THE DEVELOPMENT AND ASSESSMENT OF A REFINED METHOD TO ESTIMATE DESIGN FLOODS IN A RANGE OF URBAN AREAS IN SOUTH AFRICA

Literature Review and Proposal

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Submitted in partial fulfilment of the requirements for the degree of PhD

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April 2017

PREFACE

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ABSTRACT

Globally, more people now reside in cities than ever before, with more than half of the world's population living in urban areas in 2014 (UNDP, 2014). As more people move to cities, the sustainable development of urban areas will have to be improved, especially in developing countries, where urbanisation rates are the fastest.

It is widely accepted that urban development results in a decrease in the permeability of a catchment and will therefore result not only in larger flood peak discharges with a faster catchment response time, but also in larger total flood volumes. However, this assumption does not take into account the constructed water drainage and reticulation system, and the possibility of retention and attenuation in urban systems due to property boundary walls and/or the levelling of naturally sloping areas, which are typical in formal peri-urban (also known as suburban and formalised township) developments in South Africa. Recent studies suggest that not all aspects of storm water runoff are necessarily affected by development. Many authors agree that all the effects of urbanisation on runoff are still not properly understood and therefore the current methods to quantify runoff from peri-urban catchments need further development.

In addition, and in contrast with the perceived effects of urban development in first-world countries, runoff from informal settlements is generally lower than expected when compared to formally developed urban areas, although this has not yet been researched thoroughly. Based on the findings of a study by Van Vuuren (2012) on the influence of catchment development on peak urban runoff, it was recommended that the effect of peri-urban development on storm water runoff be reviewed.

The international trend in urban hydrological modelling is currently leaning towards models that can better simulate the spatial and temporal distribution of rainfall and consequent urban storm water runoff. However, many of the software packages currently available are relatively expensive, and require impractical amounts of input data which are often not available, especially for consultants in developing countries. It also becomes more difficult to assess the accuracy of models with increasing complexity in ungauged catchments.

In addition, the methods currently used internationally for urban design flood estimation do not necessarily provide for the unique development types present in South Africa. Many of the

methods applied in urban areas in South Africa were not developed specifically for urban or peri-urban areas and the coefficients used for urban areas were taken from studies in other countries, without considering the unique circumstances of present-day South Africa. The need has therefore arisen for the development of a simplistic method to accurately estimate design floods from both formal and informal urban and peri-urban settlements in South Africa, especially in areas with little or no reliable streamflow data.

This document contains a review of literature and currently used methods of urban design flood estimation procedures. The literature review forms the basis of a project proposal for the development of a simple, calibrated urban design flood estimation method that is applicable to South African formal and informal urban and peri-urban settlements.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol/abbreviation	Description
ACRU	Agricultural Research Unit
CBD	Central business district
CRC	Cooperative Research Centre
DCIA	Directly Connected Impervious Areas
DHI	Danish Hydraulic Institute
DWS	Department of Water and Sanitation
FSR	Flood Studies Report
FEH	Flood Estimation Handbook
HRU	Hydraulic Research Unit
HSPF	Hydrological Simulation Program – Fortran
LID	Low impact development
LULC	Land use / land cover
PMF	Probable maximum flood
RDP	Rural Development Programme
RMF	Regional maximum flood
SAWS	South African Weather Services
SCS	Soil Conservation Services
SCS-SA	Soil Conservation Services – South Africa
SDF	Standard Design Flood
StatsSA	Statistics South Africa
SWAT	Soil and Water Analysis Tool
SWMM	Storm Water Management Model
TIA	Total Impervious Areas
TOPMODEL	Topography based hydrological Model
TRIA	Transportation-related Impervious Areas
UNDP	United Nations Population Division
UNICEF	United Nations Children’s Fund
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WRC	Water Research Commission
WSUD	Water-sensitive urban design
WWTP	Wastewater treatment plant

GLOSSARY OF TERMS

Term	Description
Base flow	Stream flow that is not the direct result of a storm event, but rather the result of seepage from the ground over a long period of time. Sometimes referred to as dry weather flow (DLC and DEQ, 2000).
Catchment	The land area that contributes runoff to a specific downstream point. (DLC and DEQ, 2000).
Detention	Storage and gradual release of storm water after a rainfall event (DLC and DEQ, 2000).
Directly connected impervious areas	These areas include all impervious areas that are directly connected to drainage systems. DCIA is a good indicator of the impact of urbanisation on runoff (Lee and Heaney, 2003).
Formal development	Planned development usually making provision for civil services and storm water drainage systems (Geyer *et al.*, 2012)
Hydrological cycle	The circulation of water from the atmosphere through the ground and down streams (DLC and DEQ, 2000).
Impervious surface	An impenetrable or semi-impenetrable surface like concrete, rock or rooftops that prevents infiltration and therefore generates runoff (DLC and DEQ, 2000).
Imperviousness	The percentage of impervious cover in a defined area (DLC and DEQ, 2000).
Infiltration	The process in which surface water permeates into subsurface layers (DLC and DEQ, 2000).
Informal settlement	Settlement within or adjacent to townships on urban fringe, without formal infrastructure or civil services (Geyer *et al.*, 2012)
Peri-urban	For the purpose of this document, peri-urban will refer to areas developed on previously rural or agricultural areas on the edges of large urban centres (Braud *et al.*, 2013b). This will include all suburban, township and informal settlements (as defined elsewhere in this glossary of terms). Other definitions include UNICEF (2012) that defines it as an area between consolidated urban and rural regions.

