface and immediate subsurface in terms of broad categories, such as crop land, natural or man-made forest, grassland, settlements, water bodies or mining". Land use is the change or modification of land cover by humans, predominantly for the purposes of agriculture or settlement. Therefore, land use is the exploitation of land cover to meet various human requirements such as food, fuel and shelter (DeFries and Eshleman, 2004; Warburton, 2011).

The type of land use influences the hydrological response of a catchment, by the nature of vegetative cover, soil characteristics and the local micro-climate (Falkenmark *et al*., 1999). These characteristics of land use determine how rainfall is partitioned into the various components of the hydrological cycle such as interception, infiltration, total evaporation, surface runoff and groundwater recharge (Falkenmark *et al*., 1999; Costa *et al*., 2003; Schulze, 2004). The partition of rainfall generally occurs at three main points within a specific land use, *viz*. the vegetation, the soil surface, and the root zone (Figure 1.1). Firstly, rainfall is partitioned at the vegetation into interception, stemflow or throughfall. Intercepted water is water that is detained on the vegetation or leaf litter and is ultimately evaporated, contributing to total evaporation (Ward and Robinson, 2000). Stemflow and throughfall reach the soil surface and contribute to soil storage or runoff. The second partitioning of rainfall is found at the soil surface where water is partitioned into surface runoff or infiltration into the soil. The texture and structure of the soil determine which process, infiltration or runoff, will be favoured. The rate of runoff at the soil surface is governed by topographical features, such as slope (Falkenmark *et al*., 1999). The third partition is found at the root zone below the soil surface. The root characteristics of the vegetation determine the amount of transpiration and groundwater recharge. The partitioning of water is therefore a function of vegetation, soil as well as topography (Falkenmark *et al*., 1999). The way water is partitioned in a particular land use determines what the water balance or hydrological response of that land use will be. Any changes in land use will alter the partitioning of the water within the catchment thereby changing the water balance of the catchment. For example, an increase in evapotranspiration will likely be associated with a decrease in streamflow. Therefore, the hydrological responses of a catchment are dependent on land use and are sensitive to land use changes (Costa *et al.*, 2003; Warburton *et al*., 2010).

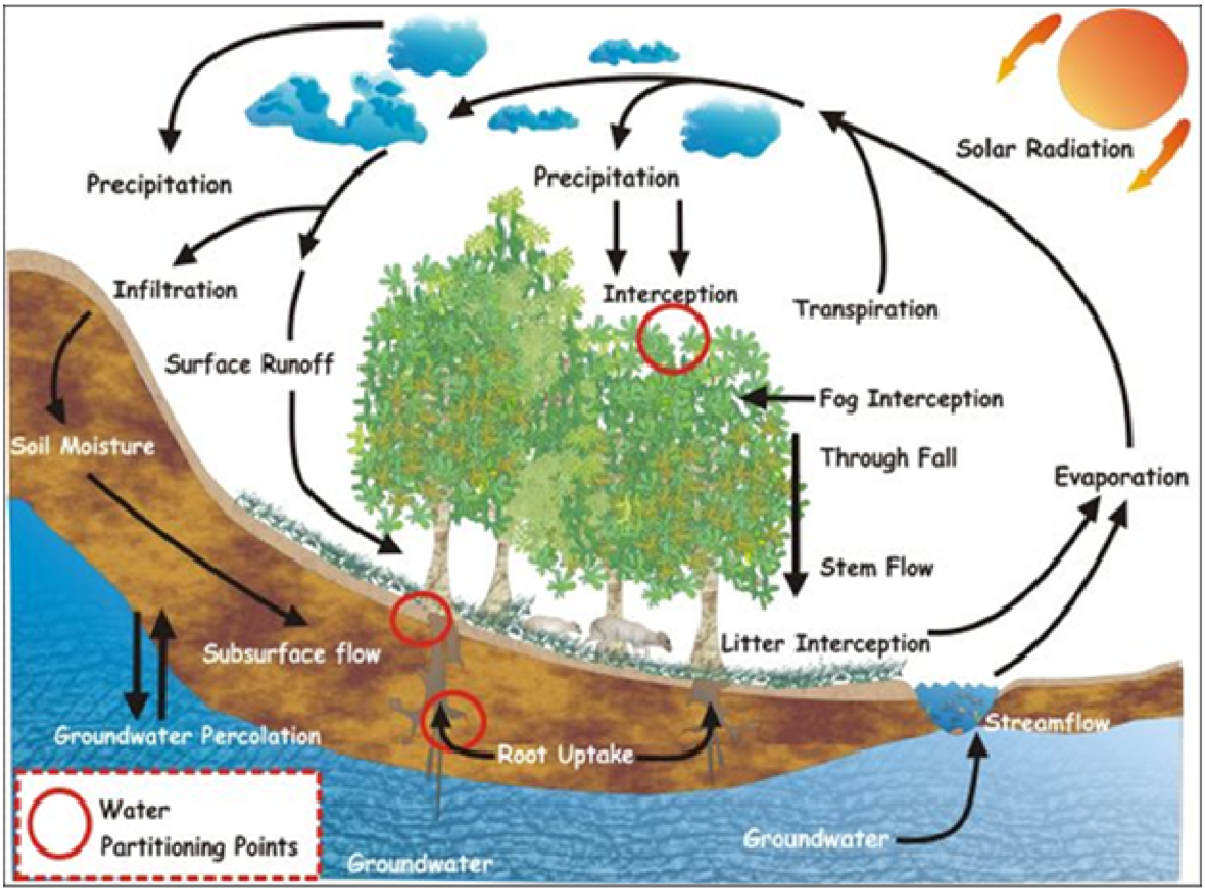

Figure 1.1 The hydrological cycle is partitioned at the vegetation, soil surface, and the root zone, as indicated by those areas circled (Jewitt, 2005)

Land use change is dynamic, occurring at a range of scales and locations (Castilla and Hay, 2007). Firstly, the scale of land use modification varies. This refers to the areal extent of the land use change; the greater the area covered by the modification the greater the hydrological impact. The degree of modification of the land use change adds an additional layer of complexity. Schulze (2004) reviews four land use categories that describe the degree of land use modification from a pristine state, in terms of the hydrological response, *viz*.:

- conserved ecosystem, where there is no change from the original, pristine environment, hence there is no alteration of the natural hydrological response,
- utilised systems, where the pristine system is being utilised, or the natural resources are being consumed; examples of this include non-plantation forestry, pastoralism and recreation. The utilised system has a negligible impact on the hydrology of the area,

- replaced ecosystems are where an ecosystem has been replaced by a simpler, less biologically-diverse ecosystem. Agriculture and exotic forestry are examples of replaced ecosystems, and
- completely replaced ecosystems, describe areas where the pristine ecosystem has been completely removed, for example, by urbanisation or mining.

Where pristine ecosystems are replaced, to some degree or completely, by a simpler ecosystem, significant changes in catchment hydrology occur in terms of water quantity and quality. The conversion to urban land use is one such land use change that is associated with the complete replacement of the pristine ecosystem with a simpler ecosystem. The hydrological impacts of urban land use will be described in the next section.

1.2 The Impact of Urban Land Use on Hydrological Response

As described by Schulze (2004), a land use or land cover change to urban land use is associated with the complete replacement of the natural ecosystem; it therefore has one of the greatest impacts on the hydrological responses within a catchment. Urban land use modifies the hydrological cycle by altering the partitioning of rainfall through the replacement of vegetative cover with impervious surfaces such as concrete, tar and roofs, which are known to impede the infiltration of rainfall resulting in elevated surface runoff and streamflows (Ward and Robinson, 2000; Rose and Peters, 2001; Marsalek *et al*., 2006). The impacts of urban land use, as a result changes in the partitioning of rainfall, are also evident in other components of the hydrological cycle such as total evaporation, interception and groundwater recharge.

Total evaporation is an important factor in the hydrological cycle, particularly for a semi-arid country such as South Africa (Schulze, 1997). The amount of total evaporation, in part, determines the amount of water contributed to streamflow. Lower levels of total evaporation are associated with greater levels of streamflow generation and *vice versa* (Praskievicz and Chang, 2009). In terms of the urban environment, water is rapidly removed from the ground surface, resulting in less water available for evaporation (Mitchell *et al*., 2001; Boggs and Sun, 2011), hence the total evaporation in urban areas is reduced in comparison to natural land covers.

Interception is the temporary storage of rainfall on the surface of the leaves and stems of plants and on the soil surface (Ward and Robinson, 2000) or on artificial surfaces such as roads, roofs and buildings in urban areas (Gash *et al.*, 2008). Interception storage in urban areas is reduced due to the replacement of vegetation with impervious surfaces (Marsalek *et al.*, 2006). The amount of interception storage on impermeable surfaces is considered to be negligible, hence this is excluded from most calculations concerning the urban hydrological cycle (Marsalek *et al.*, 2006). Since there is an insignificant amount of interception storage in the urban environment due to increased runoff, more water is available for streamflow contributions.

In terms of groundwater in the urban environment, the effects of urban land use are difficult to define as they are often site-specific (Younger, 2007). In general, because of increased impervious area, less water is able to penetrate into the soil and percolate down to the water table (Rose and Peters, 2000). However, the effects of impervious areas can be counteracted by recharge as a result of leaking sewerage and water supply lines, over-irrigation of parks and gardens and free-standing water containment areas (Lerner, 2002). Recharge via leaking water mains and sewerage lines are a common occurrence (Younger, 2007). In 2004, the eThekwini Water and Sanitation Unit published a water services development plan which stated that 30% of the water supplied to Durban (280 000 mega litres) was unaccounted for due to leakages (eThekwini Municipality, 2004). In addition to this, many urban areas are supplied from neighbouring catchments, thus there is additional water in the system available for groundwater recharge (Younger, 2007). Due to these factors groundwater recharge can be significant in urban areas.

The changes in hydrological processes of evaporation, interception and groundwater recharge as a result of urban land use generally allow for greater contributions to streamflow generation. Streamflow is the flow of water in rivers or streams (Fang, 2005) and is generated from both surface and subsurface flows in the form of surface runoff and baseflow (ASCE, 1996). As discussed before, urban areas are constructed with relatively impervious surfaces, which all impede infiltration and increase the rate of surface runoff (Ward and Robinson, 2000; Rose and Peters, 2001). Piped drainage and stormflow systems aid the rapid removal of water from impervious surfaces in urban areas, which is important for the management and control of stormwater, but ultimately results in greater flood potential downstream. The rapid transfer of stormwater to rivers or streams causes stormwater to accumulate rapidly, and this can cause downstream flooding (Ward and Robinson, 2000; Rose and Peters, 2001). Streamflow within the urban environment can also be increased due to the installation of artificial water courses, such as canals. These water courses are impervious and restrict seepage to groundwater, resulting in reduced groundwater recharge and increased streamflow. The artificial surfaces have little friction to counteract the rate of flow in the channel, causing a reduced time-to-peak and increased magnitude of stormflow (Marsalek *et al.*, 2006). Additionally, streamflows can also be increased by water that has been transferred into the system from another catchment for potable and non-potable purposes (Marsalek *et al.*, 2006). The dynamics of the relationship between urban land use and streamflow will be discussed in the following section.

1.3 The Dynamics of Hydrological Responses to Urban Land Use

When considering land use change and its subsequent hydrological impacts, the previous land use condition needs to be known before analysing scenarios of future land use (Quilbé *et al.*, 2008). The magnitude of change from a previous land use or land cover to urban land use, determines the magnitude of change in the hydrological response (Ward and Robinson, 2000). For example, where the preceding vegetation was forest, the conversion to urban land use would have a greater hydrological response than the change from a grassland land cover to urban land use. This is due to the different physiological characteristics of each vegetation type, where the forest would have higher levels of interception and total evaporation than a grassland land cover (Falkenmark *et al.*, 1999). Therefore, the magnitude of the hydrological responses to different vegetation and soil changes needs to be understood when studying urban land use change (Ward and Robinson, 2000).

The size of the catchment also has an impact on the relationship between streamflow response and land use change. For instance, in large catchments the conversion of rainfall into streamflow is generally more complex due to greater variation in catchment properties, such as soils, underlying geology and land use (Ashagrie *et al.*, 2006). Blöschl *et al.* (2007) developed a generalised theory that, due to land use being a local occurrence, any impact as a result of land use change is likely to decrease with increasing catchment size (Figure 1.2). Peel (2009) confirms this, suggesting that the effects of climate are dominant at larger spatial

(>1000 km^2) and temporal scales, while land use is dominant at smaller spatial (<1000 km^2) and temporal scales, in terms of streamflow response.

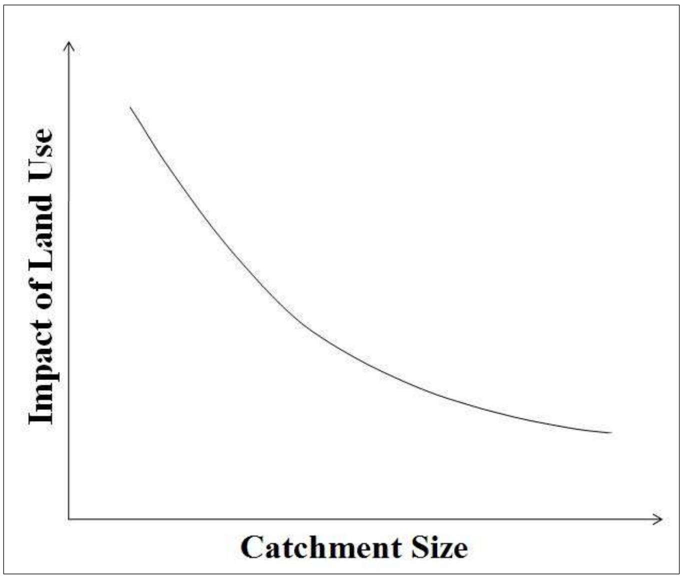

Figure 1.2 Generalised relationship between the impact of land use change on hydrological response at different catchment sizes (after Blöschl *et al*., 2007)

The streamflow generated in the catchment is also dependant on the location of impervious areas within the catchment (Mejía and Moglen, 2009; Mejía and Moglen, 2010). Many studies have proven than with increasing levels of urban land use within a catchment, the greater the hydrological response of the catchment (Rose and Peters, 2000; Chang, 2007; Choi and Deal, 2008; Mejía and Moglen, 2010; Boggs and Sun, 2011). However, studies describing the spatial distribution of impervious areas within a catchment and the resultant impacts on catchment hydrology are limited (Mejía and Moglen, 2010). Mejía and Moglen (2010) simulated four different spatial distributions of impervious areas in the Northwest Branch Anacostia River Catchment in Maryland State, USA. The four spatial distributions, as shown in Figure 1.3, were:

1) a current scenario with 17% of the catchment impervious/urban (Figure 1.3A),
2) a channel clustering scenario (Figure 1.3B),
3) a source clustering Scenario (Figure 1.3C), and lastly,
4) a uniform distribution scenario (Figure 1.3D).

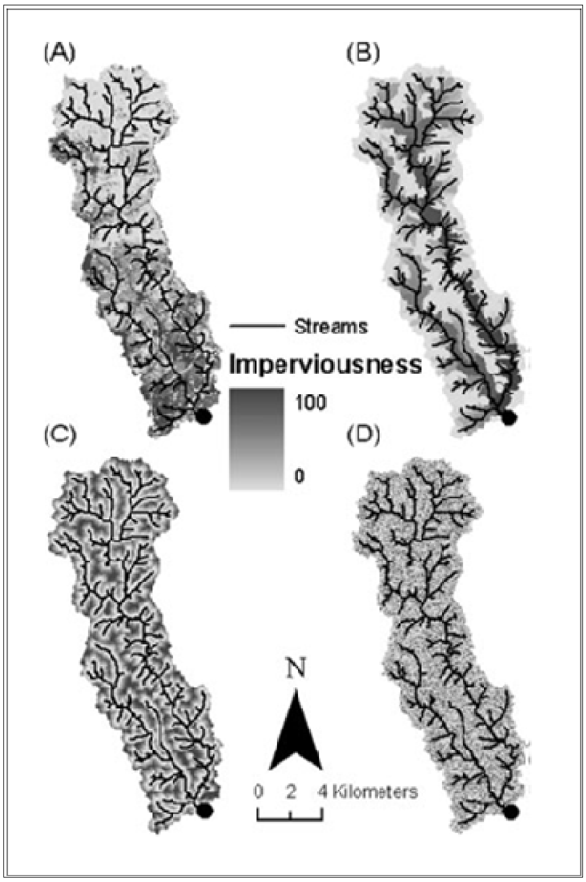

Figure 1.3 The different spatial distributions of impervious/urban areas within the Northwest Branch Anacostia River Catchment, where: (A) is the current scenario, (B) is the channel clustering scenario, (C) is the source clustering scenario, and (D) is the uniform distribution scenario (Mejía and Moglen, 2010)

Channel clustering is a scenario where the urban areas are clustered around the stream channels. Source clustering is a scenario where the impervious areas are located at the source of runoff generation. In the four scenarios only the spatial distribution of impervious/urban areas is changed, with the total of 17% impervious area in the current scenario remaining constant. The results indicated that the peak streamflow increased by 18% for the channel clustering scenario and 30% for the source clustering scenario when compared to the current scenario. This suggests that the effect of impervious areas located near the source streamflow generation, has 12% greater impact on streamflow generation when compared to those impervious areas in close proximity to the channels in this catchment. The uniform distribution scenario resulted in a 27% increase in the peak flow, which is only 3% less than the source clustering scenario. The uniform distribution scenario is an illustration of the likely streamflow from an extreme case of urban sprawl (Mejía and Moglen, 2010). It can therefore be said that the uncontrolled, unorganised sprawling urban land use can result in significant changes almost as high as the source clustering scenario.

The distance of urban areas from the outlet of a catchment is also an aspect that effects streamflow generation. A change to urban land use in the headwaters of the catchment tends to result in increased peak discharges. This is due to the fact that the headwaters are responsible for much of the runoff generation in a catchment, thus an increase in imperviousness as a result of urbanisation in these areas would decrease the lag time of a larger portion of the catchment's water (Beighley *et al*., 2003). Consequently urbanisation at the outlet would have a less significant impact on streamflow. Therefore, it is important to consider the location, scale and the degree of modification of a particular land use to understand the related hydrological impacts.

1.4 Research Objectives and Approach to Urban Growth and Hydrological Modelling

Ideally, the measurement of impact of land use changes on streamflow would best be achieved by using observed streamflow measurements throughout the period of change. However, the measurement of the impact of changes in land use conditions on streamflow requires lengthy datasets which are difficult to source and require many years of data collection. Thus, the modelling approach is often the preferred method to determining the impacts of land use change on catchments hydrological responses (Lin *et al*., 2008).

Modelling is a useful tool in the study of land use change and its hydrological impacts (Schulze, 2004; Praskievicz and Chang, 2009; McColl and Aggett, 2007). Modelling aids the prediction of present and future behaviour of a system and it allows for the testing of hypotheses and 'cause and effect' scenarios. Models can be useful in providing information for decision making by aiding the understanding and transfer of knowledge through the simplification of real-world systems (Schulze, 2004).

Projecting future urban growth through the use of an urban growth model is an essential tool to gain insight into the possible scale and location of future urban growth (Silva and Clarke, 2002). The hydrological response of a catchment to future urban land use scenarios can then be determined using a hydrological model. This can be achieved by using the simulated future urban land use to update the land use information in a hydrological model. The use of an urban growth model is preferred to merely applying a scenario approach of increasing urban areas by incremental amounts, as the spatial location and pattern of urban growth may be an important factor in the catchment's hydrological response to growth and is more accurate as urban growth is limited by factors such as slope and areas that have already been urbanised. The urban growth model selected for this study was the SLEUTH Urban Growth Model (Clarke *et al.*, 1996) and the hydrological model was the ACRU Agrohydrological Model (ACRU) (Schulze, 1995).

The Mgeni Catchment in KwaZulu-Natal, South Africa is the location for the study. Given the current and projected growth of urban areas in the Mgeni catchment, together with an understanding of the significant impacts of urban areas on streamflow, the objectives of this study are:

1) to model plausible future urban growth in the Mgeni catchment using the SLEUTH Urban Growth Model, to acquire the necessary scale and location of future urban growth in the Mgeni catchment for use in hydrological impact assessments,
2) to model the changes in streamflow responses within the Mgeni catchment under future projections of urban growth, and
3) to improve the understanding of the dynamics of the relationship between urban land use and streamflow in the Mgeni catchment in order to allow for improved water resources and land use planning.

The method used to achieve these objectives was to map predicted future urban growth for the Mgeni catchment and to quantify the resultant changes in streamflow. The approach of this method is shown in Figure 1.4.

The first step in the methodology was to model future urban growth in the Mgeni catchment using a suitable urban growth model (Chapter 2). The SLEUTH Urban Growth model was able to provide the scale and location of plausible future urban growth required to assess hydrological responses. The next step was to model the hydrological responses of the plausible future urban growth scenarios for the Mgeni catchment, generated by the SLEUTH Urban Growth Model, using the ACRU model (Chapter 3). This highlighted various areas in the Mgeni catchment that are likely to show significant hydrological responses to future urban growth.

Following the approach now accepted by the University of KwaZulu-Natal, this dissertation is structured such that findings of the research are written as a series of research papers for publication in peer reviewed journals. A literature review relevant to the specific step in the methodology being covered is provided in each research paper. As outlined in the University of KwaZulu-Natal's dissertation guidelines the referencing style for each of the research papers adheres to the journal to which the paper has been submitted.