Runoff	Discharge from precipitation or seepage events (DLC and DEQ, 2000).
Storm water	Water generated by a storm or running through a storm water drainage system (DLC and DEQ, 2000).
Suburban	Medium to low density development on urban fringes.
Surface water	Water that flows on the surface: overland, in channels or in lakes or dams (DLC and DEQ, 2000).
Total impervious area	These areas include all impervious areas, including areas connected to drainage systems and those not connected.
Township	Name derived from apartheid-era black settlements along urban fringes. Usually formalised to a degree, but does not necessarily have storm water drainage systems (Geyer *et al.*, 2012)
Transportation related impervious areas	These areas include all impervious areas in transportation systems (Lee and Heaney, 2003)
Urban	Urban areas are defined differently by various countries. As an example, in South Africa any place with some form of local authority is considered urban (UNSTATS, 2005). For the purposes of this report, urban areas are defined as formally developed medium to high density residential and business districts in or around city centres.
Urban centre	City centre, typically characterised by high density development and high percentage of imperviousness. Also sometimes referred to as the central business district (CBD) or urban core
Urban fringe	Area on the boundary of the urban centre, where medium to low density development occurs, see also “peri-urban” definition.
Urbanisation	The proportion of a country that is urban (UNICEF, 2012)
Urban sprawl	Urban sprawl refers to the spreading of low to medium density development on urban fringes, producing areas with mixed pervious and impervious surfaces (Mejia and Moglen, 2010).
Watershed	Refer to “Catchment”.

1 INTRODUCTION

Globally, more people currently reside in cities than ever before, with more than half of the world’s population, about 54 % of approximately 7 billion people, living in urban areas in 2014 (UNDP, 2014). South Africa can be categorised as a developing country where people migrate to urban areas in search of employment and better service delivery (UNDP, 2014). Geyer *et al.* (2012) noted that in the post-Apartheid era, the white population has shown decentralisation trends from urban centres towards urban fringes and smaller towns, while the traditional black townships on the outskirts of cities have experienced continued growth. The combination has led to significant development of peri-urban settlements on city outskirts.

Many authors agree that all the impacts of urbanisation on runoff are still not properly understood and therefore the current methods to estimate runoff from urban catchments still require further development (Wheater and Evans, 2009; Fletcher *et al.*, 2013; Jovanovic *et al.*, 2014). Based on the findings of a South African Water Research Commission (WRC) report (Van Vuuren, 2012), it was recommended by Van Vuuren *et al.* (2013) that, amongst others, “(t)he influence of urban development on catchment response (runoff peaks and runoff volume) be reviewed”. Various international authors have acknowledged that significant work has been done in both rural and heavily urbanised areas, but little has been done to quantify the effect of peri-urban development on hydrological responses (Burns *et al.*, 2005; Wheater and Evans, 2009; Bach and Ostrowski, 2013; Isik *et al.*, 2013; Braud *et al.*, 2013b; Ferreira *et al.*, 2016). For the purpose of this document, peri-urban will refer to areas developed on previously rural or agricultural areas, located on the edges of large urban centres (Braud *et al.*, 2013b). This includes suburban areas, township areas and informal settlements, as defined in the glossary of terms.

Braud *et al.* (2013b) state that, although progress has been made in recent years to better understand the hydrology of complex peri-urban environments, many questions are still left unanswered. They summarise these uncertainties and needs into three categories: (a) the effect of peri-urban hydrological behaviour on humans and ecosystems, (b) the impact of source-control storm water management approaches at various scales, and (c) the need for ongoing integrated modelling for the prediction of the effect of alternative storm water management policies on quality and quantity of receiving waters. McGrane (2016) adds that: (a) infiltration rates in different urban areas are not determined correctly and that recent studies have proven that some existing assumptions are invalid, (b) pipeline leakage and consequent infiltration remains poorly documented, and (c) the dynamics between pervious and impervious surfaces remains poorly understood and is still an important field of research.

Internationally, most urban hydrological calculations are performed using computer software. However, despite the range and availability of software for urban storm water modelling, research in the field is still continuing (Fletcher *et al.*, 2013). In addition, Parkinson *et al*. (2007) note the problem that many of the models currently used for urban storm water modelling require a significant amount of input data. This data will generally not be available when considering informal settlements. Fletcher *et al.* (2013) agree and state that with an increase in complexity of storm water simulation models, comes an increase in the need for reliable data. Zeng *et al.* (2015) have noted that more effort is needed to quantify the effectiveness and uncertainty of using hydrological models in design flood studies.

It is clear that there is a need for the development of a properly validated and verified estimation procedure for peri-urban runoff, specifically for peri-urban areas in South Africa, but that may also be applicable to more heavily urbanised areas in South Africa, as well as similar developments in other countries.

The main objective of this document is to review the current status of the estimation of urban and peri-urban hydrological response, both internationally and in South Africa. This will be done in order to provide a basis for a study on the development and assessment of a method for estimating design floods from urban and peri-urban areas that is applicable in South Africa.

In order to develop an applicable procedure, it is important to incorporate all the factors that play a role in peri-urban runoff, as well as to study methods currently used for urban design flood estimation. Therefore, a literature review was conducted to ascertain the various characteristics and conditions in a catchment that will contribute to response time and runoff volumes generated by rainfall events. The following three chapters contain reviews of urbanisation trends, factors influencing runoff in peri-urban developments, and methods used in the modelling of hydrological responses from urban catchments. Chapter 5 contains a discussion of the literature and the need for a simple, calibrated urban design flood estimation method for South African cities. A brief project proposal is provided in Chapter 6.

2 TRENDS IN URBANISATION

With increasing local and global trends in urbanisation, the frequency of urban flooding and subsequent damage to infrastructure and social structures is also rising. The background to the need for accurate urban and peri-urban runoff modelling, specifically considering the range of urban environments in South Africa, is discussed in this chapter.

2.1 Global Trends in Urbanisation

In 2014, more than half of the world's population lived in urban areas, with the proportion of urban dwellers set to rise to about 60% by 2030, as shown in Figure 2.1 (UNDP, 2014). As urban areas continue to expand, significant pressure is imposed on the natural dynamics, availability of resources and ecological diversity (Niemczynowicz, 1999). This is especially true in developing countries, where urbanisation rates are growing the fastest (UNDP, 2014; Zhang *et al.*, 2015) and often occur in an unbalanced and disorganised manner (Gogate and Rawal, 2015).

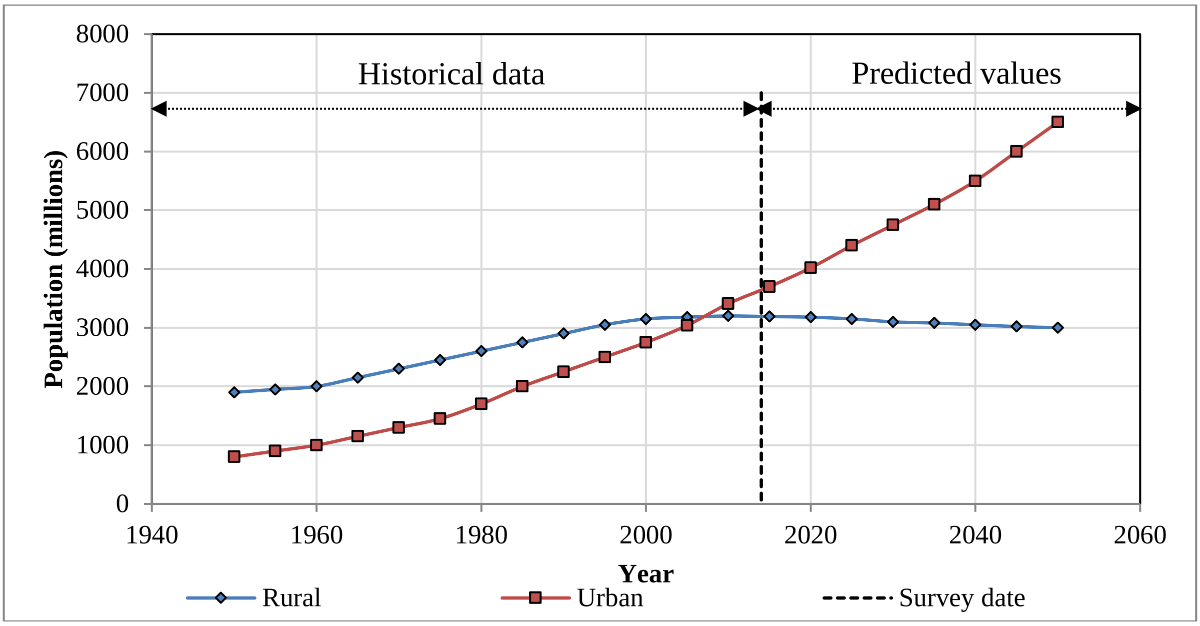

Figure 2.1 Global urbanisation trends from 1950 projected to 2050 (UNDP, 2014)

Most of the economic, government and commercial activities in a country are located in urban areas. Urban living has many advantages and is often associated with better education, health, work opportunities and social, cultural and political participation (Bhawan, 2001; UNDP, 2014). Urban areas are therefore an integral part of most countries and are set to increase and thrive in future. However, the rapid and unplanned expansion of urban areas has caused many challenges to sustainable development (Li *et al.*, 2015), and many urban areas are characterised as poor neighbourhoods or slums, where millions of people live in sub-standard living conditions. In many cities this unmanaged urban sprawl has led to pollution, unhealthy living conditions and unsustainable consumption (UNDP, 2014). Furthermore, urbanisation usually occurs at different paces in various sections of a catchment. This spatial variability results in varying degrees of impacts on runoff in different parts of a city (Tang *et al.*, 2005). Cities in South Africa are examples of this, where decentralisation away from urban centres towards metropolitan fringes is common (Geyer *et al.*, 2012).

2.2 Urbanisation in South Africa

South Africa can be categorised as a developing country where people migrate to urban areas in search of employment and better service delivery. Geyer *et al.* (2012) found that the metropolitan and most intermediate sized cities have experienced significant population increases in recent years. According to the UNDP (2014), approximately 65 % of South Africans currently live in urban areas, as shown in Figure 2.2, with many people residing in townships with substandard infrastructure (StatsSA, 2014).