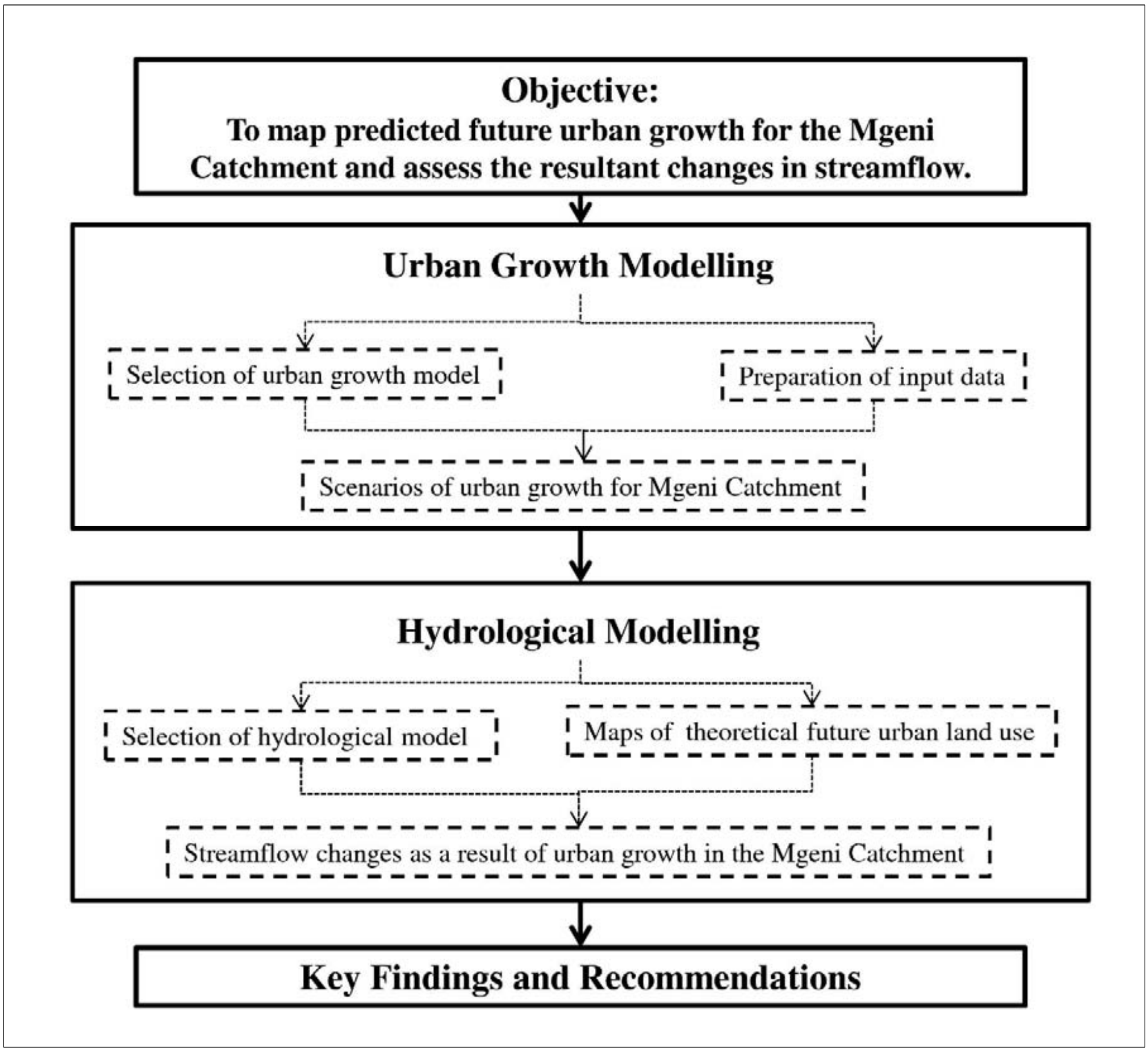

Figure 1.4 The approach of this research and the processes taken to meet the required objectives

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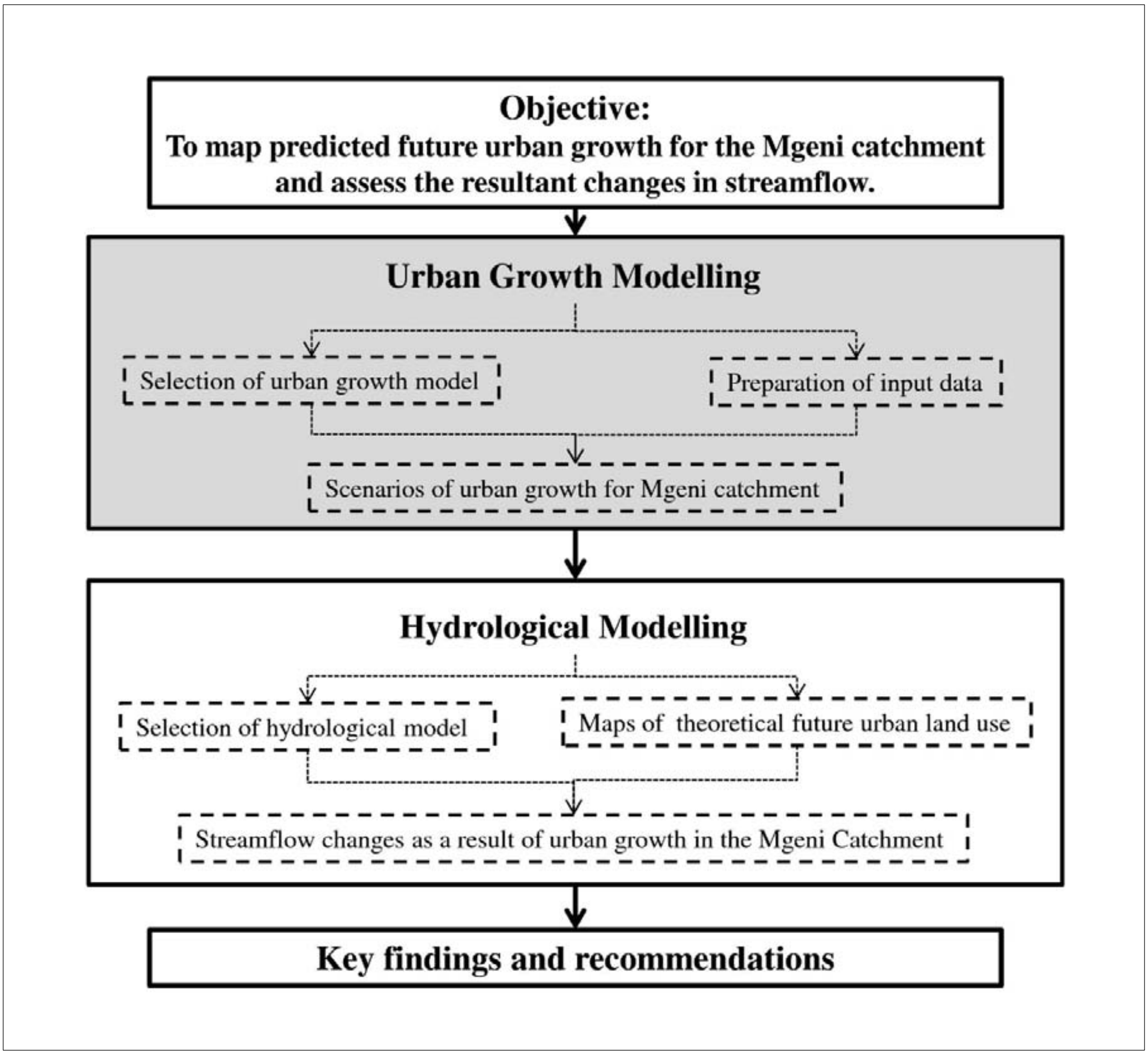
Lead in to Chapter 2

Chapter 2 focuses on the urban growth modelling in the Mgeni catchment. The SLEUTH Urban Growth Model was selected and used to fulfil the objectives of this study by providing scale and location of future urban growth as required for hydrological impact studies.



2. MAPPING AREAS OF FUTURE URBAN GROWTH IN THE MGENI CATCHMENT[1]

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Abstract

Due to increases in population and migration to cities, the areas of urban land use are increasing. This study models the plausible future urban growth in the Mgeni catchment in KwaZulu-Natal, South Africa, using the SLEUTH Urban Growth model (SLEUTH). The SLEUTH acronym stands for the input layers required for the model *viz*. **S**lope, **L**and use, **E**xcluded areas, **U**rban Extent, **T**ransport routes and **H**illshade. The purpose of this study was to predict the scale and location of future urban growth, for use in hydrological impact assessment studies. SLEUTH was calibrated and applied to the Mgeni catchment to project future urban areas. The results revealed, when assessing the highest probability class, that the areas already urbanised, would experience the highest urban growth in the Mgeni catchment by the year 2050. It was concluded that the SLEUTH Model is suitable to account for the scale and location of future urban growth in the Mgeni catchment.

Keywords: Urbanisation; Land use change; SLEUTH Urban Growth Model; South Africa

2.1 Introduction

South Africa is a country that has a complex political past, based on the segregation of people because of their race (Parnell and Mabin, 1995). This past is inextricably linked to the structure and rate of growth of urban areas in South Africa (Christopher, 1987; Davis, 1981; Seekings, 2000). The segregation of the South African people is rooted in colonial times, where cities were segregated based on economic and racial class (Christopher, 1987). The

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[1] Mauck, B.A. and Warburton, M.L. 2012. Mapping areas of future urban growth in the Mgeni catchment. Submitted to the *Journal of Environmental Planning and Management*.

*Referencing adheres to format of the *Journal of Environmental Planning and Management*

Group Areas Act of 1950, which focused on racial segregation, was introduced from 1948 onwards and divided urban areas into: ‘White’, ‘Coloured’, ‘Indian’ and ‘African’ (Seekings, 2000). It made use of ‘Influx Control’, where African people had to have a ‘pass’ to enter certain areas, thus controlling where they could work and live. African people were also made to live in ‘Bantustans’ or ‘homelands’, which served to restrict populations in major cities. Thus, the urban populations in the homelands grew rapidly resulting in sprawling informal settlements. In the mid-1980s, the ‘township uprising’ saw an increase in informal settlements developing in the major urban areas (Seekings, 2000). During the early 1990s the Group Areas Act was repealed, a democratic government was elected and the desegregation of South African cities began. Post-apartheid South Africa saw new policies aimed at reintegration being introduced, *viz.* the Reconstruction and Development Programme (RDP), and the Growth, Employment and Redistribution (GEAR) strategy (Christie, 2003; Christopher, 2005).

The political history of South African, combined with steadily increasing populations in urban areas, has led to a complex urban structure. In 2008, South Africa’s population was approximately 50 million people and it is expected to rise to 56 million by 2050 (UN, 2008). The current growth rate of urban areas is 3.5% per year, which is nearly three times the growth rate in developed countries (DEAT, 2006). Of the total population, approximately 61% currently live in urban areas and this is expected to increase to 79.6% by 2050. The total urban population for 2030 and 2050 for South Africa is predicted to be 39 million and 45 million, respectively (UN, 2009). Of the 50 million people in South Africa, 21% (approximately 10.5 million people) live in the province of KwaZulu-Natal (KZN) making it the second most populated province in South Africa (STATSSA, 2010)[2].

As a result of population growth and rural to urban migration, urban land use is increasing and these increases have resulted in a number of environmental impacts (Jenerette and Potere, 2010). Urban areas have been shown to change the local and regional climate by altering the energy and water balance within the urban environment (Bornstein and Lin, 2000; Collier, 2006; Foley *et al.*, 2005; Grimmond, 2007). The replacement of natural vegetation by impervious tar and concrete surfaces decreases water infiltration, thereby changing runoff

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[2] The population data that was available during the course of the study was used; however it is important to note that the 2011 South African census results were released during the submission of this thesis.

characteristics (Pauleit *et al*., 2005; Foley *et al*., 2005). Thus, the hydrological response of the urban environment is altered, resulting in increased flood potential and changes in the water supply to downstream users, reservoir levels, river morphology and groundwater recharge. Furthermore, urban areas are known to pollute the environment and are associated with decreased water and air quality (Foley *et al*., 2005; Grimmond, 2007).

Given the above impacts of urban areas on the environment, particularly on the hydrological responses, there is a need to understand the potential growth and spread of urban areas to enable potential future environmental impacts to be projected, enabling policies and decisions to be implemented to manage and alleviate, where possible, the impacts of future urban development. To understand the environmental impacts of urban areas, the scale and location of urban land use change must be known, as environmental impacts, particularly hydrological impacts are not only scale dependant but also dependent on the location of change within a catchment area (Mejía and Moglen, 2010). The generally accepted method to quantify the scale and location of future urban growth is through the use of an urban growth model (Silva and Clarke, 2002). There are a number of urban growth models available that can provide the required scale and location of urban growth and these are reviewed in Chapter 2.3.1; however many of these models are data intensive and difficult to use. The SLEUTH Urban Growth Model (SLEUTH) has the ability to project the scale and location of urban growth, using input data that readily available in South Africa. SLEUTH has been successfully used in the United States of America (USA), where it was developed by Clarke *et al.* (1996), the European cities of Lisbon and Porto (Silva and Clarke, 2002), in Taiwan (Lin *et al*., 2008) and in Cape Town, South Africa (Watkiss, 2008). In addition to this SLEUTH has been applied in a number of hydrological impact studies (Lin *et al.*, 2008; Beighley *et al.*, 2003; Xian and Crane, 2005). For these reasons this model was selected for use in this study.

The objectives of this study are to model plausible future urban growth in a highly developed South African hydrological catchment, *viz*. the Mgeni catchment, using the SLEUTH Model and to assess its ability to model future urban growth given the complex South African urban structure.

2.2 Mgeni catchment

The Mgeni catchment in KwaZulu-Natal (KZN), South Africa has an area of 4 349 km^2 with an altitude range of 0 to 1 913 metres above sea level. The Mgeni catchment has a relatively wet climate, receiving a mean annual precipitation (MAP) of between 700 and 1 550 mm per annum, with most of this precipitation falls in the summer season (October to March). The mean annual potential evaporation ranges from 1 567 to 1 737 mm per annum. The mean annual temperature is highly variable due to the range in altitude, with mean annual temperatures in the high altitude areas of 12 °C and warming to 20 °C near the coast (Warburton *et al*., 2010).

The land use of the Mgeni catchment varies (Figure 2.1). While, a large percentage of the catchment remains under natural vegetation, in the high rainfall upper reaches of the catchment, plantation forestry is the predominant land use. Commercial and small scale agriculture is practised in the upper and middle reaches of the catchment, whereas the urban areas in the Mgeni catchment tend to be in the southern regions in lower lying areas and towards the outlet of the catchment into the Indian Ocean, at the coastal city of Durban.

The cities of Pietermaritzburg and Durban are the main urban areas in the catchment. Pietermaritzburg is the capital of KZN and Durban is South Africa’s third largest economic centre (Dray *et al*., 2006). The catchment is a centre for economic growth and development, and is expected to experience increases in urban land use in the future (PSEDS, 2008). According to Ramnath (2009), the Msunduzi and eThekwini Water Services Authorities (WSAs), who are responsible for the provision of water to Pietermaritzburg and Durban respectively, currently supply approximately 4 million people. Socio-economic problems such as poverty, unemployment, poor sanitation and limited health care (PSEDS, 2008) are faced in the catchment. Water plays a vital role in many of these areas supplying potable water for human consumption and sanitation, and is important for industrial, agricultural and commercial activities in the catchment. Given the economic importance of the catchment, the population growth and the current socio-economic problems, the Mgeni catchment was selected as the study area. By improving the understanding of the hydrological impacts of future urban growth, this allows for better water resources planning to meet the demands of the population and economy of the Mgeni catchment.

Since the modelled future urban growth will be used in hydrological impacts studies, the urban growth will be described in the context of the catchment's Water Management Areas (WMAs) rather than assessing the growth of particular cities. The WMAs are hydrological relevant subdivisions of the Mgeni catchment based on climate, land use, soils and terrain. The WMAs represent the areas where the sum of all surface water generated within that area converges at a particular outlet point. The outlet point for each WMA is normally a point of hydrological interest such as a water-sampling station or weir (Warburton *et al*., 2011).

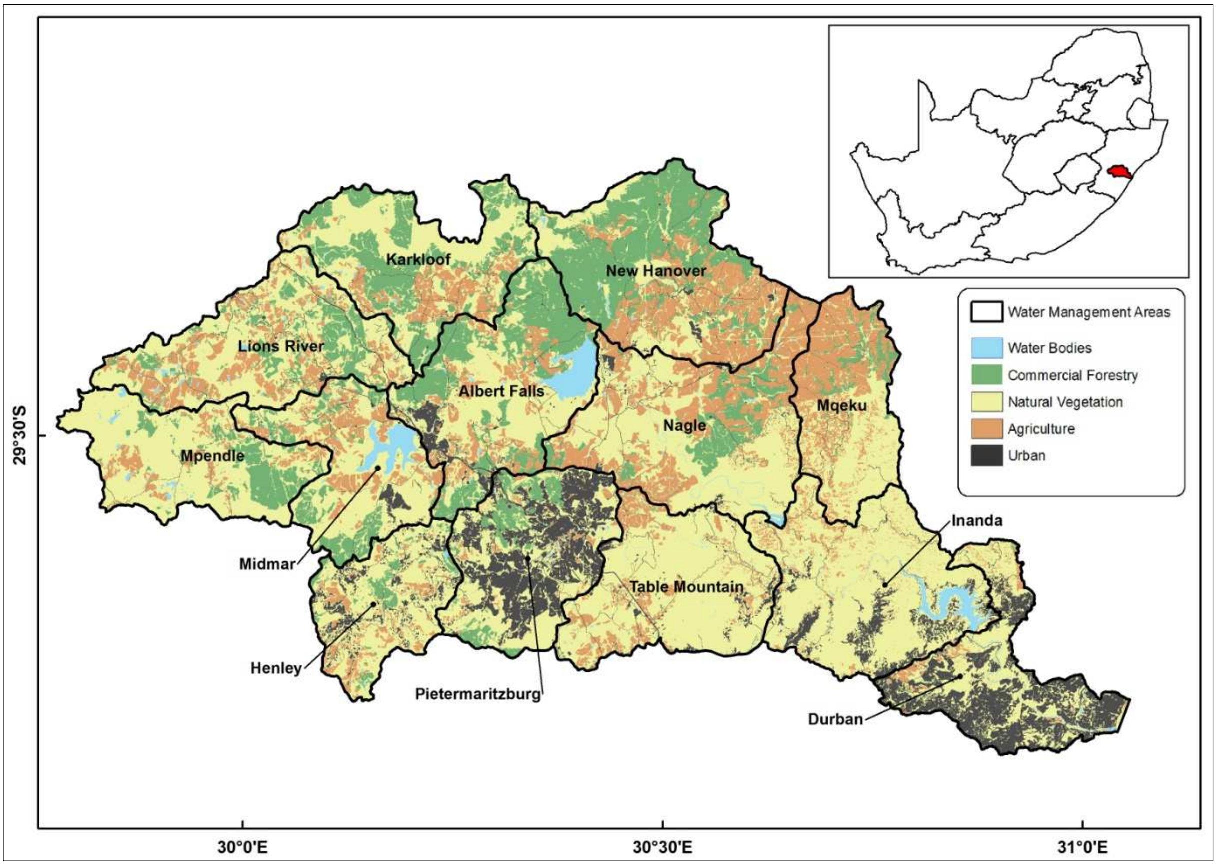

Figure 2.1 Location of the Mgeni catchment and land use distributions in the WMAs (adapted from Thompson *et al*., 2001)

2.3 Urban Growth Modelling

2.3.1 Methods of urban growth modelling

There are a number of methods for modelling land use changes and urban growth. These include the use of spatial metrics (Aguilera *et al*., 2011), artificial neural networks (Thapa and Murayama, 2012) and multicriteria evaluation (Melgarejo *et al*., 2007), and cellular automata (Aguilera *et al*., 2011; Batty, 1997; Clarke *et al*., 1996; Thapa and Murayama, 2012; Vas *et al.*, 2012). These different methods all attempt to quantify the processes that govern the shape and rate of urban growth, which in turn allows predictions to be made. A study by Zhao and Chung (2006) was useful in guiding the model selection process. The study summarised a number of established urban growth and land use change models of varying modelling methods, according to, *inter alia*, usability, modelling procedure and required data. Of the 27 models that were reviewed by Zhao and Chung (2006), UrbanSim was the preferred model. In a developing country such as South Africa, demographic, economic and property data is often not readily available; therefore many of these models were ruled out of this study due to constraints on the availability and quality of input data. For example, UrbanSim has a number of input data requirements for building, business and employment data, and property evaluations that make UrbanSim's application in a South African context complex. A number of the other urban growth and land use model such as MEPLAN, TRANUS, IRPUD, METROSIM, SAM-IM, UPLAN and LUCAS were excluded based on the unavailability of comprehensive economic, census and property data. Additionally, a number of the models such as TRANUS and METROSIM were excluded based on the high licensing and training costs. Most of the models listed by Zhao and Chung (2006) have been used for urban planning. However, some of these models have been applied in hydrological impact studies, such as the SLEUTH Urban Growth Model (Lin *et al*., 2008; Beighley *et al*., 2003; Xian and Crane, 2005) and the 'What If?' model (McColl and Aggett, 2007).

For the purposes of this study SLEUTH was selected for its ability to project the scale and location of plausible future urban growth as required for this study, and its relatively simple data requirements which are available in a developing country such as South Africa. Moreover, SLEUTH is freely available, whereas 'What if?' is relatively costly and lacks a measure of spatial interaction (Zhao and Chung, 2006), whereas SLEUTH has undergone rigorous testing using a variety of spatial metrics (Dietzel and Clarke, 2007). SLEUTH has been well tested, with over 25 applications in study areas in the USA and over 35 applications in study areas in other parts of the world (NCGIA, 2011). Increasing the confidence in the applicability of SLEUTH for a South African situation is that the model has been successfully applied in Cape Town, South Africa (Watkiss, 2008). Given the intended use of the model's output for application in a hydrological impact study, confidence in the suitability of the SLEUTH Model for this study is increased by the applications in hydrological impacts studies, as demonstrated by Arthur-Hartranft, *et al*. (2003), Beighley *et al*. (2003), Lin *et al*. (2008) and Xian and Crane, (2005). Arthur-Hartranft, *et al*. (2003) investigated implications of increased urban growth on the water balance and other climatic parameters. Beighley *et al*. (2003) and Lin *et al*. (2008) coupled the SLEUTH Model with hydrological models to assess future changes in hydrological responses as a result of urban growth. While Xian and Crane (2005), used SLEUTH to model the future locations of types of impervious surfaces, the results of which could be used for hydrological impact studies. Based on the above, the SLEUTH Model was considered suitable for modelling future urban land use for the purposes of this study.

2.3.2 The SLEUTH structure

The SLEUTH Model is a scale-independent, cellular automata (CA) urban growth model (Clarke *et al*., 1996). As a scale-independent urban growth model, SLEUTH can be applied at a local, regional and continental scale. CA is a simple method of simulating complex real world systems using certain initial conditions and behaviour rules to intelligently simulate the growth of urban areas (Clarke and Gaydos, 1998). Therefore, SLEUTH has the ability to map areas that are likely to be urbanised in the future, guided by a set of simple growth rules derived from historical urban data (as provided by the SLEUTH acronym), rather than relying on complex mathematical functions (Batty, 1997). In the application of SLEUTH, the study area is defined as a spatially referenced grid, with each cell of the grid being designated a value of either 'urban' or 'non-urban'. Consider a cell given the value 'non-urban' with two 'urban' cells adjacent to it in an initial time frame; in the following time frame the 'non-urban' cell may change to 'urban', given the correct conditions. Cells can only be converted to 'urban' if the conditions are conducive for urban growth, for example, cells must have suitable slope, proximity to transportation networks and land use. Adopting the CA approach enables SLEUTH to predict both the scale and location of urban growth, which is beneficial as the urban growth can be evaluated both numerically and visually.

SLEUTH requires a set of initial conditions, *viz*. a set of growth coefficients, an integer value to initiate the random number generator and the input data. Using these initial conditions, the model execution occurs in the form of two nested loops. The first loop ensures that the statistics of the historical urban data are retained, while the second loop executes the growth rules for each year in the future (Silva and Clarke, 2002). Monte Carlo iterations are used in the SLEUTH Model. This is a method of stochastic modelling where the model is run several times to produce a distribution of outputs, thereby attempting to account for randomness and variability within a process such as urban growth (Goldstein *et al*., 2005).

The SLEUTH modelling routine consists of three modes; the test, calibrate and predict modes. The test mode is where the model verifies the input data sets and ensures that the model is functioning correctly in its initial stages. The second mode, calibrate, is the most important, as this is where the controlling coefficients are derived. The calibrate mode attempts to find the controlling coefficients that best replicate the urban growth of the four historical urban extents; these controlling coefficients are then used in the predict mode. The controlling coefficients; dispersion, breed, spread, slope and road-gravity govern the four types of growth, *viz*. spontaneous growth, new spreading centres growth, edge growth and road-influenced growth (Figure 2.2). Spontaneous growth is the random growth of urban areas and is governed by the dispersion coefficient. The dispersion coefficient indicates how many times a particular cell will be selected for spontaneous growth; the more it is selected the greater the likelihood it will be designated as ‘urban’ (Figure 2.2A). Spontaneous growth can only occur in cells that are suitable for urbanisation. New spreading centre growth uses the spontaneous development as described above and assesses the suitability of creating growth in the cells surrounding the new urban cell, thus creating a new growth centre (Figure 2.2B). New spreading centre growth is governed by the breed coefficient. Breed governs the probability that a cell that experiences spontaneous urban growth will become the centre for further urban growth. Edge growth is an outward expansion of the currently urbanised areas as shown in Figure 2.2C, where the cells marked ‘X’ on the edge of current urban areas have the potential for urban growth. The spread coefficient controls edge growth and is defined as the probability that a cell, in old and new urban areas, will have a cell next to it urbanise.

Slope is the percentage slope of a particular cell, where less steep cells are more easily urbanised than steeper cells. Lastly, road influenced growth is the growth of urban areas that are in proximity to roads. For example, in Figure 2.2D the cells marked ‘X’ are potential urban growth areas and these occur in proximity to the road as the urban growth pattern has been influenced by the road (Silva and Clarke, 2002). The road-gravity, dispersion and breed coefficients control the road-influenced growth type by controlling the maximum distance that the model searches for roads next to a particular cell (Solecki and Oliveri, 2004; Watkiss, 2008). Table 2.1 summarises the growth types and the corresponding controlling coefficients and provides a description of the growth process.

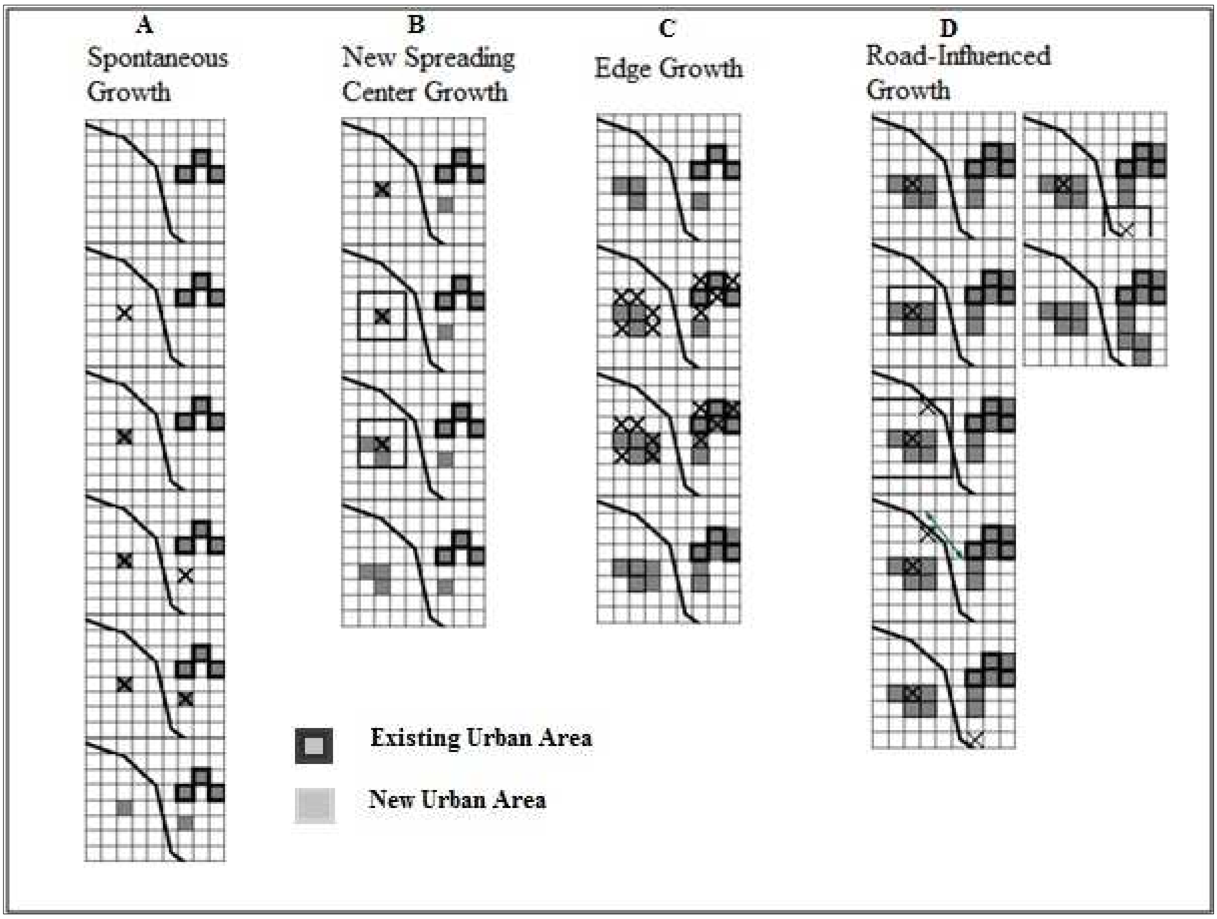

Figure 2.2 The four types of growth simulated by SLEUTH. The possible areas for new urban growth are indicated by the cells marked with an ‘X’ (after NCGIA, 2011)

Table 2.1 A summary of the different growth types and controlling coefficients used in SLEUTH (after Watkiss, 2008)

Growth Type	*Controlling Coefficients*	*Summary Description*
Spontaneous	dispersion	Randomly selects the potential new growth cells.
new spreading centre	breed	Growing urban centres from spontaneous growth.
edge growth	spread	Old or new urban centres spawn additional growth.
road-influenced	road-gravity, dispersion, breed	Newly urbanised cell spawns growth along transportation network.
slope resistance	slope	Effect of slope on reducing probability of urbanisation.

Self-modification is a second level of growth rules which is triggered by an urban growth rate that is unusually high or low in comparison with the growth rate observed between the historical urban extents (Clarke *et al*., 1996). The growth rate is the sum of the four growth types for a particular year. The model adjusts the growth rate by modifying the three control coefficients that are most sensitive to urban growth, i.e. dispersion, breed and spread, by increasing these by a multiplier of greater than one for a ‘boom’ state or by decreasing them by a multiplier of less than one for a ‘bust’ state. If the growth is too high (Critical High) the ‘bust’ state would be triggered and when the growth is too low (Critical Low) the ‘boom’ state is triggered. Self-modification in SLEUTH can be seen in other components of the model. For example the road-gravity factor increases with time to account for future infrastructure. There is also a decrease in the slope resistance factor to account for urban areas being built on steeper slopes as the amount of flat land available for urban growth becomes increasingly scarce. Self-modification in the SLEUTH Model promotes urban growth in an S-curve which is typical for urban growth, rather than producing growth that is linear or exponential (NCGIA, 2011).

2.3.3 Calibration of the SLEUTH Model

As described before, input data in the form of raster images is required for SLEUTH to perform a simulation. Each raster input image, *viz*. slope, hillshade, excluded areas, transport routes and historical urban extents, must be in a GIF image format and of the same cell size, extent and geographical projection (NCGIA, 2011). For this study the cell size of the input layers was set to 100 metres. A resolution of 100 metres was selected as the level of detail is still sufficient for the purposes of this study, but without significantly reducing the models performance.

The slope layer depicts the percentage slope of the Mgeni catchment on a cell-by-cell basis (Figure 2.3). The darker areas indicate gentler slopes than the lighter areas which indicate steep slopes. The slope of a cell determines its ability to be urbanised, where gentler slopes are better suited to urban growth. The slope layer was derived from a 20-metre resolution Digital Elevation Model (DEM) of the KwaZulu-Natal Province (Schulze and Horan, 2008). The hillshade layer, which was created from the same DEM, has no function in determining urban growth characteristics, but provides texture to the output images. Lastly, the slope limit is set in the model settings. The slope limit is the maximum slope on which urban areas can be established. The recommended values are normally between $20 - 30\%$ (Clarke, 2008). However, a desktop assessment of the slope was conducted on the study area, by comparing the most recent urban land use dataset (EKZNW, 2008) to the slope layer at a cell resolution of 100 metres. The urban land use area was sampled at random for slope. It was found that in the formal urban areas in Pietermaritzburg and Durban the urban land use occurred on slopes of up to 30%. However, in the informal urban areas within in the Henley and the Inanda WMAs, the urban development occurred on slopes of approximately 40%. Therefore, to account for urban growth as a whole, a slope limit of 40% was selected.

The excluded areas layer specifies the areas where urban growth cannot occur. This includes waterbodies, nature conservation areas or any other user-specified areas where urban growth should not occur. For this study waterbodies and conservation areas were excluded from urban growth.

At least two transportation or road layers are required by SLEUTH. A roads layer for the year 1994 was obtained from the School of Environmental Sciences, University of KwaZulu-Natal, South Africa. A roads layer for the period between 1994 and 2008 could not be sourced, but such a layer was obtained for the year 2011 from the Department of Transport which was assumed to suitably represent the roads layer for 2008 (KZN Department of Transport, 2011). The roads were weighted from 0 – 100 according to their significance, with 100 being the greatest weighting. National highways were rated 100, major roads were rated 50 and all other roads were rated 25. Urban growth is likely to be directed towards roads of a higher rating. Transportation layers are important in SLEUTH as roads play a significant role in governing where future urban growth is likely to occur as transportation is an integral part of urban life (Clarke and Gaydos, 1998).

To generate the growth coefficients SLEUTH requires four historical urban extent layers. The input data is used for the projection of past growth trends into the future (Watkiss, 2008). For this project, the urban areas for the years 1994 and 2000 were extracted from the NLC94 (Thompson, 1996) and NLC2000 (Thompson *et al.*, 2001), respectively. Urban land use extents for the years 2005 and 2008 were extracted from provincial land cover imagery sourced from Ezemvelo KwaZulu-Natal Wildlife (EKZNW) produced by Geoterraimage (Pty) Ltd (2010). All the land cover maps were derived from the classification of satellite imagery. However, the classification systems and resolution of each of the land cover image was not consistent. A comprehensive comparison of the classification systems used in the land cover images was conducted by Geoterraimage (Pty) Ltd (2010). The outcomes of this comparison were used to ensure that the selection of urban land use classes from the land cover images was consistent and comparable. For example, the land cover images for the years 2005 and 2008 had one class for urban areas. However, the land cover images for years 1994 and 2000 were a number of sub-classes within the “urban” category. Thus, using the outcomes from the Geoterraimage study, the urban sub-classes for the 1994 and 2000 land cover images, which are all classed as “urban” in the 2005 and 2008 land cover images, were identified and used.

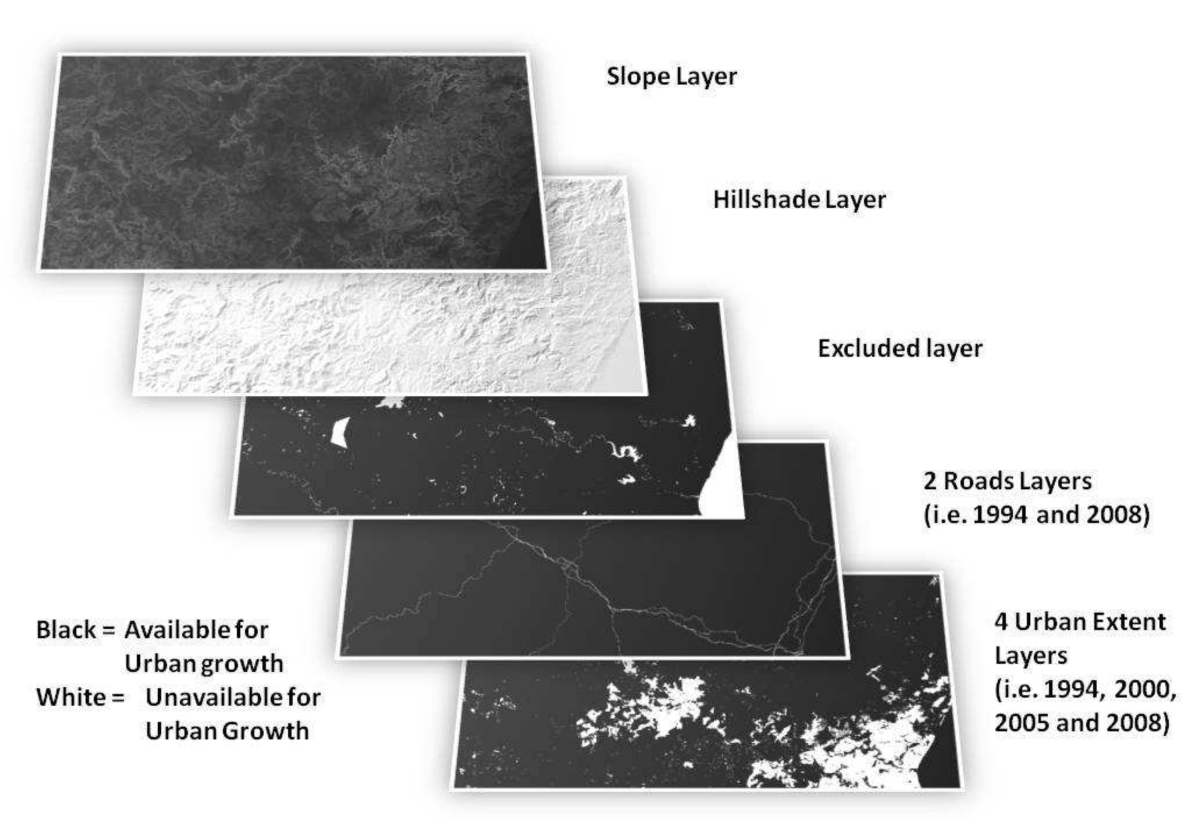

Figure 2.3 Input data prepared for the SLEUTH Model for the Mgeni catchment, KZN

All the input data as described above are used in the calibration mode to generate the controlling coefficients. The Calibrate mode is an iterative process of three stages of calibration with images at three different resolutions; course resolution, fine resolution and final resolution (Silva and Clarke, 2002). SLEUTH uses the controlling coefficients to determine how urban areas will develop into the future. The Optimum SLEUTH Metric (OSM) is used throughout the calibration mode to select the best controlling coefficients from each calibration stage; those coefficients were then used in the following calibration stage (Dietzel and Clarke, 2007). The predict mode uses the coefficients derived in the final calibration mode to predict yearly future urban extents until a user-specified end year (Silva and Clarke, 2002).

The values that resulted from the completion of the final calibration mode are shown in Table 2.2. The results of the calibration of SLEUTH in the Mgeni catchment can be compared to those of a study by Watkiss (2008) where SLEUTH was applied to the city of Cape Town, South Africa. There are some similarities in the growth controlling coefficients (*viz.* dispersion, breed and spread) between the two simulations. For example the dispersion, breed and spread coefficients show similar trends and the road-gravity coefficients are also highly comparable. The slope coefficient in the Mgeni catchment shows that slope has less of an impact on urban growth than in Cape Town.

Table 2.2 The final coefficient values from the calibration process

Controlling Coefficient	Dispersion	Breed	Spread	Slope	Road Gravity
Mgeni catchment	76	41	26	1	16
City of Cape Town	72	65	15	35	20

2.4 Results

SLEUTH generates urban growth maps showing the probability of each cell becoming urbanised for a particular year in the future. SLEUTH produced a map for each year from 2009 to 2050. The ‘seed’ urban extent for the year 2008 (Figure 2.4), provides a means of comparison from which urban growth is then able to develop in the model. Medium and long term projections of urban growth were selected for assessment *viz.* the years 2030 (Figure 2.5) and 2050 (Figure 2.6) respectively.

The urban areas in 2008 are located predominantly in the Pietermaritzburg and Durban WMAs. By the year 2030 the urban areas in the Pietermaritzburg, Durban, Henley and Inanda WMAs are starting to show increased growth. The map for 2050 shows significant urban growth in a number of WMAs, including the Pietermaritzburg, Henley, Albert Falls, Lion’s River, Midmar, Table Mountain, New Hanover and Nagle WMAs. However, the growth rate of urban areas in the Inanda and Durban WMAs is slower in 2050 possibly due to lack of space and slope limiting further growth. Much of the projected urban growth occurred in areas adjacent to the ‘seed’ layer indicating a high amount of edge growth. This spreading growth is observed in those WMAs with urban land use already present, *viz.* the Midmar, Albert Falls, Henley, Pietermaritzburg, Table Mountain and Durban WMAs. All these WMAs in the year 2050, show extensive areas of urban growth with a probability of occurrence of between 95–100% as indicated by the areas coloured red on the maps. Other areas such as the Lion’s River and Karkloof WMAs show areas of urban growth with probabilities between 80 and 95% (light green) in the 2050 map, whereas, in 2030 little growth was predicted in these areas. The light green areas tend to follow the main roads in the Lion’s River and Karkloof WMAs, showing the effects of the road gravity and the breed coefficients.

Comparison of the 2030 and 2050 maps (Figure 2.5 and Figure 2.6) illustrates an increased growth rate of urban areas between 2030 and 2050 compared to 2008 to 2030. Similarly, the total predicted area of urban growth (Figure 2.7) for the various probabilities, shows an increased rate of urban growth between 2040 and 2050 for the >50% probability class, whereas the >70% and >95% probability classes show consistent growth over the prediction period. In 2008 the total urban area was 684 km^2 which increases to 1 330 km^2 in 2 030 and 3 284 km^2 in 2050.

The increased growth in the 2030 to 2050 period may be attributed to the high dispersion and breed coefficients, possibly replicating the sprawling, uncontrolled growth found in informal settlements. As more cells are selected for spontaneous urban growth via the dispersion coefficient, the development of new spreading centres is increased via the breed coefficient. This explains why the growth in these areas occurs later and why the rate of growth increases. It also explains why the probabilities of urban growth are lower in the new urban areas as they are further away from urban areas present in the ‘seed’ layer, whereas urban growth near areas present in the ‘seed’ layer, such as edge growth, are associated with higher probabilities.