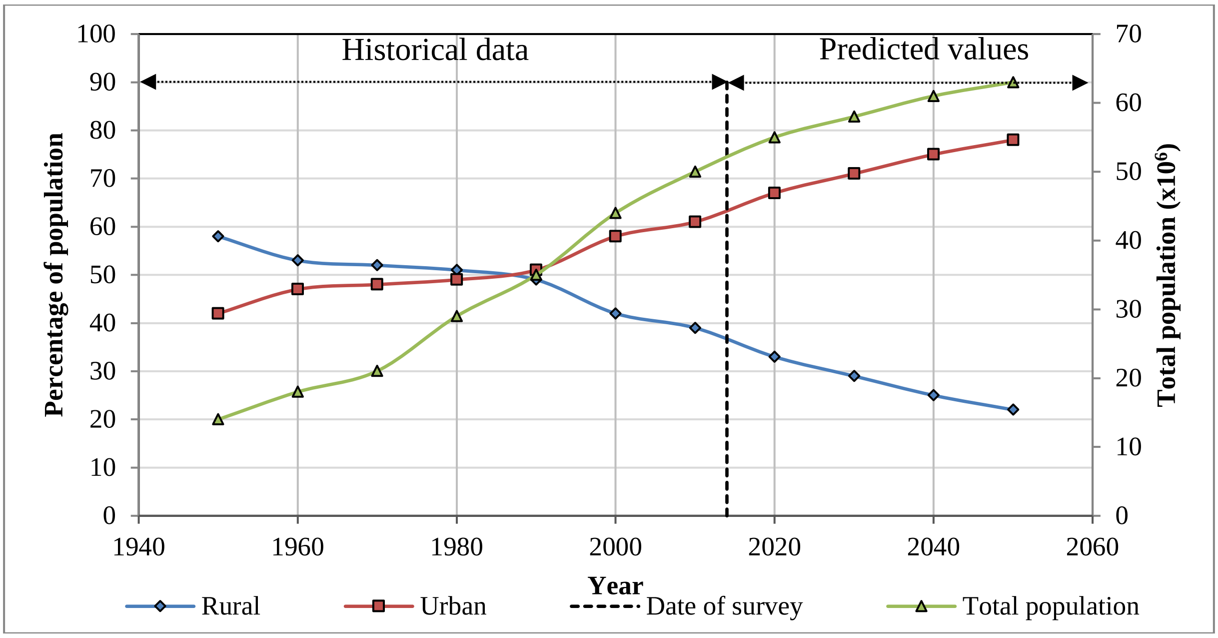

Figure 2.2 Proportion of urban and rural population in South Africa from 1950 projected to 2050 (UNDP, 2014)

Geyer *et al.* (2012) also noted that in the post-Apartheid era, the white population has shown decentralisation trends from urban centres towards urban fringes and smaller towns, while the traditional black townships on the outskirts of cities have experienced continued growth. The combination has led to significant development of peri-urban settlements on the outskirts of cities. According to StatsSA (2014) there has been a significant increase in the percentage of households living in formal dwellings from 73.7 % in 2002 to 77.7 % in 2013. In 2013 approximately 13.6 % of the population lived in informal dwellings and 7.8 % in traditional dwellings, as shown in Table 2.1. In Gauteng, which is the most urbanised of all nine provinces in South Africa, almost 20 % of the households resided in informal dwellings in 2013.

It should also be noted that more than 13 % of the households in formal dwellings were living in state subsidised, or 'RDP', houses in 2013. Despite the improved access to RDP-standard sanitation facilities, many households in these neighbourhoods continued to be without any proper sanitation facilities in 2013 (StatsSA, 2014). Although official statistics are not available, the storm water systems in these neighbourhoods are also often not formalised and these areas would generally experience similar hydrological responses to informal settlements. Similar situations abound in other developing countries, like India, where financial restrictions limit the provision of urban drainage infrastructure (Bhawan, 2001).

Table 2.1 Proportion of the South African population living in formal, informal and traditional dwellings by province in 2013 (StatsSA, 2014)

Type of Dwelling	Percentage of Total Dwellings [%]									
	WC	EC	NC	FS	KZN	NW	GP	MP	LP	RSA
Other	1.9	0.6	3.7	0.3	0.3	0.3	1.5	0.0	0.2	0.9
Informal	16.0	7.8	11.9	15.6	9.2	22.1	19.8	8.2	3.7	13.6
Traditional	0.1	32.6	1.9	2.1	18.4	1.1	0.0	6.2	3.3	7.8
Formal	82.0	59.0	82.5	82.1	72.1	76.5	78.6	85.6	92.8	77.7

It is clear that urbanisation is a global trend, with South Africa as a developing country showing an especially high tendency of urban migration. The development associated with urbanisation could lead to significant impacts on hydrological responses of catchments. The next chapter will consider these impacts in more detail.

3 THE IMPACTS OF URBANISATION ON HYDROLOGICAL RESPONSES

Since the 1960s many studies have been conducted to analyse the impacts of urbanisation on hydrological responses (Aichele and Andresen, 2013). As first proposed by Leopold (1968), the international consensus from most of these studies has been that an increase in urban and peri-urban development would have a significant impact on catchment response to rainfall events (Dunne and Leopold, 1978; Huang *et al.*, 2008; Braud *et al.*, 2013a).

These impacts include, amongst others: increased flood frequency, increased peak flow particularly for low-order floods (Aichele and Andresen, 2013), decreased base flow and decreased catchment response time (Chang, 2007; USEPA, 2008; Gallo *et al.*, 2013; Choi *et al.*, 2015). Wheater and Evans (2009) argue that as vegetated areas are replaced with impermeable areas, overland flow increases and infiltration reduces, leading to less attenuation in the system. According to Konrad (2003), even in suburban settlements the thin soils associated with lawns and permeable landscaping could be saturated quickly, producing increased overland flow and runoff. In addition, the flow paths and velocities are altered, as runoff is generally collected by pipes and conveyed rapidly to streams. This combination would result not only in larger and faster forming flood peaks, but also smaller base flows and less groundwater recharge (Semadeni-Davies *et al.*, 2008; Praskievicz and Chang, 2009). Other studies (Konrad, 2003; Putro *et al.*, 2016) found generally increasing trends in hydrological responses in catchments as urbanisation occurred. These impacts are shown in Figure 3.1.

However, some studies (Grifffin, 1995; Brun and Band, 2000; Chin and Gregory, 2001; Burns *et al.*, 2005; Wheater and Evans, 2009; Aichele and Andresen, 2013; Fletcher *et al.*, 2013; Gallo *et al.*, 2013) suggest that not all aspects of storm water runoff are necessarily impacted by development. The materials, and types of infrastructure used in some developments, as well as local topography and slope changes, could impact on the rate and flow pathways of storm water runoff (McGrane, 2016). The following sections contain a review of the influences of development on various catchment characteristics and the subsequent effect on catchment response.