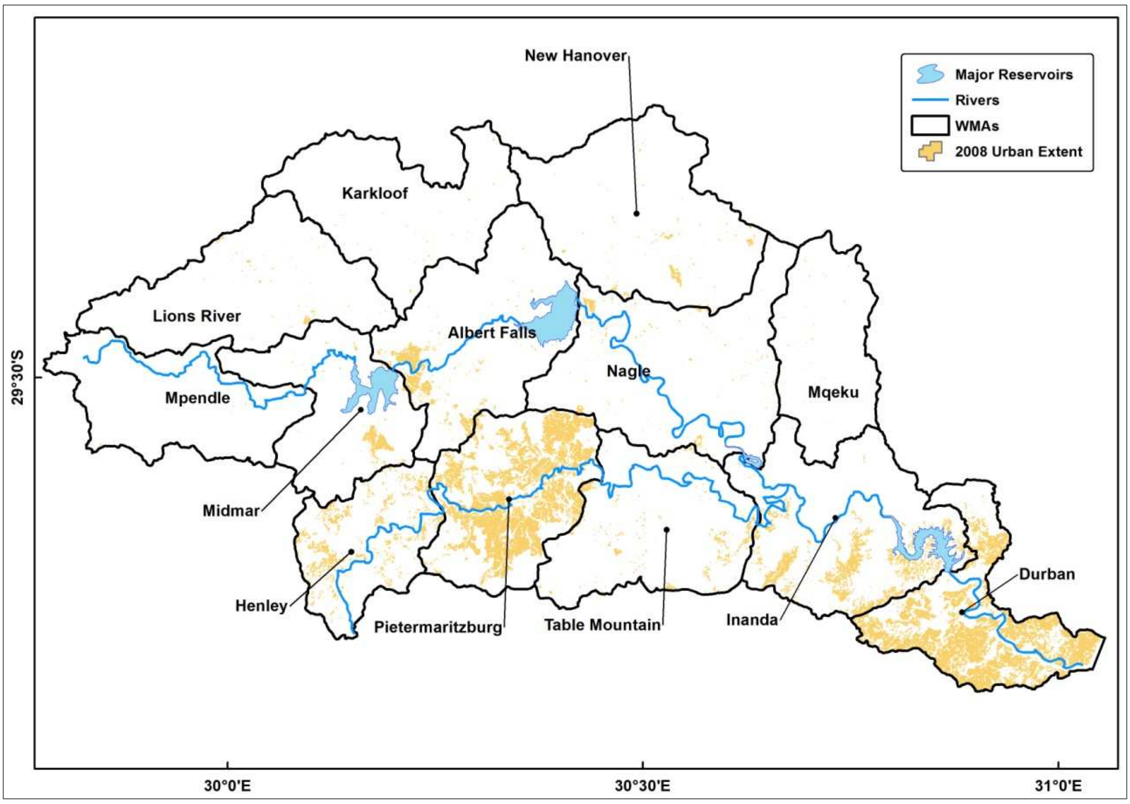

Figure 2.4 Urban extent for the year 2008 in the Mgeni catchment

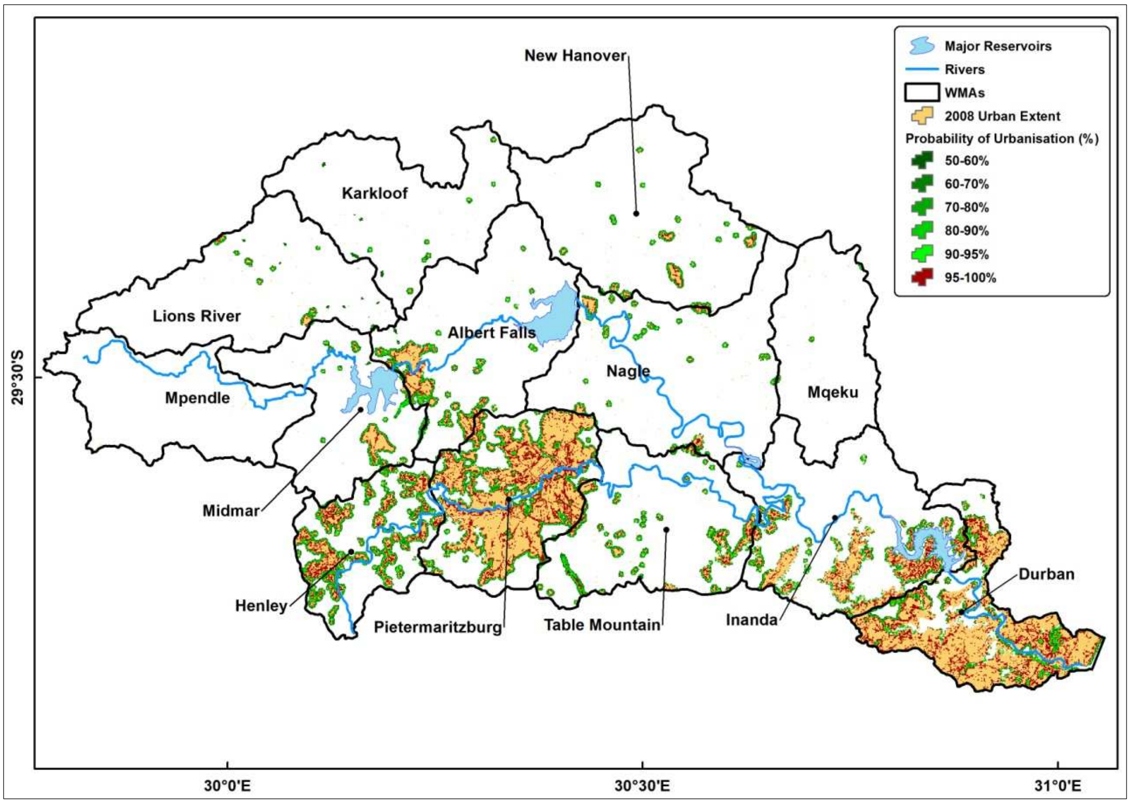

Figure 2.5 Projected urban growth for the year 2030 for the Mgeni catchment

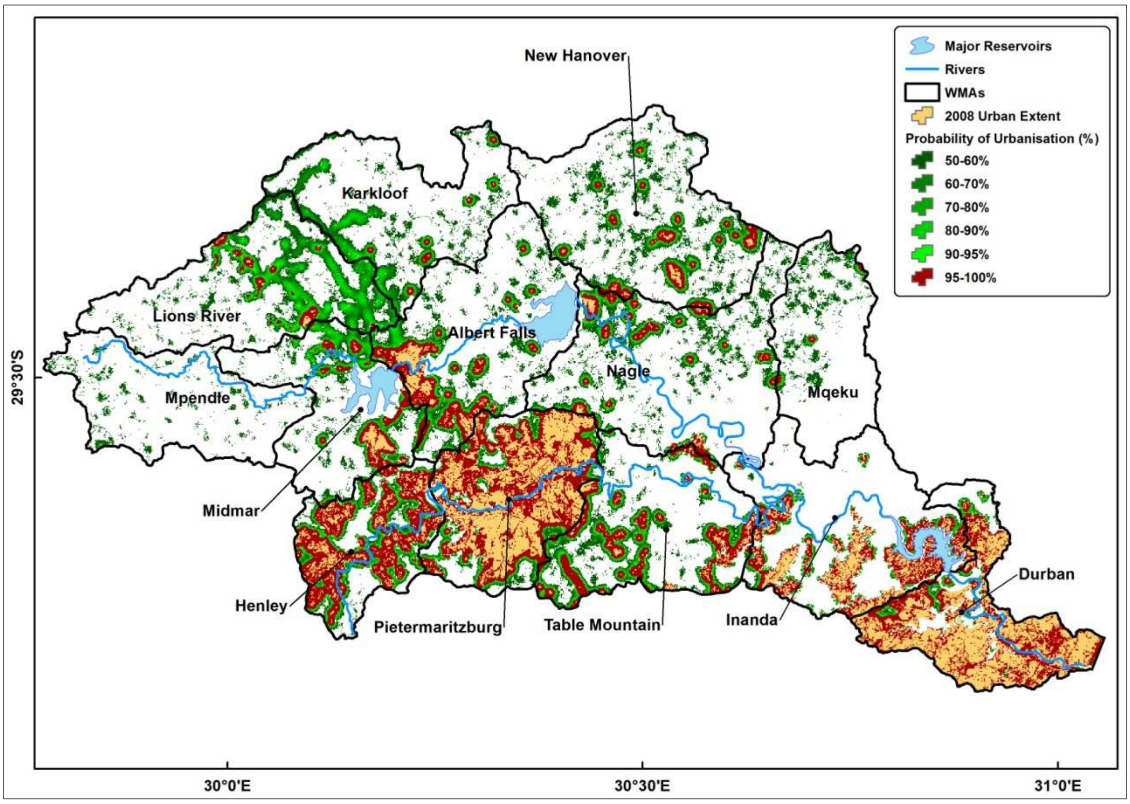

Figure 2.6 Projected urban growth for the year 2050 for the Mgeni catchment

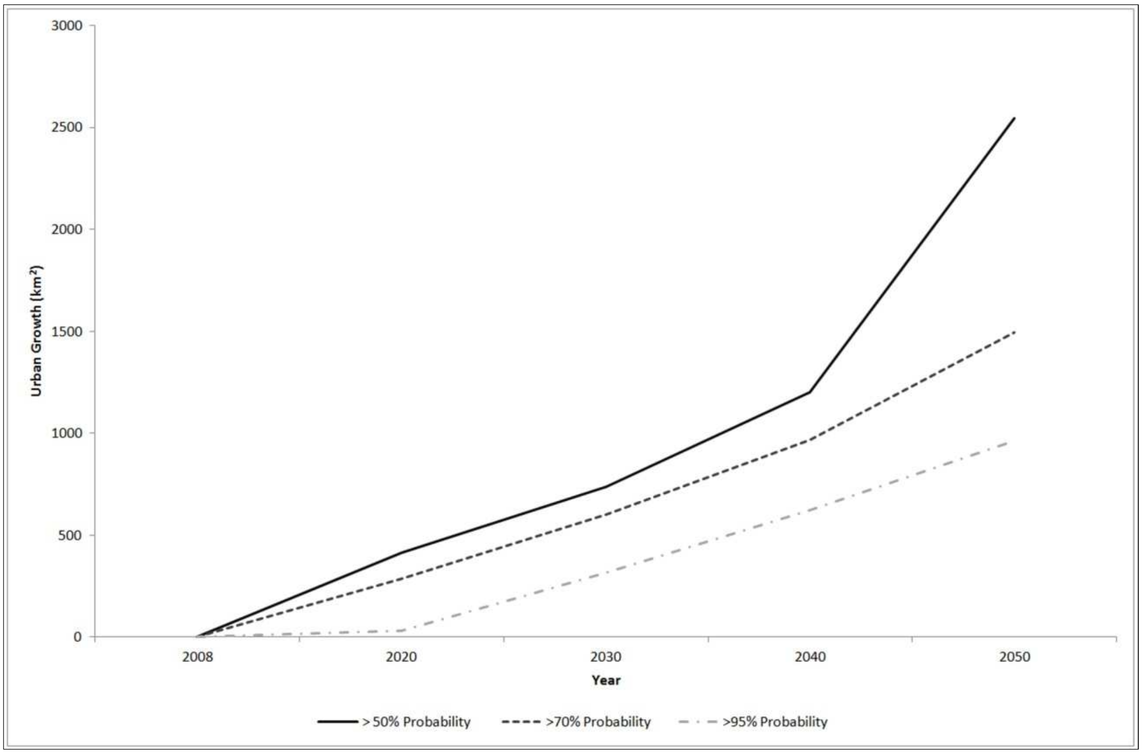

Figure 2.7 The total predicted area (km^2) of urban growth for the Mgeni catchment

When assessing the potential urban growth in each of the WMAs, it is important to consider the cells of an urban growth probability of between 95−100%, as these are the areas where predicted future urban growth is most likely to occur and therefore can be used as a confident representation of the general trends or urban growth in an area (Table 2.3). The urban growth can be assessed in absolute (km^2) and relative (%) terms for each of the WMAs in the Mgeni catchment (Table 2.3). The Pietermaritzburg (115.7 km^2), Henley (91.3 km^2), Durban (80.9 km^2) and Inanda (61.5 km^2) WMAs show the largest growth in urban areas in absolute terms by the year 2050 (Table 2.3). For hydrological applications it is important to understand the amount of urbanisation as a percentage of each WMA. This provides an indication of which WMAs are the most severely impacted by the predicted urban growth. The 2030 prediction shows a relative urban growth of 17% for the Pietermaritzburg and Durban WMAs, which is the highest relative urban growth in the Mgeni catchment for 2030. However, in 2050 the Henley WMA shows the most urban growth at 42%, followed by the Pietermaritzburg WMA at 36% and the Durban WMA at 29%. These results suggest that Henley, Pietermaritzburg and Durban WMAs could be the most effected by urbanisation and in turn could experience the greatest hydrological impacts.

Table 2.3 The urban growth at a probability of 95-100% for each of the WMAs from 2008 to 2050

WMAs	**Total Area (km^2)**	**Urban Area 2008 (km^2)**	**Urban Area 2030**		**Urban Area 2050**	
			Absolute (km^2)	**Relative (%)**	**Absolute (km^2)**	**Relative (%)**
Albert Falls	392.0	17.2	25.7	2.2	56.1	9.9
Durban	275.4	129.0	177.4	17.6	209.9	29.4
Henley	220.0	24.1	49.4	11.5	115.3	41.5
Inanda	412.4	41.2	65.8	6.0	102.7	14.9
Karkloof	334.3	0.6	0.8	0.1	5.2	1.4
Lions River	362.0	1.9	2.9	0.3	12.6	3.0
Midmar	269.2	6.6	10.0	1.2	29.8	8.6
Mpendle	295.7	0.2	0.2	0.0	0.2	0.0
Mqeku	243.9	0.5	0.6	0.1	2.2	0.7
Nagle	453.7	6.0	9.2	0.7	30.4	5.4
New Hanover	429.5	4.8	8.1	0.8	27.2	5.2
Pietermaritzburg	318.6	126.2	182.5	17.7	241.8	36.3
Table Mountain	342.8	11.0	20.5	2.8	66.0	16.0
Mgeni catchment	4 349.4	369.2	553.0	4.2	899.3	12.2

2.5 Discussion

The SLEUTH Model was used as a means of attaining the scale and location of future urban growth in the Mgeni catchment for use in hydrological impact studies. SLEUTH is able to produce maps of future urban growth at yearly time steps into the future; hence SLEUTH is able to provide the spatial scale and location that is required for a hydrological impacts study. The calibration of the SLEUTH Model for the Mgeni catchment showed a similar trend in the growth controlling coefficients (dispersion, breed and spread) values to those obtained in the study by Watkiss (2008) for Cape Town, i.e. high dispersion values, followed by consecutively lower breed and spread coefficients, while the road-gravity coefficients were also comparable. However, the slope coefficient was different between the two study areas, suggesting that urban development in the Mgeni catchment is less restricted by slope than in Cape Town. The similarity in the growth-controlling coefficients observed in the Mgeni catchment and Cape Town shows that the model may performed in a similar manner when predicting urban growth in different regions of South Africa. For example, the high dispersion coefficients in both the Mgeni catchment and Cape Town may be related to the sprawling urban growth which is a characteristic of South Africa’s informal settlements. However there is a need for further testing to verify these similarities. The verification of SLEUTH’s performance and applicability in South Africa would be achieved if the number of applications of SLEUTH in South Africa were increased, as this is only the second known application of SLEUTH in South Africa. From the assessment of the calibration of SLEUTH performed in Cape Town and in the Mgeni catchment, it is plausible that SLEUTH is capable of producing consistent urban growth forecasts in a South African context.

Given the results achieved in this study, a number of limitations were experienced in the application of the SLEUTH. Firstly, SLEUTH is limited by the availability and quality of input data. The availability of land use data in South Africa is limited, with only four land use maps available for the KwaZulu-Natal area, *viz*. the NLC94 and NLC2000 and the EKZNW land cover maps for the years 2005 and 2008. Since there were only four urban extents, which is the minimum number required to run SLEUTH, a verification of the model results could not be completed.

The selection of land cover maps for use as input data instead of digitising from topographical maps was due to the higher resolutions that could be achieved using classified satellite imagery. However, there is no consistent method or system of land use classification in South Africa, thus the land cover classes vary between the four land cover maps used in this study. This makes studies that assess changes over time difficult as the classification is not consistent. Thus, it would be recommended that a consistent land cover classification system be developed for South African conditions.

There are also limitations in the SLEUTH Model itself, for example SLEUTH is unable to account for socio-economic and political factors that may influence the growth of urban areas. South Africa is a country with a complex political and socio-economic past of segregation under the Apartheid government. Such past policies not only shaped the past but will influence the future as well. The existence of informal settlements and past zoning of residential areas according to race are some indications of such segregation. Therefore, in a South African context it may be imperative for future applications of SLEUTH to incorporate parameters to quantitatively account for the political and socio-economic climate of the study area. SLEUTH can indirectly assess political and socio-economic factors by weighting the excluded layer, which acts as a representation of various policies and plans that are at work in these areas. However, this does not quantitatively assess the socio-economic and political influence on urban growth. In this application the model was able to replicate the dispersive growth seen in the historical urban extents and produced similar controlling coefficients to those observed in Cape Town by Watkiss (2008). An additional limitation of SLEUTH is that, when the model is functioning as an urban growth model as opposed to a land use model, there is no distinction between the types of urban land use nor does it incorporate competition from other land uses. For example, there may be a future demand for agricultural land use which in turn would restrict future urban growth.

The output of this study will be used to determine the hydrological impacts of future urban growth in the Mgeni catchment. Increased areas of urban land use in a catchment are associated with increased runoff and streamflow (Hall, 1984; Shaw, 1994; Ward and Robinson, 2000). Therefore the results of the hydrological modelling could possibly show increases in the streamflow in many parts of the catchment that have experienced significant urban growth such as the Pietermaritzburg, Henley, Inanda and Table Mountain WMAs.

Those WMAs in the upper reaches of the catchment, such as Henley and Pietermaritzburg are expected to have a greater impact on the hydrological responses of the catchment than those near the outlet of the catchment such as Inanda and Durban, as a unit of urban growth in the upper reaches of the catchment generally has a more significant hydrological impact than the same urban growth located at the outlet of the catchment (Beighley *et al*., 2003).

Plausible future urban growth can be used in conjunction with other land use changes or climate change scenarios to assess the impacts of global environmental change on hydrological responses. Other applications may include the use of future urban areas in planning of future water infrastructure and the required supply of water needed for future urban areas. For example, with an idea of the scale and location of future urban areas, planners will be better prepared to site the development of new dams, and ensure that water infrastructure can efficiently be installed in areas of new urban development.

2.6 Conclusion

The application of the SLEUTH Model for mapping future urban growth for use in hydrological impact studies is feasible, as the model provides maps of plausible future urban growth. From these maps the required spatial scale and location of urban growth can be obtained at a yearly time step. The SLEUTH Model is relatively simple to apply, however data in a South African context may be difficult to locate and may require a significant amount of data processing. In terms of output, SLEUTH seems to cope with the complexities of the South African urban environment, due to the use of past urban extents to predict plausible future urban growth. However, this is based on the assumption that current urban growth trends, for which the model was calibrated, will be continued into the future.

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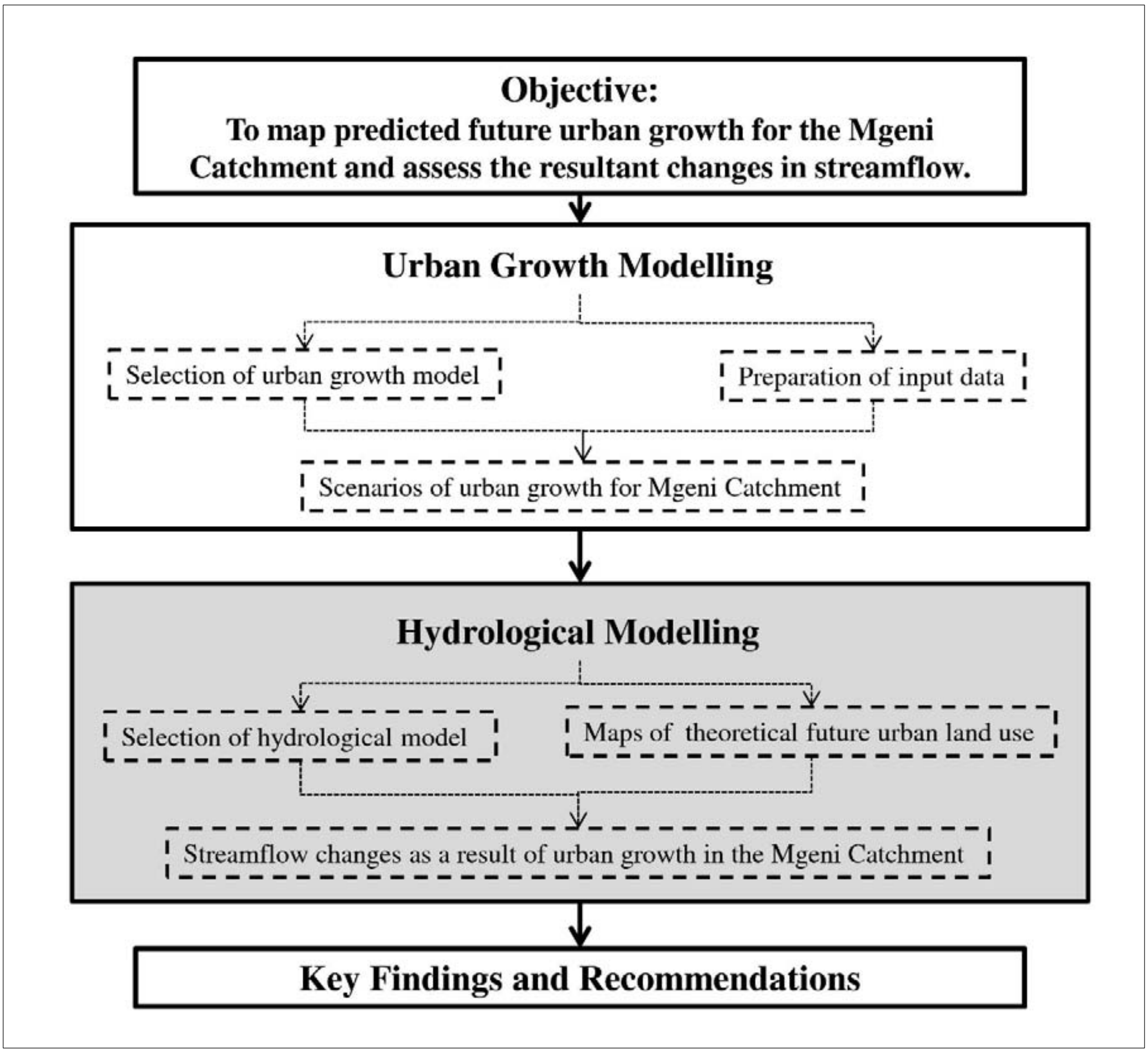
Lead in to Chapter 3

In Chapter 3, the urban growth generated by the SLEUTH urban growth model (Chapter 2) is modelled to assess hydrological responses using a hydrological model. The ACRU Agrohydrological Model was selected to model the hydrological responses to urban land use changes. This fulfils the objectives of the study by providing the hydrological response (streamflow change) of the Mgeni catchment and providing insight into the dynamics of the relationship between urban land use and streamflow.



3. THE IMPACT OF FUTURE URBAN GROWTH ON STREAMFLOW IN THE MGENI CATCHMENT[3]

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ABSTRACT

One of the most severe and irreversible land use changes is the conversion of land to urban land use, which is associated with increases in urban population and rural to urban migration. Urban land use is associated with a number of environmental impacts, one of which is the altering of streamflows through the modification of the surface conditions. To assess the hydrological responses to urban growth in the Mgeni catchment in South Africa, scenarios of plausible future urban growth are used. The results showed extensive urban growth of >95% probability in a number of Water Management Areas (WMAs). Increases in mean annual streamflows were observed in many of these areas; however the Henley, Pietermaritzburg and Table Mountain WMAs were shown to have greater increases in mean annual streamflow than other areas. Thus, indicating that these WMAs could be more sensitive to urban growth in the future. Furthermore, the results showed that the type of urban land use is important in determining the hydrological responses to urban land use as the imperviousness differs between the different urban land uses. Given the impacts of urban land use, it is important to consider the future hydrological responses of a catchment to guide and develop urban growth policies that are sensitive to hydrological response.

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[3] Mauck, B.A. and Warburton, M.L. 2012. The impact of future urban growth on streamflow in the Mgeni catchment. *Submitted to: WaterSA.*

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3.1 Introduction

Human-induced land use changes are occurring at an unprecedented scale and rate (Castells, 2010; Jenerette and Potere, 2010). Land use change involves the use of natural land cover for human purposes, such as agriculture, commercial forestry and urban land use to meet human demands (Lambin et al., 2001). One of the most severe and irreversible land use changes is that of urbanisation (Schulze, 2004). Urbanisation is a global phenomenon that is occurring at a rapid rate, primarily due to urban population increases and migration to urban areas (Tang et al., 2005; Hill and Lindner, 2010; Mishra et al., 2010). Urbanisation in this study refers to the process of increasing urban areas.

An increase in urban land use is associated with a number of environmental impacts (Jenerette and Potere, 2010), these include; loss of biodiversity (Jenerette and Potere, 2010), pollution (Molina and Molina, 2004), changes in micro-climate (Bornstein and Lin, 2000; Collier, 2006; Foley et al., 2005; Grimmond, 2007) and changes in hydrological response (Pauleit et al., 2005; Foley et al., 2005). Of particular concern in this study, are the impacts of urban growth on the hydrological responses of a catchment, which are dependent, *inter alia*, upon the land use of the catchment, and are sensitive to changes in land use (Schulze, 2000; Bewket and Sterk, 2005). Urban areas are constructed of primarily impervious surfaces, such as concrete, tar and roofs, which impede infiltration and increase the rate of surface runoff (Ward and Robinson, 2000; Rose and Peters, 2001). Urban areas also have piped drainage and stormwater systems that aid the rapid removal of water from roads and pavements, these systems are important for the management and control of stormwater, but ultimately results in greater flood potential downstream (Hall, 1984; Shaw, 1994; Ward and Robinson, 2000; Rose and Peters, 2001). Enhanced surface runoff in turn contributes to elevated streamflows in urban areas (Rose and Peters, 2001). Past urban hydrology research has tended to focused on streamflow, stormflow and surface runoff (Leopold, 1968; Hollis, 1975; Hall, 1984; Shaw, 1994; Ward and Robinson, 2000). More recently studies have been conducted on the changes in groundwater (Lerner, 2002; Younger, 2007), total evaporation (Praskievicz and Chang, 2009) and urban climate (Bornstein and Lin, 2000; Collier, 2006) due to urbanisation. All these studies provide a good understanding of the localised hydrological impacts associated with urban land use. However, limited research has been undertaken to understand the influence of the location, scale and intensity of urban land use on hydrological responses at a catchment scale.

The location of impervious areas within a catchment has a significant impact on catchment hydrological responses (Mejía and Moglen, 2009; Mejía and Moglen, 2010). A number of studies (Rose and Peters, 2000; Chang, 2007; Choi and Deal, 2008; Mejía and Moglen, 2010; Boggs and Sun, 2011) have shown that as more of a catchment is urbanised, the greater the alteration in the hydrological response. However, few studies have shown the impact of the spatial distribution of urban land use on the hydrological responses within a catchment (Mejía and Moglen, 2010). Mejía and Moglen (2010) showed that the distance of an urban area from the stream channel influences the magnitude of the hydrological response and that the distance of an urban area from the outlet of a catchment also plays a role in determining the hydrological response. For example, urban areas at the headwaters of the catchment tend to result in more significant changes in streamflow when compared to urban areas at the outlet of the catchment. This is due to the headwaters being responsible for much of the runoff generation in a catchment and having greater slopes, thus an increase in imperviousness as a result of urbanisation in these areas would increase the amount and rate at which rainfall is converted into streamflow (Beighley et al., 2003). The size of the catchment where change is occurring will also influence the magnitude of hydrological impacts. In large catchments the conversion of rainfall into streamflow tends to be more complex than in smaller catchments, as there is generally a greater variation in catchment properties, such as land use and soil characteristics (Ashagrie et al., 2006). Blöschl et al. (2007) theorised that due to land use being a local occurrence, any impact of change is likely to decrease with increasing catchment size. Peel (2009) reiterated this, suggesting that the effects of climate are more dominant at larger spatial (>1000 km^3) and temporal scales, while land use is dominant at smaller spatial (<1000 km^3) and temporal scales, in terms of hydrological response.

In addition to understanding the impact of the location of urban areas on hydrological responses, it is important to appreciate the role of preceding land use conditions (Quilbé et al., 2008) and catchment size (Ashagrie et al., 2006) in determining hydrological responses. The preceding land use determines the magnitude of land use change, which determines the magnitude of the hydrological response due to urban land use change (Ward and Robinson, 2000). For example, some preceding land uses may have minimised runoff and enhanced total evaporation and infiltration, such as agriculture and forestry (Falkenmark, 1999). In these cases the change to urban land use would have a more significant impact on the streamflow than a change from natural vegetation.

The hydrological dynamics of current urban land use is complex and the addition of future growth of urban land use deepens this complexity. Given the uncertainty of the relationship between streamflow, urban land use and other environmental changes, such as climate change, there is a need to plan and prepare for the hydrological impacts that may arise from urban growth. Projecting future urban growth through the use of urban growth modelling is the most common method used to gain insight into the possible extent of future urban developments (Lin et al., 2008). The SLEUTH Urban Growth Model (SLEUTH) was selected to model urban growth as it able to account for the scale and location of future urban growth as required for this hydrological impact study. SLEUTH was developed in United States of America by Clarke et al. (1996), where it has been successfully applied in 27 different locations (NCGIA, 2012), as well as in European cities (Silva and Clarke, 2002), Taiwan (Lin et al., 2008) and in Cape Town, South Africa (Watkiss, 2008). SLEUTH has also been used in a number of hydrological applications, as demonstrated in the studies by Arthur-Hartranft et al. (2003), Beighley et al. (2003), Lin et al. (2008) and Xian and Crane, (2005). Given its past applications and ability to account for the scale and location of urban growth, SLEUTH was determined to be suitable to model future urban land use for the purposes of this study, as shown in Mauck and Warburton (2012).Given that the scale and location of urban land use is an important determinant of hydrological response of the catchment, the model must account for the scale and location of urban growth. The hydrological responses of the catchment to the plausible future urban land use can then be modelled.

The ACRU Agrohydrological Model (Schulze, 1995) was selected to perform the hydrological modelling of the different urban growth scenarios generated by SLEUTH. ACRU has been proven to be sensitive to land use, and changes thereof, as demonstrated in the studies by Tarboton and Schulze (1992), Kienzle et al. (1997), Schulze et al. (2004) and Warburton et al. (2010). ACRU was developed in South Africa, for South African conditions and has been used extensively in the Mgeni catchment (for example Tarboton and Schulze, 1992; Kienzle and Schulze, 1995; Kienzle et al., 1997; Schulze et al., 2004; Summerton, 2008; Warburton et al., 2010). For these reasons ACRU was selected to model the hydrological response of the Mgeni catchment under urban growth.

Given the rate of urbanisation and its associated environmental impacts, along with other land use changes and climate change there is a need to assess how these changes impact on the hydrological responses of a catchment. The Mgeni catchment is undergoing a number of changes, of which urban growth is one of the most significant. Therefore, the objectives of this study are to determine the changes in the hydrological responses as a result of urban growth in the Mgeni catchment. This would be achieved through the successful coupling of and urban growth model (SLEUTH) and a hydrological model (ACRU) to provide information on the hydrological responses of plausible urban growth scenarios. This study will assess the changes in annual and seasonal simulated streamflows under a number of different plausible urban growth scenarios, as well as assess the impact of the type of urban land use on the hydrological responses.

3.2 Mgeni catchment

The Mgeni catchment in KwaZulu-Natal (KZN), South Africa (Figure 3.1) has an area of 4 349 km^2 with an altitude range of 0 to 1 913 metres above sea level. The climate is relatively wet, with a mean annual precipitation (MAP) of between 700 and 1 550 mm per annum. Most of the precipitation occurs in summer (October to March). The mean annual potential evaporation ranges from 1 567 to 1 737 mm per annum. The mean annual temperature is highly variable due to the range in altitude, where mean temperature in the high altitude areas is 12°C and 20°C near the coast (Schulze et al., 2008).

For the purposes of this study, urban growth will be considered in the context of the catchment’s Water Management Areas (WMAs). The WMAs are sub-catchments of the Mgeni catchment, which represent the area where the sum of all surface water generated within that area converges at a particular outlet point. The outlet point for each WMA is typically a point of hydrological interest such as a water sampling station or weir (Warburton et al., 2011). Therefore, WMAs are hydrological relevant subdivisions of the Mgeni catchment based on climate, land use, soils and terrain.

The Mgeni catchment consists of two main rivers the Mgeni River and the Msunduzi River (Figure 3.1). The Mgeni River is fed by the Lion's River, Midmar, Karkloof, New Hanover, Albert Falls and Nagle WMAs, while the Msunduzi River is fed by the Henley, Pietermaritzburg and Table Mountain WMAs. The Msunduzi River converges with the Mgeni River in the Inanda WMA which continues to exit the catchment through the Durban WMA into the Indian Ocean (Figure 3.1). The land use of the Mgeni catchment (Figure 3.1) is varied. Currently, 40% of the Mgeni catchment is under natural vegetation. Plantation forestry is also a dominant land use in upper areas of the catchment where the rainfall is relatively high. Commercial agriculture is found in the northern parts of the catchment. The urban areas of Pietermaritzburg and Durban both fall within the Mgeni catchment and are located in the southern, low altitude areas of the catchment along the Msunduzi River and the lower reaches of the Mgeni River. Thus, the land use of the Mgeni catchment shows that the Msunduzi River and the lower reaches of the Mgeni River have a greater level of urbanisation than the upper reaches of the Mgeni River where land uses such as plantation forestry and commercial agriculture dominate.

Pietermaritzburg is the capital of KZN and Durban is South Africa's third largest economic centre (Dray et al., 2006). The Mgeni catchment supplies water to 15% of the country's population and is responsible for approximately 20% of South Africa's gross domestic product (Schulze et al., 2004). Thus, the Mgeni catchment is a centre for economic growth and development, and is expected to experience increases in urban land use in the future (PSEDS, 2008). There are socio-economic factors which are areas of concerns in the Mgeni catchment, such as poverty, unemployment, poor sanitation and limited health care (PSEDS, 2008). The Mgeni catchment is a highly water engineered catchment, with four major dams, *viz.* Midmar, Albert Falls, Nagle and Inanda dams which supply potable water to Pietermaritzburg and Durban. In addition to the dams, a transfer scheme is in place for times of critical periods of water stress, which pumps water from the adjacent Mooi River catchment into the Mgeni River (Summerton, 2008). The Mgeni catchment is water stressed, due to the current water requirements of agriculture, plantation forestry and urban areas. As a result the Mgeni catchment is currently closed to further introduction of streamflow reduction activities such as forestry. Understanding the hydrological impacts of urban growth is critical to ensure that the water requirements of the population and economy of the Mgeni catchment, are met.

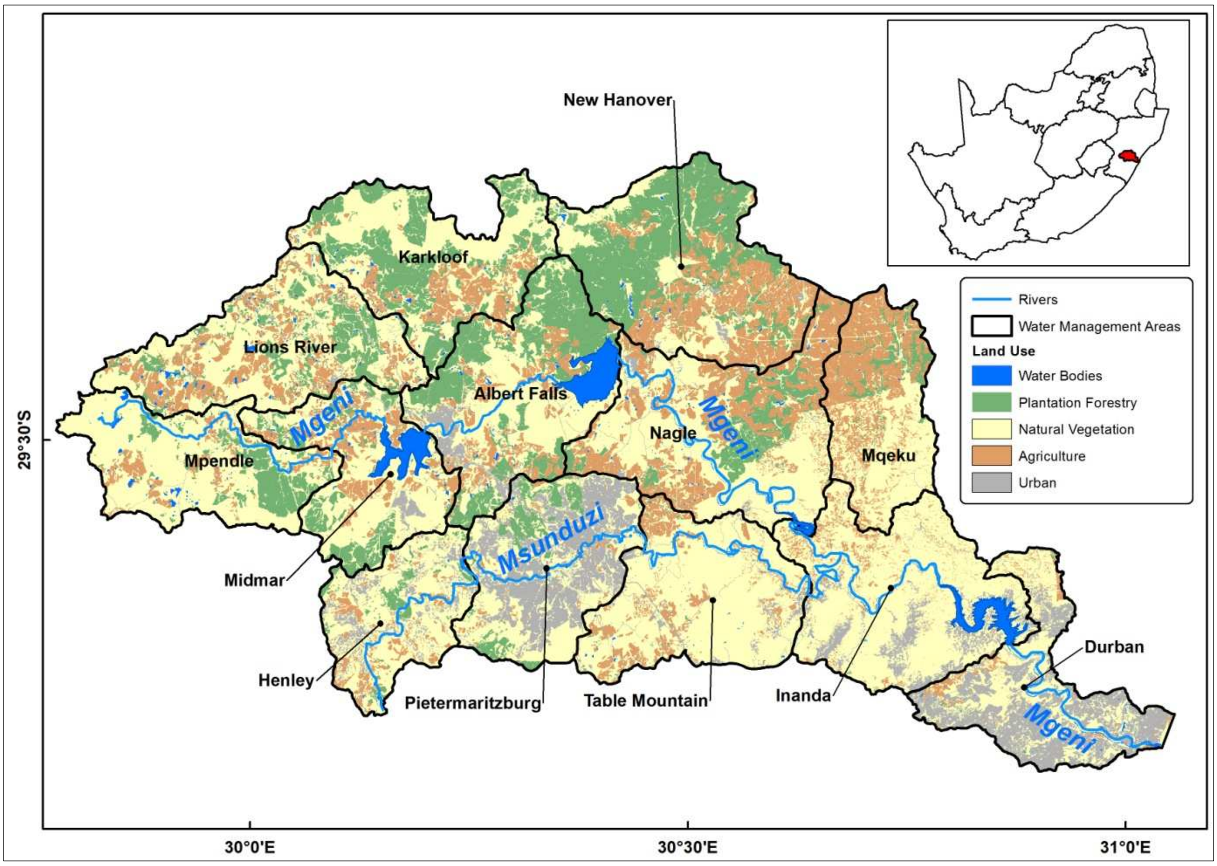

Figure 3.1 The land use of the Mgeni catchment and its associated WMAs in South Africa (adapted from Thompson et al., 2001)

3.3 Methodology

Ideally, the effects of land use changes on hydrological response would be accessed through physical measurements, for example paired catchment studies or small-scale experimentation. However, these methods are time consuming, expensive and the data records that are collected are often too short. Given these limitations, an alternative is to use a hydrological model to assess the impacts of land use change on hydrological response (DeFries and Eshleman, 2004). Hydrological modelling aids in the prediction of present and future behaviour of a system and allows for the testing of hypotheses and ‘cause and effect’ relationships (Schulze, 2009).

3.3.1 Model Selection

The ACRU Agrohydrological Model (Schulze, 1995) was selected as it has been applied extensively in South Africa to assess land use impacts on water resources (for example Tarboton and Schulze, 1992; Kienzle et al., 1997 and Schulze et al., 2004). ACRU's ability to represent changes in land use has recently been confirmed in a study by Warburton et al. (2010) where the ability of the model to simulate the hydrological responses to land use changes in three diverse catchments, with varying climates and land uses, was confirmed. Therefore, the ACRU model was deemed well-suited to assess the hydrological responses to urban land use change in the Mgeni catchment.

The ACRU Agrohydrological model is a physical-conceptual, daily time-step, multi-layer soil water budget model (Schulze, 1995; Smithers and Schulze, 2004). Being a physical conceptual model, ACRU does not rely on the calibration of parameters to produce a 'good fit' between the simulated and observed data, but rather physically based variables are estimated from actual catchment characteristics (Smithers and Schulze, 2004; Warburton et al., 2010). ACRU's multi-layer soil water budgeting (Figure 3.2), accounts for the partitioning and redistribution of soil water (Smithers and Schulze, 2004).

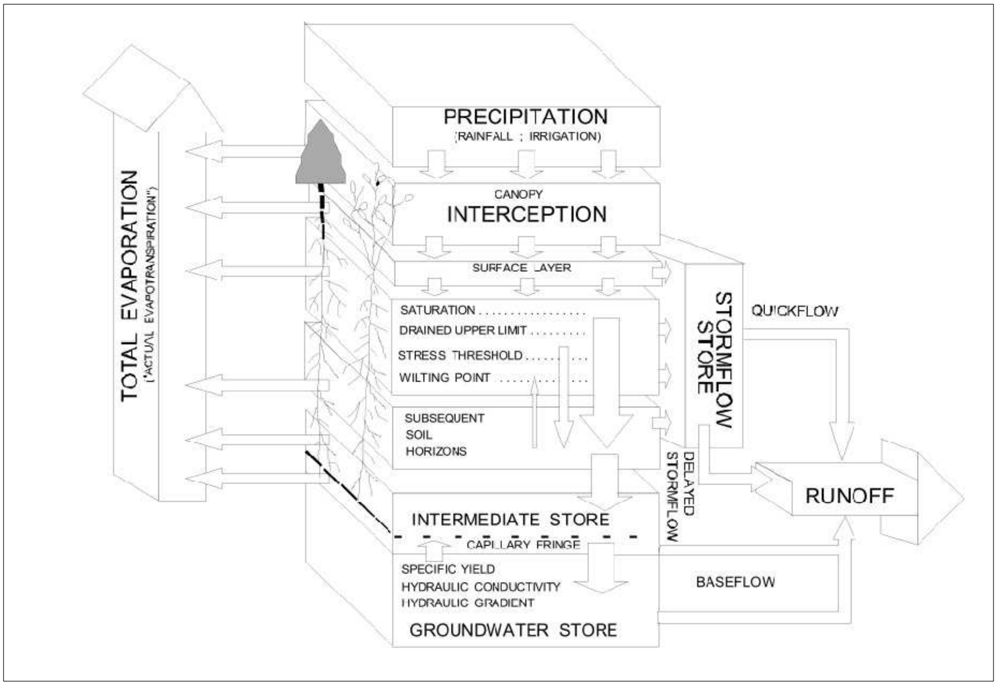

Figure 3.2 A schematic of the multi-layer soil water budget in the ACRU Model (Smithers and Schulze, 2004)

ACRU conceptualises the hydrological behaviour of a land use by accounting for the manner in which water is partitioned in the hydrological cycle according to the physical characteristics of the vegetation and soil (Schulze, 1995). Firstly, ACRU describes the partitioning of water at the vegetated surface, accounting for the interception and total evaporation from the vegetated surface. Total evaporation includes the evaporation of intercepted water, soil water evaporation and transpiration. Transpiration is governed by the plants' physiological characteristics, and is represented by a crop coefficient in the model (Schulze, 1995). Secondly, soil conditions are represented in the model, which governs the partitioning of water at the ground surface and the root zone. Soil texture and structure, soil depth and soil moisture variables are required inputs into the model (Schulze, 1995). All these factors determine the rate at which water infiltrates into the soil, hence determining the components of soil water storage, ground water recharge and runoff.