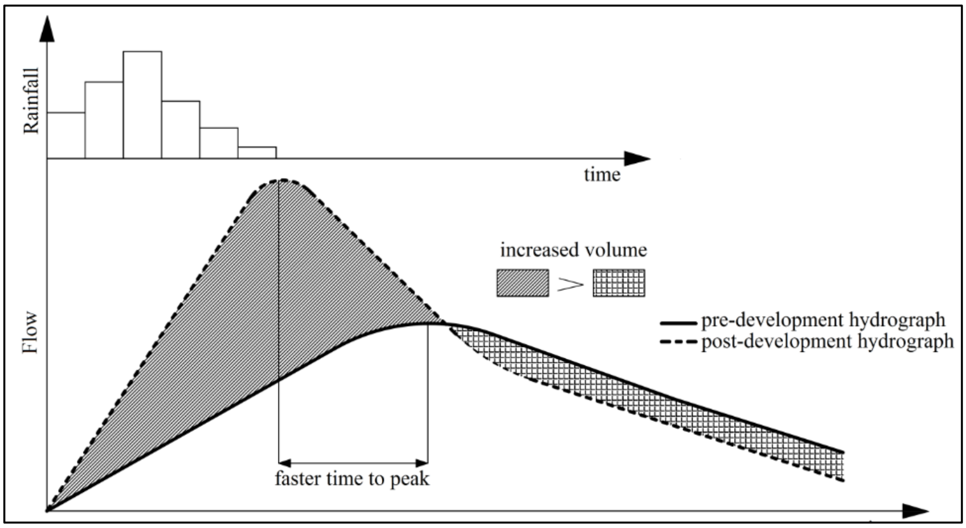

Figure 3.1 The perceived effect of urbanisation on runoff (Houghton-Carr, 1999)

3.1 The Influence of Development on Catchment Permeability

The percentage of impervious areas in an urban environment has a significant effect on the water environment in general (Arnold and Gibbons, 1996; Wickham *et al.*, 2014) and on storm water runoff in particular (Lee and Heaney, 2003). However, some studies have questioned the conventional theory that an increase in imperviousness would always result in increased runoff, decreased recharge and shorter catchment response times (Aichele and Andresen, 2013) and many studies have examined the effects of impervious area connections to drainage systems (Lee and Heaney, 2003; Roy and Shuster, 2009; Yao *et al.*, 2015).

Lee and Heaney (2003) noted the significant effect of Directly Connected Impervious Areas (*DCIA*) on runoff. These include all impervious areas that are directly connected to drainage systems. They found that *DCIA* had a much larger contribution to increased runoff than disconnected impervious areas and have therefore proposed the use of *DCIA* as the key indicator of the impact of urbanisation on runoff. This is supported by Miller *et al.* (2014).

Some recent studies have also indicated that an imperviousness threshold may exist above which hydrological response can be considered urban (Booth and Jackson, 1997; Brun and Band, 2000; Nirupama and Simonovic, 2007; Yang *et al.*, 2010; Jacobson, 2011; Wang *et al.*, 2015). The studies found thresholds of anything between 3 % (Yang *et al.*, 2010) and 20 % imperviousness (Wang *et al.*, 2015), above which catchments responses could be classified as urban.

According to Jacobson (2011), the difference between the Total Impervious Area (*TIA*) and *DCIA* could be a contributing factor to explain the discrepancies in thresholds in the different study areas. However, in urban areas the *DCIA* may be difficult and expensive to measure, as different systems might function for different rainfall intensities (Yang *et al.*, 2011; Aichele and Andresen, 2013). A case study conducted by Roy and Shuster (2009) in Cincinnati, Ohio, confirmed the variability between *TIA* and *DCIA*. They derived Equation 3.1 for calculating *DCIA* from *TIA*, both calculated as percentages (%) based on the entire study area:

$$DCIA = (1.046 \times TIA) - 6.23\% \tag{3.1}$$

Equation 3.1 was based on an empirical formula developed by Alley and Veenhuis (1983) and shown in Equation 3.2:

$$DCIA = 0.15 \times TIA^{1.41} \tag{3.2}$$

However, Roy and Shuster (2009) found that the equation created for the entire study area from reliable data did not accurately predict *DCIA* in many of the sub-catchments. They therefore suggested that, although *TIA* could be accurately assessed using aerial photos, it would be necessary to conduct field investigations to determine *DCIA*.

A study by Ragab *et al.* (2003) confirmed that infiltration and evaporation losses occur even on perceived impermeable urban surfaces. An assumption of zero infiltration into road surfaces, which in many cases comprise a significant percentage of *DCIA* (Lee and Heaney, 2003), would therefore lead to an overestimation of runoff from road surfaces (Ragab *et al.*, 2003). This was supported by Mansell and Rollet (2006) who found significant infiltration in brickwork paving and significant evaporation from concrete, bitumen and asphalt. A recent study by Redfern *et al.* (2016) confirmed this by finding that infiltration rates in infrastructure can vary seasonally and over time due to degradation. They confirmed that current established infiltration rates may underestimate infiltration in certain types of development.

Isik *et al.* (2013) noted that, although various potential impacts of land use and land cover changes have been extensively studied, it is still difficult to accurately quantify these impacts on water resources. Brandes *et al.* (2005) noted that a possible reason for this problem is that, while there are various development features that would increase runoff, there are others that would have the opposite effect. Therefore, they conclude that it would be highly unlikely to find a specific threshold applicable to encompass all the effects of urbanisation.

In contrast with the effects of dense urban development in first-world countries, Parkinson *et al.* (2007) found that runoff from informal settlements is generally lower than expected. They cite possible reasons for this as a combination of a lack of paved surfaces, resulting in higher infiltration rates, and incomplete drainage systems which lead to ponding in low-lying areas.