ACRU accounts for impervious areas in the urban land use unit by requiring the fraction of the subcatchment that is impervious. A distinction is made between the impervious areas in the subcatchment that are directly connected to a stream or stormwater system, i.e. adjunct impervious areas, and those areas that are adjacent to pervious areas, i.e. disjunct impervious areas (Schulze, 1995). In this study, typical values for the different types of urbanisation developed by Tarboton and Schulze (1992) were used (Table 3.1). These values have also been used in recent land use studies for the Mgeni catchment in Warburton et al., 2010 and Warburton et al., 2012. For the areas of urban growth, the urban growth within a subcatchment was assumed to be of the same urban-type currently present in the subcatchment.

Table 3.1 The percentages of adjunct and disjunct impervious area for the different types of urban land use

Urban Land Use Type	Adjunct Impervious Area (%)	Disjunct Impervious Area (%)
Informal Residential	12	10
Formal Residential	25	15
Informal Residential	30	20

3.3.2 Data Sources and Model Configuration

For this study, the ACRU model input variables and configuration for the Mgeni catchment as described in Warburton et al. (2010) was used. The Mgeni catchment was subdivided into 145 subcatchments by Kienzle et al. (1997), according to catchment characteristics, such as altitude, topography, soil, land use, water management and the location of gauging stations. The subcatchments are relatively homogeneous, with the exception of land use. Therefore, the subcatchments were further subdivided into land use units. ACRU requires historical climate data, such as rainfall and reference evaporation at a daily time step. Fifteen driver rainfall stations were selected for the Mgeni catchment, based on the reliability of the record, the altitude of the rainfall station and the location of the station within the catchment. A 40 -year record (1960-1999) of rainfall data was extracted from a rainfall database compiled by Lynch (2004) and reference evaporation was calculated using the Hargreaves and Samani (1985) daily reference evaporation equation. This equation requires daily maximum and minimum temperatures which were extracted from a database compiled by Schulze and Maharaj (2004). The soil information, such as the depth of topsoil and subsoil, and the water holding characteristics, such as the field capacity and wilting point, were obtained from a database of the ‘South African Atlas of Climatology and Agrohydrology’ (Schulze et al., 2008). The current land use data for this study was based on the National Land Cover map for the year 2000 (NLC2000) which was developed by Thompson et al. (2001).

3.3.3 Future Urban Land Use

The projected areas of future urban land use were determined using the SLEUTH Urban Growth model. SLEUTH provides maps of future urban growth for each year into the future until a particular end year. Each cell of urban growth is assigned a probability of becoming urban between 50 and 100%. The future urban land use for the years 2030 and 2050 was used, at three probability intervals, *viz.* >50%, >70% and >95%. These scenarios were overlaid with the NLC2000, resulting in six maps of plausible future urban growth for each urban growth scenario and for the two years of interest, *viz.* 2030 and 2050.

3.3.4 Baseline Land Use: A Means of Comparison

Modelling the hydrological response due to land use change generally relies on a comparative assessment of the hydrological responses of future land use to a current land use or pristine land cover; this is known as the baseline land use/cover. The baseline land cover determines the magnitude of the land use change observed over a time period in the area under investigation (Warburton et al., 2011). Currently, the South African Department of Water Affairs (DWA) supports and accepts the use of "natural vegetation" in the form of the Acocks' (1988) Veld Types as the reasonable standard or reference land cover against which to assess land use impacts (Schulze, 2004; Jewitt *et al*., 2009). In this study, both the current land use and Acocks (1988) Veld Types were used as a baseline to which the future urban extents were compared.

3.4 Results

The results for this study consist of two sections. Firstly, the results of urban growth modelling performed with the SLEUTH Urban Growth Model (SLEUTH) are summarised and secondly, the results of the subsequent hydrological modelling of urban land use changes using the ACRU Model.

3.4.1 Urban Growth Modelling

SLEUTH was found to be suitable to determine urban growth for use in hydrological applications as indicated by Mauck and Warburton (2012). SLEUTH provides the required scale and location of urban growth needed for hydrological applications, coping with the prediction of South Africa's complex urban growth. The urban growth generated by SLEUTH was mapped in relation to the 13 WMAs of the Mgeni catchment (Figure 3.3). The maps for the years 2030 and 2050 were selected to represent urban growth for the 41 year prediction period between 2009 and 2050 (Figure 3.3). The dark green areas indicate areas that have been assigned a probability of urbanisation of between 50 – 80%, the light green areas are assigned a probability of between 80 – 95% and the red areas show the highest probability of between 95 – 100% urban growth.

The results show that by 2030, urban growth is projected to occur predominantly on the edges of the current urban areas within the Henley, Pietermaritzburg, Inanda and Durban WMAs with little urban growth occurring in the WMAs in the upper parts of the Mgeni catchment, such as the Mpendle, Lion’s River and New Hanover WMAs. By 2050 extensive urban growth is seen in a number of WMAs, with most urban growth of a probability of urbanisation of greater than 95% occurring in the Midmar, Albert Falls, Henley, Pietermaritzburg, Table Mountain, Inanda and Durban WMAs (Table 3.2). Much of the urban growth in 2050 occurs in the upper parts of the Mgeni catchment (Henley, Pietermaritzburg and Table Mountain WMAs), thus suggesting that significant hydrological impacts will be seen in these WMAs when undertaking the hydrological impacts modelling under urban growth scenarios.

Furthermore, at the probability level of >95%, urban areas in the Mgeni catchment increase by 124% by 2050, while by 2030 the urban areas only increase by 31%, indicating that for the period 2030 to 2050 a higher growth rate was projected than between 2009 to 2030. This increased growth rate may be attributed to sprawling urban growth as a result of informal residential development.

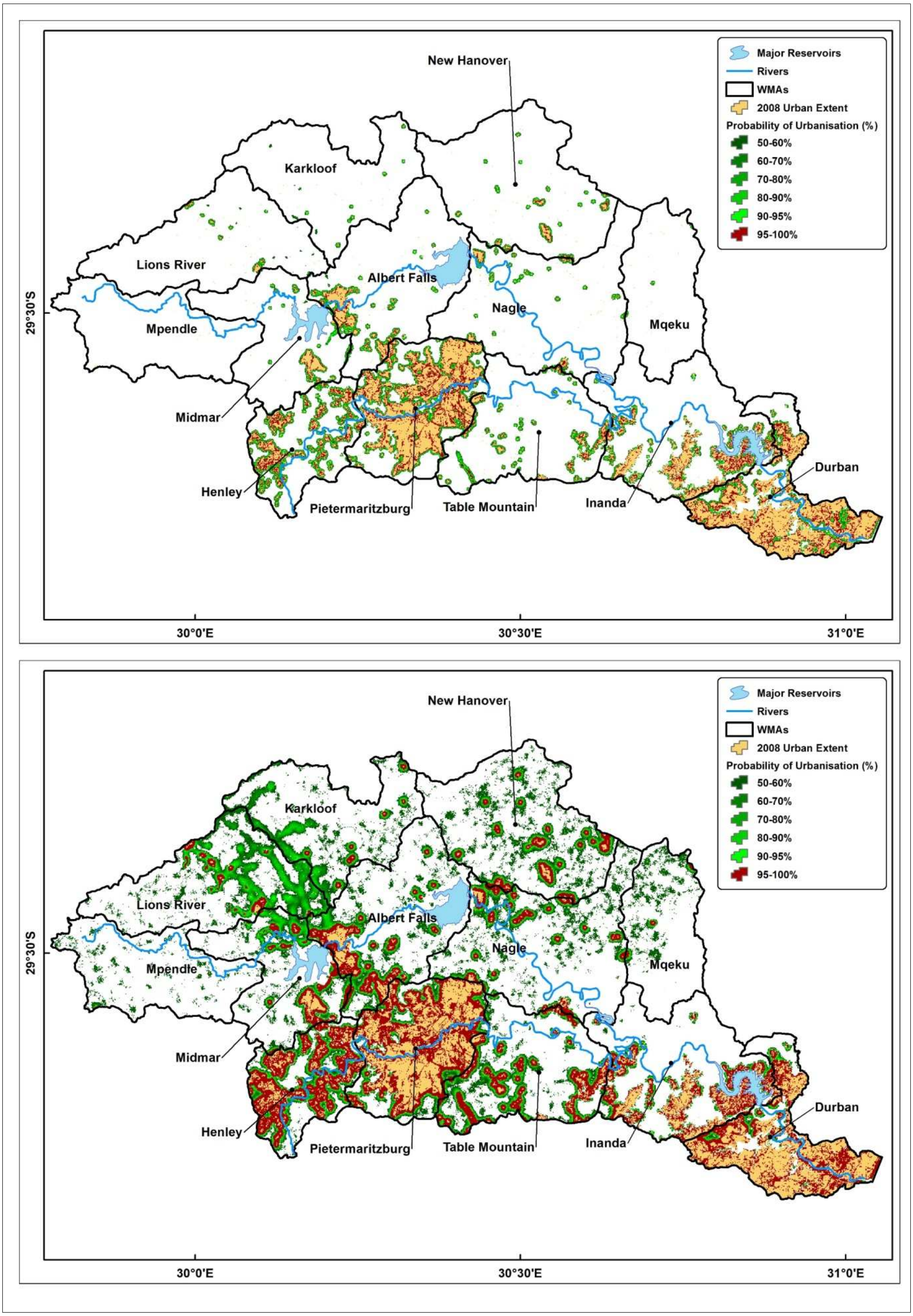

Figure 3.3 The predicted urban growth for the Mgeni catchment for the years 2030 (top) and 2050 (bottom)

Table 3.2 The absolute urban area (km^2) and the percentage of the WMA urbanised for the >95% probability urban growth scenario for the years 2030 and 2050

WMAs	**Area (km^2)**	**Urban Area (km^2)**			**Percentage of WMA Urbanised (%)**		
		2000	**2030**	**2050**	**2000**	**2030**	**2050**
Mpendle	295.7	0.2	0.2	0.2	0.1	0.1	0.1
Henley	220.0	54.3	62.5	112.8	24.7	28.4	51.3
Pietermaritzburg	318.6	114.3	150.7	208.5	35.9	47.3	65.5
Table Mountain	342.8	8.2	14.6	60.1	2.4	4.3	17.5
Lion's River	362.0	1.3	1.9	11.5	0.4	0.5	3.2
Midmar	269.2	4.6	5.5	29.6	1.7	2.0	11.0
Karkloof	334.3	0.1	0.1	4.7	0.0	0.0	1.4
Albert Falls	392.0	13.5	19.4	50.5	3.4	5.0	12.9
New Hanover	429.5	0.9	3.8	23.7	0.2	0.9	5.5
Nagle	453.7	2.6	5.1	26.8	0.6	1.1	5.9
Inanda	412.4	48.5	64.0	97.5	11.8	15.5	23.7
Mqeku	243.9	5.8	5.9	7.5	2.4	2.4	3.1
Durban	275.4	102.2	134.8	167.5	37.1	48.9	60.8
Mgeni catchment	4 349.4	356.6	468.7	800.9	8.2	10.8	18.4

3.4.2 Hydrological Modelling

The ACRU Model was used to simulate the accumulated streamflow for each of the urban growth scenarios for 2030 and 2050 for the Mgeni catchment. For the purposes of this study the >95% urban growth scenario will be assessed in greater detail. The >95% urban growth scenario is deemed the most plausible scenario for 2030 and 2050, because it is associated with the highest probability of occurrence.

3.4.2.1 Changes in streamflow simulated under current land use and projected urban growth scenarios

A comparison of the changes in mean annual accumulated streamflow generated under the current land use to those generated under the >95% urban growth scenario for 2030 and 2050 is shown in Figure 3.4. This comparison indicates the impact of urban growth on catchment streamflows, under the assumption that the urban growth is the only land use change from current land use patterns. For the year 2030, results indicate that even with a 30% growth in urban areas in the Mgeni catchment there is no change in annual accumulated streamflows over most of the catchment, with the exception being the areas within the Pietermaritzburg WMA that show increases in mean annual accumulated streamflows of up to 25%, together with small isolated areas of increases in mean annual accumulated streamflows of up to 15% in the Midmar, Albert Falls, Inanda and Durban WMAs.

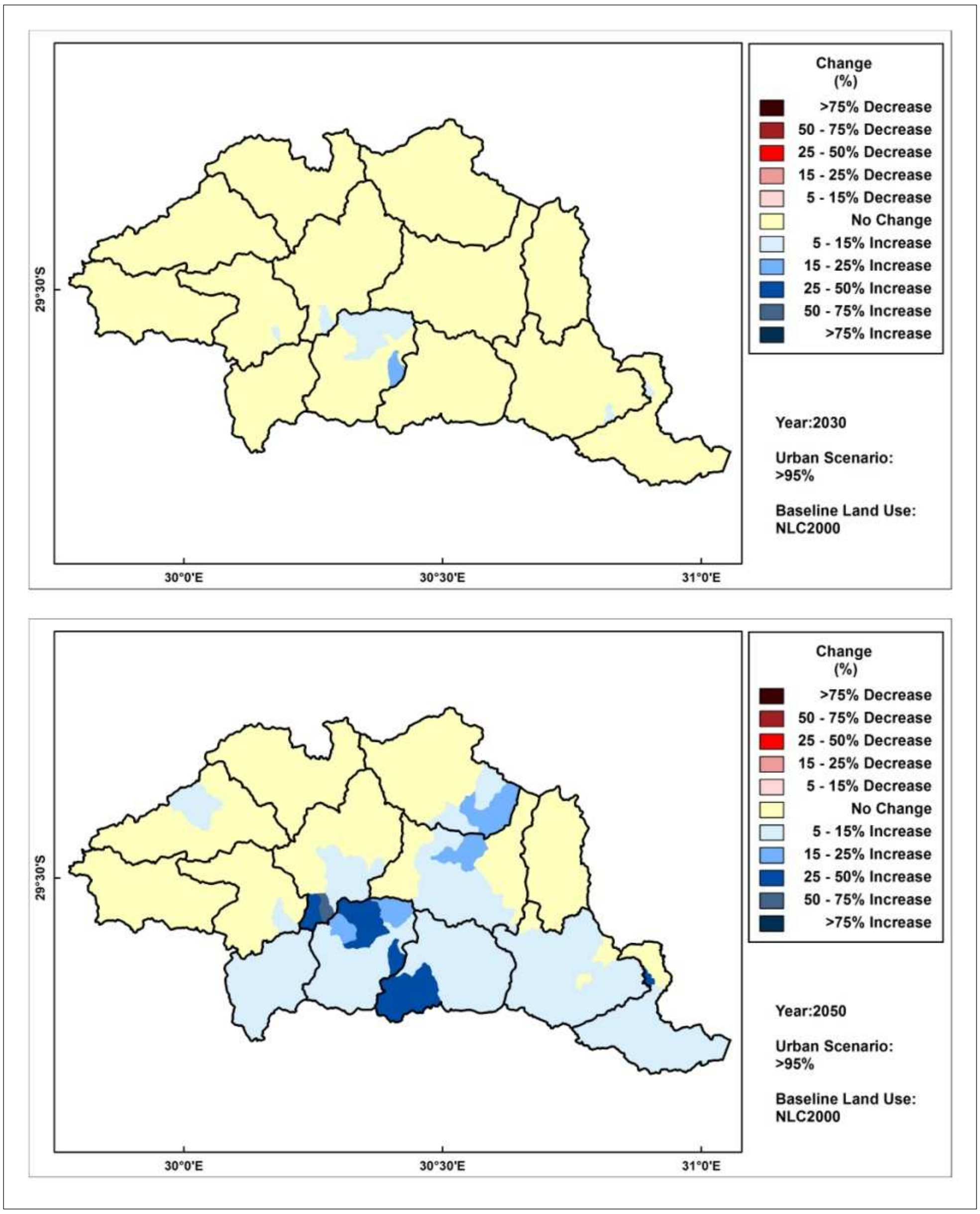

Figure 3.4 The percentage change in mean annual streamflow (%), between current land use and the >95% urban growth scenario, for the years 2030 (top) and 2050 (bottom)

However, marked increases in mean annual accumulated streamflows in 2050 are evident in most of the WMAs in the Mgeni catchment; particularly those on the Msunduzi River, *viz*.: Henley, Pietermaritzburg, Table Mountain, Inanda and Durban WMAs. Correspondingly, these WMAs have the highest projected urban growth in both the 2030 and 2050 scenarios (Table 3.2). The Lion's River, Nagle and Albert Falls WMAs show areas of increased mean annual accumulated streamflow for the 2050 urban growth scenario that were not evident for the 2030 urban growth scenario. The larger number of WMAs projecting increased annual accumulated streamflows in 2050, and the higher percentage increase in flows, corresponds with the increased urban growth rate between the period 2030 – 2050 in comparison to 2009 – 2030.

The results indicate a potentially higher sensitivity of streamflow to changes in urban land use in the Pietermaritzburg WMA than in the Durban WMA. This supports the theory suggested earlier that urban growth occurring in the headwaters of a catchment is likely to show a greater impact on hydrological response than at the outlet of the catchment. The Pietermaritzburg and Durban WMAs show similar levels of urbanisation, ~65% and ~61%, respectively (Table 3.2). For the Pietermaritzburg WMA significant increases in mean annual streamflows of up to 50% are evident, whereas in the Durban WMA only increases in mean annual streamflows of up to 15% are evident. The areas of significantly increased mean annual streamflows in the Pietermaritzburg WMA do not have any contributions from upstream subcatchments, indicating that any streamflow increases generated solely from urban growth within that specific subcatchment. The increases in the Durban WMA are, however, the accumulated effects of upstream impacts.

3.4.2.2 Changes in simulated streamflow under current land use, projected urban growth scenarios as compared to Acocks (1988) land cover

Comparing streamflows simulated under projections of urban growth and current land use to streamflows simulated under a baseline land use allows the changes in streamflow as a result of urban growth to be assessed together with the moderating or amplify effects of other hydrologically significant land uses. Figure 3.5 shows the percentage change in mean annual, summer (December, January, February) and winter (June, July, August) accumulated streamflows under current land use, and the >95% probability urban growth scenarios for 2030 and 2050 as compared to streamflows simulated under Acocks (1988) land cover.

Under current land use, increases in mean annual accumulated streamflows are evident in the Henley, Pietermaritzburg and Table Mountain WMAs and parts of the Inanda WMA due to the urban areas of the current land use scenario. There are also increases in mean annual streamflow in the New Hanover, Nagle and Mqeku WMAs which are attributable to presence of small farming towns in the north of the catchment. Reductions in mean annual accumulated streamflows are evident in the Mpendle, Lion's River, Karkloof and New Hanover WMAs due to the presence of plantation forestry and sugarcane. The Midmar, Albert Falls and Nagle WMAs and parts of the Inanda WMA show decreased streamflow, which can be attributed to regulation of flows and storage of water in the Midmar, Albert Falls, Nagle and Inanda dams, respectively. The Durban WMA shows a slight decrease in streamflows due to the accumulated upstream effects.

The simulated mean annual accumulated streamflow changes generated under the 2030 urban growth scenario show increases primarily in the Pietermaritzburg and Table Mountain WMAs when compared to streamflow change under current conditions. These areas show streamflow increases from 5–15% under current land use, while under the 2030 urban growth scenario increases of 15–25% are evident, with more severe changes occurring in the Pietermaritzburg WMA with some areas showing up to 75% or greater increase in streamflow generation (Figure 3.5). These streamflow increases are, however, attenuated downstream, with the Inanda and Durban WMAs showing streamflow decreases of 5–15%. Under the 2050 urban growth scenario further increases in mean annual streamflow in the Henley, Pietermaritzburg and Table Mountain WMAs are evident, with most of the Henley and Pietermaritzburg WMAs showing upwards of a 25% increase in mean annual accumulated streamflow, in comparison to the 5–15% increase in streamflow under current land use (Figure 3.5). The increases in mean annual streamflow in the Henley, Pietermaritzburg and Table Mountain WMAs have reached a point where they have exceeded the downstream attenuating influences seen in the 2030 urban growth scenario and in the Inanda and Durban WMAs where the streamflow changes have now increased to 'No Change' (Figure 3.5). The New Hanover, Nagle and Mqeku WMAs only start to show increases in mean annual streamflow in the 2050 urban growth scenario, as these areas only start to experience significant urban growth by 2050. The Lion's River WMA indicates some areas that show decreases in the mean annual streamflow of 25–50% for the current urban scenario that have increased to 15–25% in 2050. The decreased mean annual streamflows that were dominant in the current scenario, due to the presence of commercial forestry, have experienced increases in mean annual streamflow as a result of urban growth in the Lion's River catchment, which only started to show significant impacts on hydrological responses in 2050.

Due to the mean annual streamflow averaging seasonal variations, it is necessary to assess the impacts of urban growth on seasonal streamflows. The changes in mean summer streamflow under current land use show significant decreases in the Midmar, Albert Falls and Nagle WMAs, as a result of the dams storing water generated by higher summer rainfalls. The opposite is evident in winter, where the water stored during summer is released from the dams resulting in increased flows downstream during winter. As a result, the downstream Inanda and Durban WMAs experience decreased mean summer streamflow and increased mean winter streamflow relative to the baseline condition (Figure 3.5). The Midmar, Lion’s River and Karkloof WMAs show significant decreases in both winter and summer streamflow, which emphasises the impact of plantation forestry, most notably on winter low flows.

The mean summer and winter streamflows under the 2030 urban growth scenario show little change with only slight increases in summer streamflows in the Pietermaritzburg and Table Mountain WMAs. In contrast, the mean summer streamflows in 2050 show significant increases in the Pietermaritzburg and Table Mountain WMAs, which cascades downstream increasing summer streamflow in the Inanda and Durban WMAs. The reductions in mean summer streamflows due to plantation forestry in the Lion’s River WMA have decreased in 2050 compared to the current scenario. This is attributed to replacement of plantation forestry and other land uses such as agricultural land and natural vegetation with urban land use. However, there is no change in the mean winter streamflow for the Lion’s River WMA indicating that the increases in urban land use may have a greater impact during summer than in winter. The mean winter streamflows in 2050 show relative increases in the Pietermaritzburg and Table Mountain WMAs in comparison to the current scenario, however most of the other WMAs show little change in streamflow from the current scenario.

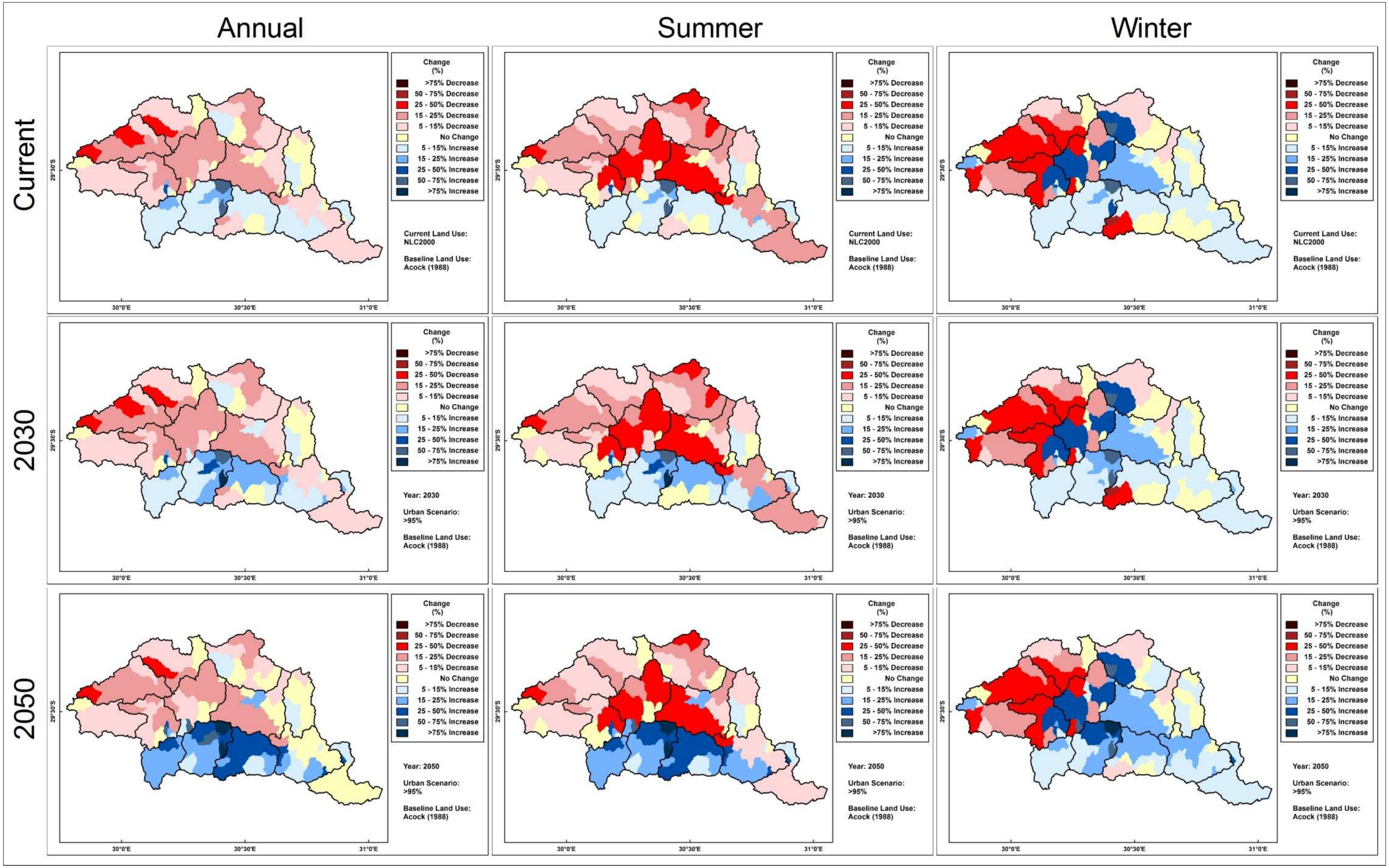

Figure 3.5 Percentage changes in annual (left), summer (middle) and winter (right) mean accumulated streamflows simulated under current land use and the >95% urban growth scenarios for 2030 and 2050 as compared to Acocks (1988) land cover

The simulated mean monthly streamflows generated under the urban growth scenarios for various urban growth probabilities, i.e. >50%, >70% and >95%, for the year 2050 were assessed in comparison to streamflows generated under current land use at three locations in the Mgeni catchment, *viz.* the Mgeni River slightly upstream of its confluence with the Msunduzi River (Figure 3.6), the Msunduzi River slightly upstream of its confluence with the Mgeni River (Figure 3.7) and at the outlet of the Mgeni catchment (Figure 3.8). All the locations (Figure 3.6 Figure 3.7 and Figure 3.8) show significant increases in streamflow during the summer months (December, January, February) for the >50%, >70% and >95% urban growth probabilities whereas the changes in mean monthly streamflow during the winter months (June, July, August) show only small increases, indicating that streamflow change is more sensitive to urban land use changes during the high rainfall summer months than in the low rainfall winter months. The Msunduzi River (Figure 3.7) shows higher streamflows than those seen on the Mgeni River (Figure 3.6), and the outlet of the Mgeni catchment (Figure 3.8). This is due to the absence of streamflow attenuating land uses, such as commercial sugarcane and plantation forestry, and major reservoirs on the Msunduzi River. In comparison, there are a number of streamflow attenuating land uses and major reservoirs on the Mgeni River prior to its confluence with the Msunduzi River and upstream of the catchment outlet. The >50% urban growth scenarios shows a more significant response than the other urban scenario, which is indicative of the increased urban area as a result of sprawling urban growth as described in Section 3.4.1.

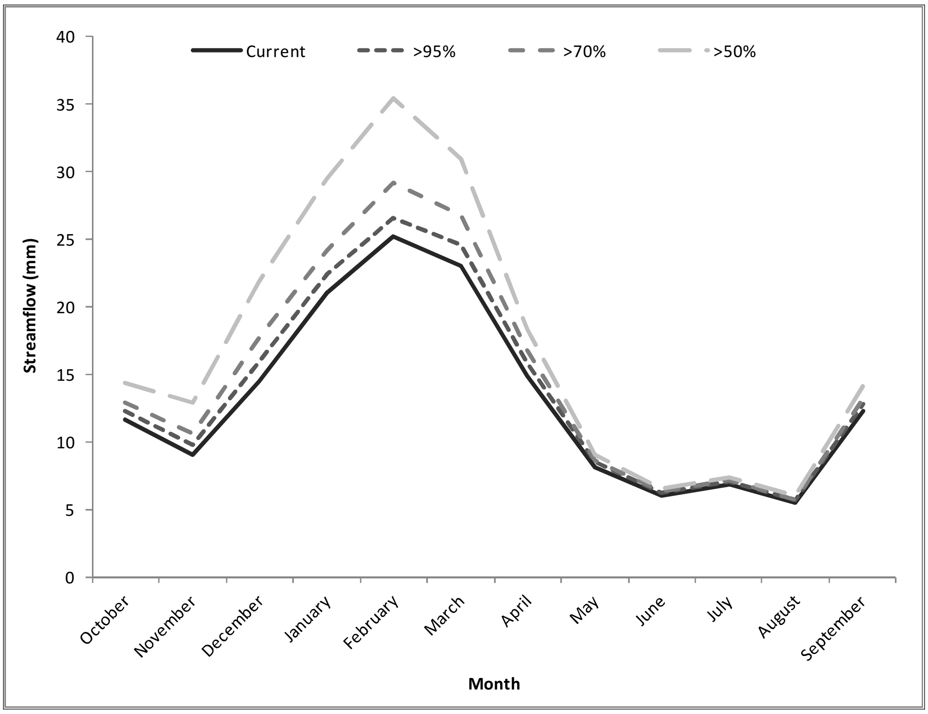

Figure 3.6 The simulated streamflow generated for the Mgeni River slightly upstream of its confluence with the Msunduzi River, for the different urban growth scenarios for the hydrological year 2050

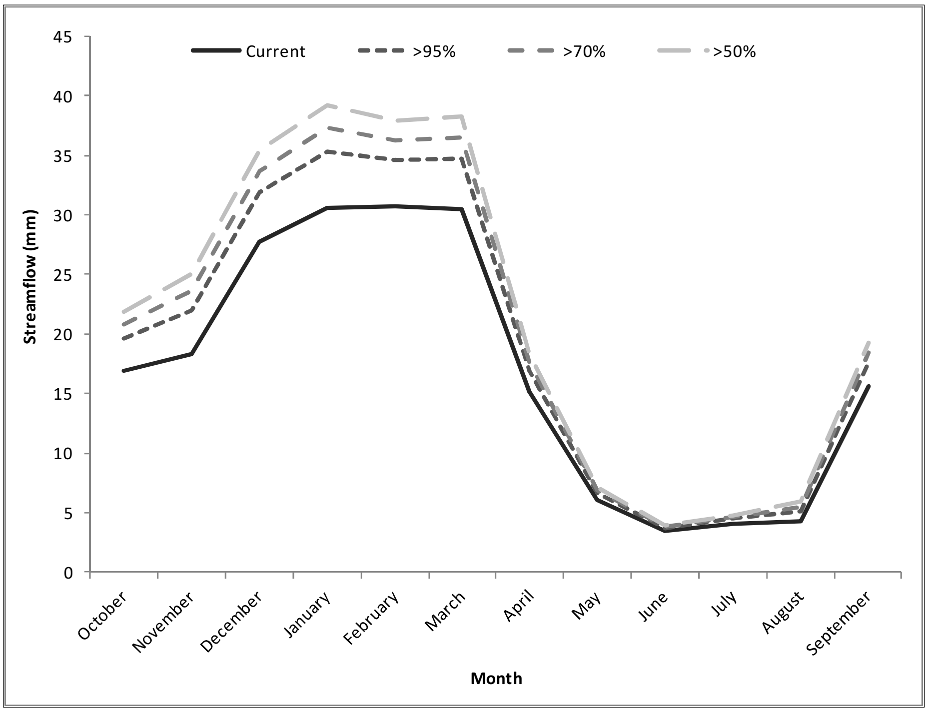

Figure 3.7 The simulated streamflow generated for the Msunduzi River slightly upstream of its confluence with the Mgeni River, for the different urban growth scenarios for the hydrological year 2050

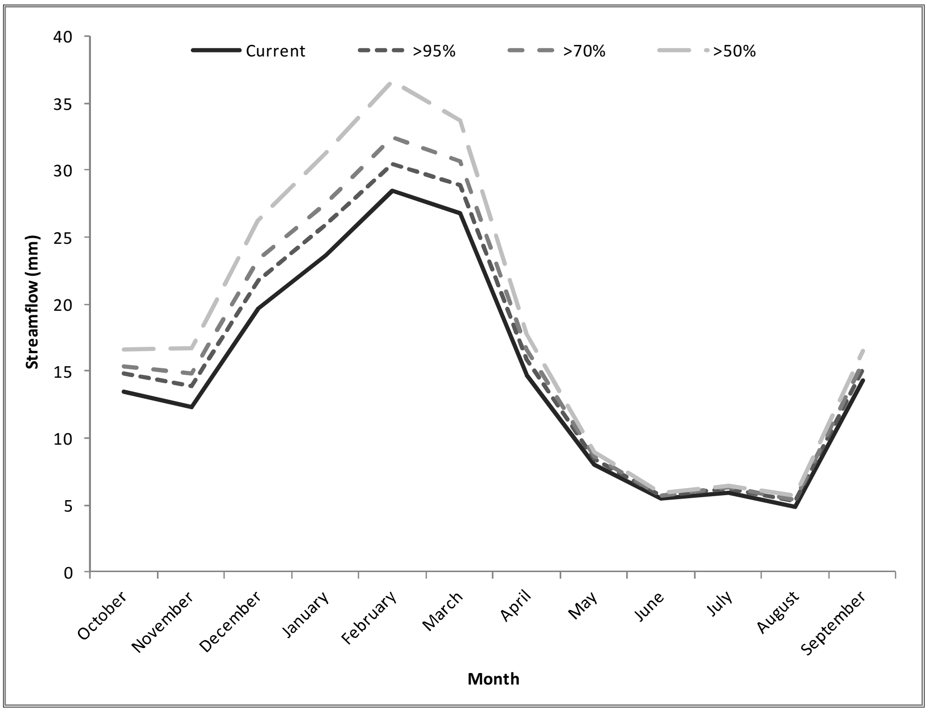

Figure 3.8 The simulated streamflow generated for the Mgeni River its outlet into the Indian Ocean, for the different urban growth scenarios for the hydrological year 2050

3.4.2.3 The Effect of the Nature of Urban Land Use on Streamflow

It is not simply urban growth which influences streamflow, but also the nature of the urban growth as the different types of urban land use are associated with different levels of impervious area. To evaluate the effect of the type of urban land use on streamflow responses, modelled streamflows from three theoretical subcatchments with identical soils and climate and varying urban land use types were compared to streamflows generated for the same subcatchment under baseline land cover. The urban land use in the first subcatchment was assumed to be informal residential areas. This type of urban land use has the lowest impervious area of 22%, with much of this assumed to be *disjunct* to streams. The second subcatchment was assumed to be formal residential areas, with the impervious area being 40%. The last subcatchment was assumed to be built up urban areas. This type of urban area has the highest percentage of impervious areas, i.e. 50%, with most areas impervious areas being connected to storm water systems and streams.

Informal residential areas with a total impervious area of 22% (Table 3.1) resulted in a 45% increase in streamflow when compared to baseline vegetation (Figure 3.9), while the built up urban land use with a total impervious area of 50% resulted in a 106% increase in streamflow relative to baseline vegetation (Figure 3.9). Therefore, built up urban land use has 2.36 times the impact on streamflow change than informal residential urban land use and formal residential urban land use has 1.78 times the impact on streamflow change compared to the informal residential urban land use.

The WMAs in the Mgeni catchment which are projected to experience significant urban growth by 2050 are shown in Table 3.3, and the presumed weighting of the type of urban area based on the distribution of urban types in the current scenario in that WMA. The Henley WMA is projected to be ~51% urban by 2050 (Table 3.2), while the Pietermaritzburg WMA is projected to be ~65% urban. Although the amount of urban land use in each of the WMAs is similar, the resultant changes in streamflows due to urban growth are different, with the Pietermaritzburg WMA projected to experience far greater streamflow increases (Figure 3.5). This is attributable to the type urban growth in the Henley catchment being assumed to be only informal residential areas, while the Pietermaritzburg WMA is presumed to experience growth in all three types of urban land use.

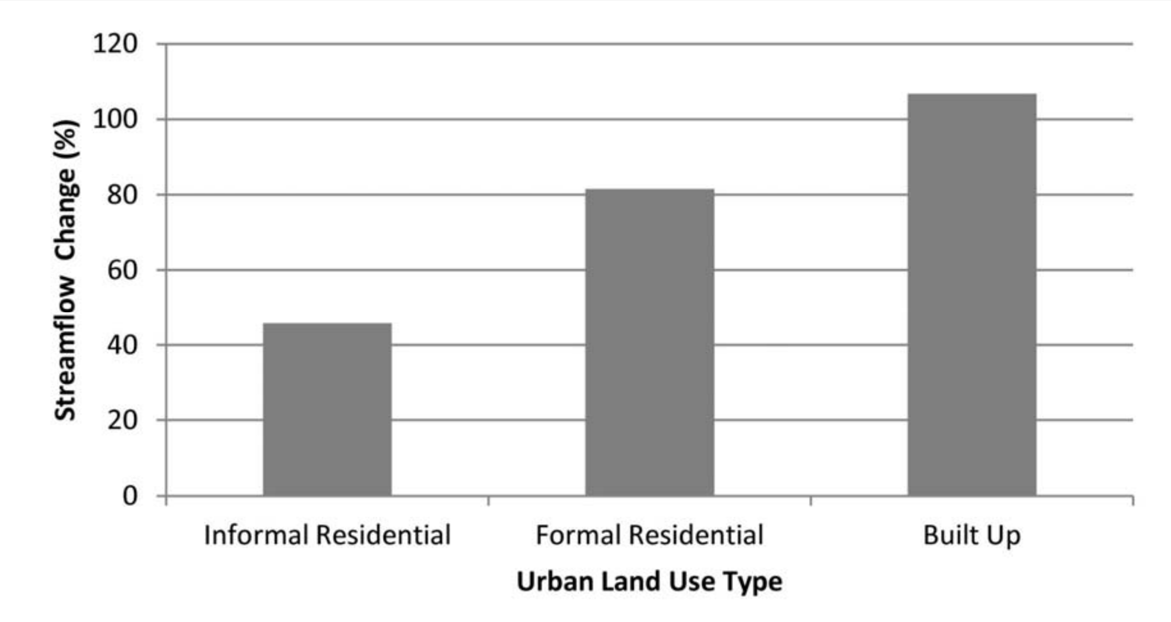

Figure 3.9 The sensitivity of streamflow changes generated from the three urban land use types

Table 3.3 Selected WMAs that have shown the most urban growth and associated weighting of the urban growth types for current urban areas

WMA	Total Urban Area (km^2)	Informal Residential	Formal Residential	Built Up
		% Area	% Area	% Area
Albert Falls	13.5	5.0	85.0	10.0
Durban	102.2	27.0	59.0	14.0
Henley	54.3	100.0	0.0	0.0
Inanda	48.5	98.0	2.0	0.0
Midmar	8.0	90.0	10.0	0.0
Pietermaritzburg	114.3	46.0	42.0	12.0
Table Mountain	8.2	61.0	18.0	21.0

3.5 Discussion

In a previous study, SLEUTH was found to be suitable for urban growth modelling in the Mgeni catchment (Mauck and Warburton, 2012). The projections of urban growth generated by SLEUTH were used to update the NLC2000 to create urban growth probability scenarios, *viz.* >95%, >70%, >50%, for the years 2030 and 2050, which were used as input to the ACRU Agrohydrological Model to simulate resultant streamflows.

The >95% urban growth scenario was focused on as it represents the areas of urban growth that are associated with the highest probability of urbanisation; thus making this the most likely scenario. The comparison of mean annual streamflows generated under future urban land uses to those generated under current land use isolates the impacts of increased urban growth, excluding the influence of other land uses on streamflow change. The mean annual streamflow generated from the >95% urban growth scenario for 2030 showed little change; however, by 2050 significant increases in mean annual streamflows in a number of areas within the Mgeni catchment (Figure 3.4) were evident. Some of these changes in streamflows are attributable to development of small farming towns, for example in the New Hanover, Nagle and Mqeku WMAs, while other areas show urban growth along transportation routes such as along the national highway between Durban and Johannesburg (Albert Falls WMA) and the transport routes surrounding Pietermaritzburg.

The comparison of streamflows simulated under projections of urban growth to that simulated under a baseline land use (Acocks, 1988), includes the influence of other hydrologically sensitive land uses such as plantation forestry, commercial sugarcane and agriculture, in addition to urban land use (Figure 3.5). By 2030, slight increases in mean annual streamflow are evident in the Pietermaritzburg and Table Mountain WMAs. However by 2050, significant increases in mean annual streamflows are evident in the Henley, Pietermaritzburg and Table Mountain WMAs. The projected urban growth between 2030 and 2050 is indicative of uncontrolled and sprawling urban growth and is the reasoning behind the Henley WMA only responding hydrologically to urban growth in 2050. Much of the urban growth projected for the Mgeni catchment is expected to occur around the current Pietermaritzburg urban area, thus influencing the Msunduzi River which flows through the Pietermaritzburg WMA (as well as the upstream and downstream WMAs). The areas on the Mgeni River such as Lion's River, Midmar, Karkloof and Nagle WMAs show reductions in mean annual streamflow in 2050 due to the presence of plantation forestry, commercial sugarcane and major dams. However, the increases in mean annual streamflow on the Msunduzi River in 2050 have started to override the accumulated reductions seen in the Inanda and Durban WMAs in the current and 2030 scenarios. The seasonal influence of urban land use on streamflow was also highlighted, where mean summer streamflows were shown to be more responsive to urban land use than mean winter streamflows. The impact of seasonal streamflow changes are seen where the increases in mean summer streamflow as a result of urban land use starts to override the streamflow-reducing influence of other land uses. This is shown where the streamflow generated under the 2050 land use begins to lower the reducing influence of plantation forestry in summer, whereas there is no change in the mean winter streamflow under 2050 land use.

Any increases in streamflow on the Mgeni River as a result of urban land use are not significant enough to overcome the attenuating influence of the presence of major dams (Figure 3.5). These dams lower the sensitivity of streamflow to increases in urban land use on the Mgeni River. The demand for water in the Pietermaritzburg and Durban urban areas is mostly supplied by the Mgeni River; therefore the Mgeni River is currently subject to reductions in streamflow due to transfers of water into the Pietermaritzburg WMA to meet the requirements of urban demand. These transfers of water ultimately increase the streamflow in the Msunduzi River through the increases in return flows from urban areas.