3.2 The Influence of Development on Catchment Drainage Paths

One of the influences of catchment development on runoff is the impact that development can have on the drainage paths in a catchment. The influence of development on drainage paths is closely linked to the influence of *DCIA*, discussed in Section 3.1. However, drainage paths will not always be made more efficient by development, with various factors potentially impacting on flow retardance and longer drainage paths (Rademeyer, 2016). Van Vuuren (2012) noted that in many South African developments, solid boundary walls are often constructed around properties, causing temporal storage in the system. He also recommended that the hydraulic routing effect of culverts and bridges on peak discharge from urban areas, should be assessed.

According to Braud *et al.* (2013b), one of the major research challenges in peri-urban areas is the fact that these catchments have a combination of fast and slow hydrologic responses, depending on the flow paths in the catchment, where responses can range from areas dominated by baseflow to those drained by pipe networks. Gogate and Rawal (2015) found that in developing countries, like India, storm water drainage structures have not been constructed for many of the roads, resulting in stagnation, ponding and potholes in roads.

3.3 The Influence of Development on Catchment Slopes

It is generally accepted that the gradient of the watercourses and flow paths in a catchment will have a significant influence on storm water runoff (Gogate and Rawal, 2015), with runoff generally increasing with gradient, if all other variables are kept constant (Kirkby *et al.*, 2002). However, not many studies on the impacts of imperviousness in urban catchments have also analysed the effects of slope. Jacobson (2011) provides a possible reason for this as the difficulty of obtaining reliable field measurements which quantify the effect of slope between catchments with similar characteristics. Although information from agricultural catchments is helpful, the pervious areas located in urban settings are often covered in grass and further research, including model simulations, is needed (Jacobson, 2011).

3.4 The Influence of Development on Base Flow and Flow Peaks

As discussed in Sections 3.1 and 3.2, many of the hydrological impacts of urbanisation are rooted in the increased impervious area of a catchment. An increase in imperviousness leads to a decrease in rainwater infiltration and subsequent increase in storm water runoff (Jacobson, 2011). Intensive research into the effect of urbanisation on catchment runoff started in the 1960s, when major urban areas in Europe and the USA began rapidly expanding. A study by Leopold (1968) found that the distinct effects of urbanisation on hydrology included, amongst others, changes in both peak discharges and total runoff. Most studies over the next decades confirmed Leopold's findings that runoff increases, groundwater recharge decreases and base flow decreases with an increase in imperviousness caused by urbanisation (Jacobson, 2011).

Various studies have also reported reduced base flow, increased storm peaks and decreased lag times due to urban development (Smakhtin, 2001; Shuster *et al.*, 2005; Gogate and Rawal, 2015). However, some activities associated with urbanisation, including inter-basin transfers and wastewater flow, may well change the net impact on hydrological responses (Brandes *et al.*, 2005; Whitney *et al.*, 2015). Wheater and Evans (2009) state that the lower the natural runoff in a catchment, for example due to permeability and geology, the larger the impact of development on hydrology. Antecedent soil moisture conditions will have a smaller effect on urban catchments than similar, undeveloped areas, resulting in possible flooding even when the soil is unsaturated in the dry season. Kalantari *et al.* (2014) found that the spatial distribution of land use features, as well as the size and timing of storm events, have a significant influence on catchment discharge.

It can therefore be concluded that, due to the complexity of urban areas, both competing and reinforcing effects of urbanisation are present in some catchments. The complexity is further enhanced by the difficulty of apportioning the impacts of recent developments from past influences (Allan, 2004). The challenge in urban hydrological modelling is to properly account for all these factors in order to produce a realistic representation of the physical characteristics of a catchment. The next chapter will focus on urban hydrological response modelling procedures and lead into a discussion on which procedures would be best suited for application in this study.

4 MODELLING URBAN HYDROLOGICAL RESPONSES

The hydrological or the hydraulic processes in a catchment can be modelled, depending on the required application. Usually only the conservation of volume is considered for hydrological modelling. For hydraulic modelling, flow is simulated by simultaneously solving continuity and dynamic equations (Zoppou, 2001). There are various approaches to the modelling of hydrological responses from urban catchments.

4.1 Categorisation of Hydrological and Hydraulic Response Modelling

A mathematical model uses mathematical relationships to represent a real world system. The different types of models used for hydrological response modelling all fall somewhere on the continuum between a purely deterministic and a purely stochastic approach. In a strictly deterministic model, all parameters are correct and the model is a perfect representation of the physical system being simulated. Conversely, a strictly stochastic model will produce varying output in different simulations (Nix, 1994). In reality, no model is perfectly deterministic, nor does it completely ignore physical relationships. Therefore, all hydrological models are parametric models that include both deterministic and stochastic qualities, although most urban models tend to be deterministic models (Nix, 1994; Zoppou, 2001).

Deterministic modelling approaches are based on the conservation laws governing fluid behaviour. The conservation of volume, the conservation of momentum or the conservation of energy in a system can be considered. According to Zoppou (2001), the process being modelled generally determines whether hydrology or hydraulics is the focus. For example, rainfall-runoff is regarded as hydrology and the modelling of open channel flow as hydraulic or transport modelling.

Hydrological modelling can be broadly grouped into rainfall-runoff modelling, in which a water balance is simulated, and design flood estimation, in which either a design flood peak or flood hydrograph can be calculated (O'Loughlin and Robinson, 1987). Design flood estimation can be further categorised into event-based or continuous modelling. The major difference between event based and continuous design flood estimation is that in the former, losses are estimated at the start of the storm (Smithers *et al.*, 2013). However, as the continuous simulation process incorporates a catchment water balance, the need for assumptions about losses is eliminated (Boughton and Droop, 2003).

Many catchments do not have adequate length and quality of observed hydrological data for accurate runoff estimation. In these cases, rainfall-runoff modelling can be used to simulate the required runoff time series for frequency analysis (Zeng *et al.*, 2015). There are various characteristics of rainfall-runoff modelling approaches that can be used for model classification. These include classification according to temporal resolution, spatial resolution, or duration of analysis of the model (Fletcher *et al.*, 2013).

There are various ways of classifying hydrological models (Zoppou, 2001; Zeng *et al.*, 2015), but for the purposes of this study, models will be considered as event-based or continuous models. The crucial differences between the approaches are: the data required, the information that can be extracted from the model, the complexity of the analysis, and the simulation period.

4.2 Hydrological Modelling of Urban Areas Models used in Urban Runoff Estimation

Most hydrological models have been built and calibrated specifically for rural catchment studies. However, many studies have used hydrological models to simulate the possible impacts of land use changes, like urbanisation, on runoff patterns in ungauged catchments (Smithers *et al.*, 2013; Kalantari *et al.*, 2014). The following sections will consider event-based design flood estimation and continuous hydrological modelling procedures used both in South Africa and internationally.

4.2.1 Event-based design flood modelling approaches

Design flood estimation is necessary for quantifying the risk of failure of hydraulic structures and therefore forms an integral part of the engineering design process (Smithers, 2012). Most design flood estimation procedures currently used in South Africa have not been developed specifically for urban areas. However, some methods have been adapted for use in urban catchments (Van Vuuren *et al.*, 2013). These methods, with recommended catchment sizes, are summarised in Table 4.1. These models, as well as the Revitalised Flood Hydrograph (ReFH) model developed in the UK (Kjeldsen *et al.*, 2006) and the Australian variation to the Rational method (O'Loughlin and Robinson, 1987), will be discussed in this section.

Table 4.1 Application and limitations of selected flood estimation methods used in South Africa (after Van Vuuren *et al.*, 2013)

Hydrological Data Required	Method	Recommended Area [km²]	Applicable Return Periods [years]	Reference
Stream flow records	Flood frequency analysis	No limitation (larger areas)	2 – 200 (record length dependent)	(Van Dijk *et al.*, 2013)
Rainfall records	Rational Method 1	< 15 (but has been used successfully for much larger areas)	2 – 100, PMF	(Mulvaney, 1851)
	Rational Method 2	No limitation	2 – 200, PMF	(Van Dijk *et al.*, 2013)
	Rational Method 3	No limitation	2 – 200, PMF	(Van Dijk *et al.*, 2013)
	SCS-SA method	< 30	2 – 100	(Schmidt and Schulze, 1987)

4.2.1.1 Flood frequency analysis

If historical flow data is available in a catchment, statistical methods can be applied to estimate design floods from the data. It is important to note that, as statistical models are used to develop a relationship from a specific data set for a specific location, it is only true for that specific site. For any significant change in spatial patterns or processes, new data must be collected and a new relationship developed. In addition, the accuracy of a statistical analysis depends heavily on the reliability and length of record of the data set (Van Dijk *et al.*, 2013).

4.2.1.2 The Rational method

The Rational method was introduced by Irish engineer Mulvaney in 1850 and was one of the first design flood estimation methods. Although the Rational method is seen as subjective and inaccurate (Alexander, 2002; Smithers, 2012), it is still one of the most widely applied methods (Lee and Heaney, 2003; Goyen *et al.*, 2014; Coombes *et al.*, 2015). It is used especially in developing countries, where practitioners often cannot use more sophisticated methods due to the cost, data requirements and skills necessary in application of these methods (Parkinson *et al.*, 2007; Zhang *et al.*, 2015).

The basis for the Rational method lies in the law of the conservation of mass and the assumption that the peak flow rate of a catchment will be directly proportional to the size of the contributing area and the rainfall intensity (Van Dijk *et al.*, 2013). A runoff coefficient, that represents the proportion of rainfall that runs off to the catchment outlet, as well as a factor to allow for simplified routing, is included (O'Loughlin and Robinson, 1987; Mansell, 2003):

$$Q = \frac{CIA}{3.6} \tag{4.1}$$

where

Q = flow [m^3/s],
C = runoff coefficient [dimensionless],
I = design storm intensity [mm/h], and
A = contributing catchment area [km^2].

and

$$C = \alpha(C_1 \times F_t) + \beta C_2 + \gamma C_3 \tag{4.2}$$

where

α = rural distribution factor [dimensionless],
C_1 = runoff coefficient for rural area [dimensionless],
F_t = adjustment factor for initial saturation [dimensionless],
β = urban distribution factor [dimensionless],
C_2 = runoff coefficient for urban area [dimensionless],
γ = lake distribution factor [dimensionless], and
C_3 = runoff coefficient for lakes [dimensionless, usually zero].

In South Africa, the runoff factor (*C*) for urban areas is commonly calculated using the values proposed by the South African National Roads Agency Limited (SANRAL), as shown in Table 4.2. The values have been adapted from Horner and Flynt (1936), Vorster (1940) Chow (1964) by the (then) Directorate of Water Affairs and first published in the Drainage Manual in 1983 (Rooseboom *et al.*, 1983). The Department of Water Affairs and Sanitation (DWS) recommends the same values as SANRAL for return periods of up to 20 years. The recommended runoff factor values for larger floods are shown in Table 4.3.