Conversely, the Msunduzi River does not have the same attenuation of streamflow by reservoirs, nor does it have the same demands to supply water for urban usage. Given the limited demands placed on the Msunduzi River, the absence of regulating reservoirs, the hydrological responses of the river system are projected to be sensitive to the urban growth projected for the WMAs. In addition, with increased urban growth on the Msunduzi River the demand for water is likely to increase and therefore would increase the demands on the Mgeni River. The transfer of water from the Mgeni River to the Pietermaritzburg WMA for urban use, would increase streamflows in the Msunduzi River and enhance the reductions on the Mgeni River in the future. Therefore the planning of future urban growth must recognise the higher sensitivity of streamflows to urban growth along the Msunduzi River, in areas such as the Pietermaritzburg WMA.

The results of the theoretical catchment simulation indicate that streamflow generation is sensitive to the type of urban land use. Two WMAs which experience a similar growth in urban areas may experience different changes in hydrological responses due to the type of urban growth occurring in each of the WMAs. For example, the Henley WMA, which is predominantly informal residential urban land use, shows less streamflow change than the WMA Pietermaritzburg, which has greater amounts of built up urban land use. The sensitivity of streamflow to urban land use is dependent on the location of urban areas within the catchment and the type of urban growth. Since streamflows are sensitive to the type urban land use, the representation of urban land use within a hydrological model is important. Therefore, when developing future land use policies and plans it is pertinent to consider type of urban land use, as each type of urban land use is associated with different degrees of imperviousness and hence varying hydrological responses.

Given the projected hydrological responses to the various scenarios of urban grow; water resources planning needs to incorporate urban growth and spread not only from the perspective of additional demand for water but also the impacts on catchment responses. Furthermore, given the relationship between urban land use and streamflow, land use planning and water resources planning cannot occur in isolation. Using scenarios of plausible urban growth can be beneficial in aiding decisions-making in the management of urban water resources, in urban land use planning and can be used to inform the development and planning of water-related policy.

3.6 Conclusion

Scenarios of plausible urban growth, generated by an urban growth model (SLEUTH), provide valuable insight into the likely hydrological response of future urban growth. The scale and location of urban growth was important as this determined the hydrological responses within the catchment. The results indicated that the Henley, Pietermaritzburg and Table Mountain WMAs are the most hydrologically sensitive WMAs due to increases in urban land use and the absence of streamflow attenuating activities such as plantation forestry, commercial sugarcane and major dams. The results also indicated that the type of land use has a significant impact on streamflow change. It is these sensitive areas that will require the most consideration when developing policies and plans regarding urban land use and its impacts on streamflow.

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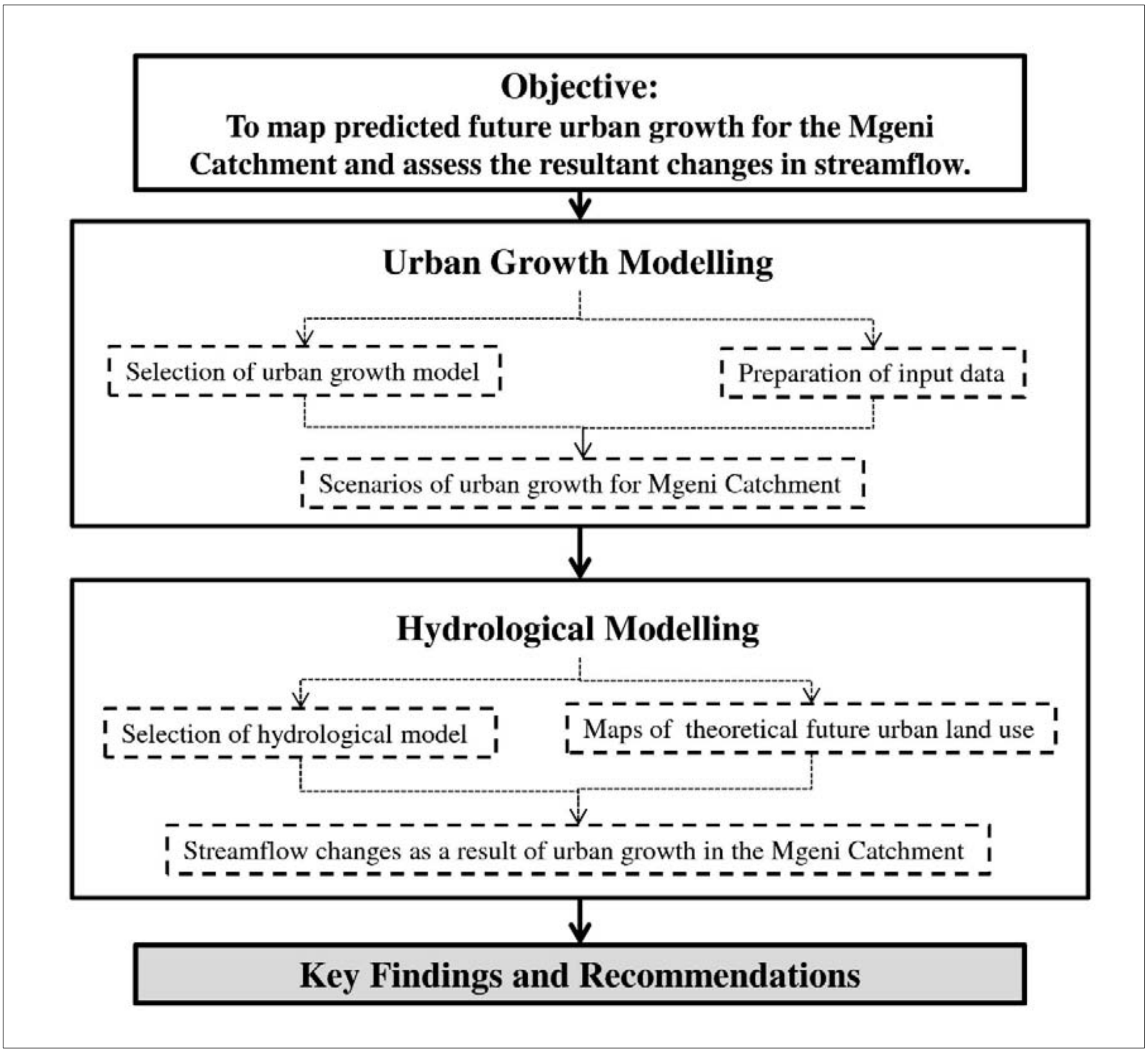
Lead in to Chapter 4

The key findings from Chapters 2 and 3 are consolidated in Chapter 4. These finding can be used to guide water resources management through the use of forecasting tools, such as urban growth modelling, for the development of policy and planning and enhancing the understanding of the urban land use and its relationship with hydrological response.



4. SYNTHESIS: KEY FINDINGS AND RECOMMENDATIONS

The research conducted in the two papers highlighted a number of key issues both in the modelling of urban growth in a South African context for the purposes of hydrological impact studies, and the relationship between urban growth and its resulting impacts on streamflow. The first paper (Chapter 2) demonstrated the potential of an urban growth model (SLEUTH) to provide scenarios of plausible urban growth for a South Africa situation for the purposes of hydrological impact assessment. The second paper (Chapter 3) described streamflow responses under plausible scenarios of future urban growth for the Mgeni catchment, while considering the dynamics of urban land use and streamflow response. The key findings of this research were:

- that the SLEUTH Model was able to model plausible future urban growth for the Mgeni catchment, thus demonstrating that the SLEUTH model has the potential to be applied successfully to a South African urban environment;
- the SLEUTH and ACRU models could be loosely coupled, to provide information on the hydrological impacts of urban growth;
- that streamflow responses are sensitive to the scale and location of urban growth in the Mgeni catchment. Specific areas, such as the WMAs along the Msunduzi River, were identified as potentially sensitive to urban growth;
- that summer streamflows are more sensitive to urban land use changes than winter streamflows;
- that increases in streamflows due to urban growth start to over-ride other hydrologically sensitive activities such as commercial forestry and commercial sugarcane by 2050, whereas in other areas increases in streamflows are mitigated by major dams; and
- that the type of urban land use has a significant impact on streamflow responses.

These key findings are discussed in the following sections, concentrating on the use of an urban growth model in hydrological impact studies and the relationship between hydrological responses and urban land use.

4.1 The Use of Urban Growth Models in Hydrological Impact Studies

The modelling of plausible urban growth provides insight into the nature of future urban areas (Silva and Clarke, 2002). An understanding of urban growth, and future land use changes in general, is pertinent to understanding future hydrological responses (Lin *et al*., 2008). Therefore, the loose coupling of an urban growth model and a hydrological model is a valuable means to gain an understanding of the nature of the hydrological responses to future urban land use. With the concern surrounding the impacts of global environmental change, it is necessary to consider how these changes relate to one another (Harding and Kabat, 2007). The scale and location of urban growth is necessary for hydrological impact studies and it was found that the SLEUTH Model was able to meet these requirements. In this study the urban growth generated by SLEUTH was not considered as a prediction as such, but rather a set of plausible scenarios of urban growth.

The application of SLEUTH is associated with a number of uncertainties relating to input data and model adequacy. South African conditions present a number of challenges in terms of the data required for SLEUTH. For instance, during the configuration of the SLEUTH Model, it was evident that fine scale South African land use and infrastructure data are difficult to source and may be subject to various incompatibilities. These incompatibilities refer predominantly to the land cover maps available *viz.* NLC94 (Thompson, 1996), NLC2000 (Thompson *et al*., 2001) and the 2005 and 2008 EKZNW land cover maps (Geoterraimage (Pty) Ltd., 2010). These four available land cover maps were mapped at different resolutions and the land cover classification systems used, varied. In addition, given the limited number of land cover maps available, model verification was not possible as this requires a fifth land cover layer. This means that the model's representation of urban growth in South Africa could not be comprehensively proven other than through comparison to the only other documented application of SLEUTH in South Africa conducted by Watkiss (2008).

The uncertainty associated with the input data could lead to inaccurate growth coefficients in the model, resulting in poor model performance. Therefore, as discussed before, the urban growth generated by SLEUTH should only be used as a plausible scenario of possible future urban growth rather than a prediction. Given the uncertainty of the input data it is suggested that the input data be improved (this is addressed further in Section 4.4). In addition to improved input data, as further land cover datasets are released for South Africa a comprehensive validation of the model should be performed, which will improve the models application for South African conditions. It would also be beneficial to extend the range of the historical urban extents, as the earliest data is for 1994. Since there was a significant change in politics during the early 1990's which has impacted the structure of urban areas, it may be beneficial to develop a land cover map for prior to this period.

There is also uncertainty associated with the model, as the model is only a simplification of actual urban growth processes and cannot incorporate all the factors that influence urban growth and represent them explicitly. For example, SLEUTH does not incorporate political and demographic variables, which creates uncertainty as these factors are important to urban growth (Zhao and Chung, 2006). Even under ideal conditions, having perfectly accurate data and a model that explicitly represents urban areas, there is still uncertainty that exists as a result of future events and circumstances. This may be in the form of political change, economic change or even a change in the environment such as natural disasters. Therefore, it must be acknowledged that the modelling of urban growth and future systems is in general, innately uncertain and should rather be viewed as scenarios of plausible future outcomes.

Despite these hindrances and uncertainties, it was found that the SLEUTH Model is capable of projecting future urban growth in a South African context and was able to cope with the urban development associated with South Africa's complex political and economic past. The benefits of urban growth modelling are not limited to hydrological impact studies, but can be used to assess other environmental impacts associated with urban areas and providing a tool for urban planning. Through the use of an urban growth model the opportunity to assess the environmental impacts of urban growth during the planning phase is provided, and feedbacks from this can be incorporated into urban planning. Thus, urban growth models are beneficial for use in hydrological and environmental impact studies, however the limitations to urban growth modelling should be considered when attempting urban growth modelling in a South African context.

4.2 The Relationship between Hydrological Response and Urban Land Use

The relationship between urban land use and hydrological response is already a complex one (Marsalek, *et al*., 2006) and can be expected to be further complicated in the coming decades with increasing urbanisation and other land use changes (Lambin *et al.*, 2001). It is important to understand the impacts of current and future urban land use, so that urban planning can be undertaken with its associated hydrological responses in mind. With the projections of plausible future urban growth available from urban growth modelling, the hydrological responses to changes in urban land use can be modelled. The *ACRU* Model was used to model changes in streamflow in the Mgeni catchment because it has been proven to be sensitive to land use change and to changes thereof (Tarboton and Schulze, 1992; Kienzle *et al*., 1997; Schulze *et al*., 2004 and Warburton *et al*., 2010). ACRU was well suited to test the dynamics of the relationship between land use changes and hydrological responses in the Mgeni catchment.

There are uncertainties involved in the hydrological modelling of land use changes. The model in itself is a simplification of the hydrological system and this simplification is a source of uncertainty. A further source of uncertainty is the data used in the modelling process. For example, climate data is often taken at various points and then interpolated to represent a larger area using geospatial statistics; therefore those interpolated areas are associated with a certain level of uncertainty. The data series themselves may also be subject to various uncertainties, for example systematic errors associated with the measurement of physical variables, and uncertainty involved in the statistical infilling of missing variables (Lynch, 2004). The land use representation within the hydrological model is another potential source of uncertainty as a certain level of simplification is required to represent land uses in the hydrological model.

The hydrological responses of the Mgeni catchment were shown to be sensitive to both the scale and location of urban land use change. The impact of urban land use changes on streamflow varied across the catchment. Urban growth in the upper parts of the catchment showed large increases in streamflow generation whereas urban growth near the outlet of the catchment showed lower increases in streamflow generation, even though both areas show similar percentages of urban growth. As a result, specific areas of the Mgeni catchment could be highlighted for their sensitivity to streamflow change due to future urban growth, such as the areas along the Msunduzi River.

Streamflow changes due to an increase in urban areas showed marked seasonal impacts. Mean summer streamflows responded significantly more to a growth in urban areas than mean winter streamflows, indicating that streamflow responses to urban land use are greater in the higher rainfall summer months than the lower rainfall winter months.

The influence of increased urban land use in conjunction with other land uses has varying impacts across the catchment. Increases in streamflow due to urban growth have reached a point where they have exceeded the streamflow reducing influence of other hydrologically significant land uses such as commercial forestry and sugarcane by 2050. However, the increases in streamflow from urban areas were not great enough to overcome the attenuating effects of major dams. The increases in urban land use are associated with increases in urban water demand. This could mean that water would be transferred from the Mgeni River to the urban areas on the Msunduzi River which would ultimately increase streamflows in the Msunduzi River due to return flows.

Another finding was that the type of urban land use has a significant impact on the hydrological responses. Built up and formal residential areas have a more significant impact on streamflow than informal residential areas. Beyond highlighting the sensitivity of the hydrological responses to the type of urban land use; it indicates that the hydrological responses simulated by the ACRU model are sensitive to the representation of the type of urban land use within the model. Therefore it is important that the representation of urban land use is as detailed as possible when modelling hydrological response.

An understanding of the sensitivity of hydrological responses to the scale and location of urban growth is important, to allow for better land use and water resources planning and policy development. The possible policy and planning measures will be described in more detail in the next section, with regard to water resources management.

4.3 The Relationship between Urban Growth and Water Resources Management

Decision makers need to consider the influence of a number of different social, economic and environmental issues before a decision can be reached (Jakeman and Letcher, 2003). This is particularly true for water resources managers where the allocation and use of water has social, economic and environmental consequences and impacts (Pahl-Wostl, 2007). Therefore, land use change, through its impact on hydrological response, may have social, economic and environmental impacts. Pahl-Wostl (2007, pg 50) describes water management as “a purposeful activity with multiple and partly conflicting goals to maintain and improve the state of water resources”. The management of water resources uses a wide range of tools to accomplish its goals, such as efficient water allocation, water purification, and large infrastructure such as dams, as well as technology and knowledge (Pahl-Wostl, 2007).

Modelling is a valuable tool that can be used in the development of water-related policy, as it facilitates the better understanding of the physical processes at work, improves the transferability of knowledge (Giupponi and Sgobbi, 2008) and allows for future scenarios to be tested (Schulze, 2009). Assessing the hydrological impacts of future scenarios such as population increases and urban growth, allows for the potential negative and positive consequences of these scenarios to be ascertained. By determining and understanding the potential negative and positive consequences of these scenarios, advanced planning can be undertaken to ensure that the negative consequences are minimised and the positive consequences are maximised (O’Brian and Leichenko, 2003; Warburton, 2012). The understanding gained from the use of prediction tools such as urban growth modelling, can be used to improve adaptive water management. Pahl-Wostl (2007, pg 51) describes adaptive management as “the ability to change management practices based on new experience and insights”. The emphasis of adaptive water management is to increase the adaptive capacity of water resources, where adaptive capacity is the capability of a system to adjust and cope with future stresses (Pahl-Wostl, 2007). Therefore, modelling the hydrological responses under scenarios of future urban growth can be used as a means of improving the adaptive capacity of current urban areas ensuring that the appropriate structures are in place so that in the event of a future stress as a result of urban growth, the urban system or water system will be able to adapt. This research is useful as it enables a policy maker or urban planner to locate and design sustainable and cost-effective urban environments. For example, the positioning of future urban land use to minimise the impacts on hydrological responses, may reduce the need for water-sensitive urban design required to minimise hydrological responses.

There are a number of water resources management issues that may need to be addressed as a result of urban growth in the Mgeni catchment. The Msunduzi River was highlighted in Chapter 3 as an area that is likely to be significantly impacted by future urban growth. Therefore, this region needs to focus on the design of the urban areas so that the impacts of urban infrastructure on water are reduced and that policies are implemented that minimise the social, economic and environmental impacts of increased streamflows. Social issues may include the increased likelihood of flooding or poor water quality associated with urban land use. There are economic implications of increased streamflow; if the water quality is poor the cost of the purification of water may increase. Environmental impacts are an area of concern where the change in the flow of a river may threaten sensitive species or alter the channel characteristics of a river (McColl and Aggett, 2007). The impacts of changes to water resources are not exclusive, for example a social issue will have economic and environmental impacts.

With increases in urban land use there is an increased demand for water. In the Mgeni catchment much of the current urban land use is situated on the Msunduzi River, and the lower parts of the Mgeni River, after its confluence with the Msunduzi River. However, most of the water used to meet the demands of these urban areas is sourced from the Mgeni River. Therefore increases in urban land use in the Mgeni catchment are likely to cause further increase streamflows on the Msunduzi River because of increased return flows from the urban areas in the Henley, Pietermaritzburg and Table Mountain WMAs. As the demand increases there may be a need to transfer water from other catchments into the Mgeni catchment further exacerbating the impacts of urban land use on streamflows from increased return flows generated by urban areas.

The increased streamflows may affect dams and dam management, as increased streamflows are generally associated with increased sediment loads (Moore and Anderholm, 2002). The increased sediment load of rivers may increase the rate of siltation in dams, lowering their storage capacity. Therefore dams in the future may have to revise their operating rules to accommodate increases in streamflow, while ensuring environmental flows are maintained.

4.4 Recommended Future Research

Future research in the fields of urban land use modelling, and the modelling of the hydrological responses to urban growth, must attempt to minimise uncertainties related to both urban growth and hydrological modelling.

As discussed previously there were a number of limitations in terms of input data required for the SLEUTH Model. These limitations create uncertainty as assumptions were required to overcome the varying resolution of the land cover maps. The resolution of the maps varied due to inconsistent classification of the satellite imagery used to develop the maps, making the assessment of land use changes difficult. It is suggested that further investment be made into developing a consistent classification system for the land cover maps in South Africa, so that changes in land use can be more confidently identified. This would require that the classification be able to account for improving resolution of satellite imagery, while producing land cover layers that are consistent with past classifications. The classification of satellite imagery can be performed at varying levels of accuracy and resolution. This raises the question of what level of accuracy is required for land use models to function correctly and again to what extent the hydrological model is sensitive to these different levels of accuracy? These are some of the questions future urban growth or land use change models should seek to answer to improve the accuracy of land use predictions and its impact on hydrological response.

Further application of the SLEUTH Model in other South African cities will be beneficial in validating the applicability of the model in South Africa. It may be beneficial to test the performance of other urban land use/land use change models. Broader land use change models may be necessary in future research to gauge the hydrological responses of urban land use, and other potential land use changes, for example increases in plantation forestry or agriculture. The selection of other models, however, raises further research needs of improved population information, land use and infrastructure coverage’s, which is difficult in a South African context due to lack of capital and capacity.

Further research needs to assess in greater detail, the characteristics of the relationship between streamflow and urban land use, and the change thereof. This could be best achieved by using a series of hypothetical urban land use growth scenarios for which the hydrological responses can be determined. An understanding of the characteristics of a system allows the drivers of the system to be defined and communicated which could aid the decision making process.

In addition to this, results from this study have indicated that the type of urban land use (i.e. built-up urban areas, formal residential or informal residential) has a significant impact on streamflow responses. Given this, an improved understanding and representation of the types of urban land in hydrological modelling is necessary.

4.5 Contributions to New Knowledge

The contributions of this research to new knowledge are summarised as follows:

- The generation and mapping of future urban growth scenarios for the Mgeni catchment, South Africa.
- Highlighted the importance of the understanding of urban hydrological responses in water resources management and urban planning.
- Enhanced the understanding of the sensitivity of streamflow responses in the Mgeni catchment to urban growth.
- Enhanced the understanding of the influence of the location of urban growth on streamflow response.
- Confirmation of the sensitivity of summer streamflows to urban land use.
- Analysed the impacts of future urban growth in relation to other hydrologically sensitive activities such as commercial forestry, commercial sugarcane and major dams.
- Enhanced the understanding of the influence of the type of urban land use on streamflow responses.
- Provided guidance for the inclusion of both the results from the urban growth and hydrological modelling in urban and water resources planning.

These contributions further the understanding of the relationship between urban land use and streamflow change. An improved understanding of both these systems will help to ensure that water resources are managed effectively, while minimising the environmental impacts of future urban growth.

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