Table 4.2 Rational method runoff factor values for urban areas recommended by SANRAL (after Van Dijk *et al.*, 2013)

Area	Description	Factor
Lawns	Sandy, flat (<2%)	0.05 – 0.10
	Sandy, steep (>7%)	0.15 – 0.20
	Heavy soil, flat (<2%)	0.13 – 0.17
	Heavy soil, steep (>7%)	0.25 – 0.35
Residential areas	Houses	0.30 – 0.50
	Flats	0.50 – 0.70
Industry	Light industry	0.50 – 0.80
	Heavy industry	0.60 – 0.90
Business	City centre	0.70 – 0.95
	Suburban	0.50 – 0.70
	Streets	0.70 – 0.95
	Maximum flood	1.00

Table 4.3 Rational method runoff factor values suggested by DWS (after Rademeyer, 2016)

Recurrence interval (years)	Area	Factor
20 to 50	Lawns	0.35 – 0.50
	Other	0.70 – 1.00
Greater than 50	All	1

The runoff factor will be influenced by initial saturation. As the effect of the return period on runoff is smaller for steep and impermeable catchments than for flat permeable catchments, adjustment factors have been incorporated into the calculation of the runoff coefficients. The adjustment factors as proposed by SANRAL and DWS are given in Table 4.4.

Table 4.4 Adjustment factors for C_1 as recommended by SANRAL and DWS

Reference	SANRAL (Van Dijk *et al.*, 2013)		DWS (Rademeyer, 2016)
Recurrence interval (years)	Factor for steep and impermeable catchments [F_t]	Factor for flat and permeable catchments [F_t]	Adjustment factor [F_r]
2	0.75	0.50	0.32
5	0.80	0.55	0.50
10	0.85	0.60	0.61
20	0.90	0.67	0.71
50	0.95	0.83	0.83
100	1.00	1.00	0.92

A probabilistic approach to the Rational method, where equations and values are based on statistical analysis of recorded data, is followed in urban areas in Australia. O'Loughlin and Robinson (1987) proposed a mathematical expression to calculate the runoff coefficient for the 10 year recurrence interval flood peak using the following mathematical expression:

$$C_{10} = 0.9 \times f + C_{10}^{1} \times (1 - f) \tag{4.3}$$

and

$$C_{10}^{1} = 0.1 + 0.0133 \times ({}^{10}I_1 - 25) \tag{4.4}$$

where

C_{10} = 10 year recurrence interval runoff coefficient [dimensionless],

C_{10}^{1} = the pervious area runoff coefficient [dimensionless],

f = the fraction imperviousness (0.0 to 1.0), and

${}^{10}I_1$ = the 10 year recurrence interval, 1 hour duration rainfall intensity [mm].

For recurrence intervals other than 10 years, the C_{10} value is multiplied as follows:

$$C_{y0} = F_y \times C_{10} \tag{4.5}$$

where

C_{y0} = the C value for recurrence intervals other than 10 years, and

F_y = frequency factor as given in Table 4.5.

Table 4.5 Frequency factor for runoff coefficients (O'Loughlin and Robinson, 1987)

Recurrence interval [years]	Frequency factor [F_y]
1	0.80
2	0.85
5	0.95
10	1.00
20	1.05
50	1.15
100	1.20

According to Van Dijk *et al.* (2013) the Rational method gives good results when compared to other methods, if used with caution. It is generally accepted that user experience and correct selection of runoff coefficients are crucial in order to obtain accurate results with the Rational method (Parak and Pegram, 2000; Smithers, 2012; Van Dijk *et al.*, 2013). However, Smithers (2012) noted that a regional probabilistic approach to the Rational method would enable direct conversion from rainfall to a design flood of the same return period and thereby the need for assumptions would be eliminated. The Standard Design Flood (SDF) method (Alexander, 2002) is effectively a probabilistic-based calibration of the Rational method (Smithers, 2012). This method does however not consider small urban catchments, but rather larger rural catchments. Various evaluations of the SDF method have been performed, with varying results (Gorgens, 2002; Van Bladeren, 2005; Gericke, 2010) although none of the evaluations considered urban catchments specifically.

4.2.1.3 The SCS method

The SCS method is a simple method for estimating surface runoff from catchments dominated by Hortonian overland flow. It accounts for both land use and soil effects through a Curve Number (CN) variable (Isik *et al.*, 2013). It is one of the most widely applied methods of design flood estimation used globally (Boughton and Droop, 2003) and forms the basis for infiltration calculation in various modelling software programmes (Harbor, 1994; Aichele and Andresen, 2013).

According to Smithers (2012), the application of the SCS method is less subjective than the Rational method and can be used in both urban and rural catchments for hydrograph calculation. However, it should be noted that this method has many associated uncertainties and the CN values will differ if calculated using different approaches (Randusova *et al.*, 2015). The method was originally adapted for South African conditions in the 1980s (Schulze and Arnold, 1979; Schulze, 1982; Schmidt and Schulze, 1984; Dunsmore *et al.*, 1986; Schmidt and Schulze, 1987), but with the additional data and computer capability available now, the method can be improved to incorporate new information and techniques (Smithers and Schulze, 2003).

Storm water runoff is calculated in the SCS model using the following expression (Van Dijk *et al.*, 2013):

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \text{ for } P > I_a \tag{4.6}$$

where

Q = stormflow depth [mm],

P = daily rainfall depth [mm],

S = potential maximum soil water retention [mm], and

I_a = initial losses (abstractions) prior to the commencement of stormflow, comprising of depression storage, interception and initial infiltration, recommended as 0.1S for use in South Africa [mm].

The potential maximum soil water retention, *S*, is associated with hydrological soil properties, land cover and the antecedent soil moisture status of the catchment. These factors are combined in a dimensionless response index known as the catchment's Curve Number (CN). *S* and *CN* are related as shown below:

$$S = \frac{25400}{CN} - 254 \tag{4.7}$$

where

S = potential maximum soil water retention [mm] and

CN = Curve Number, as given in (Schulze *et al.*, 2004) [dimensionless].

Table 4.6 Initial curve numbers for urban land use classes (after Schulze *et al.*, 2004)

Land Treatment/ Practice/ Description	Hydrological Soil Group						
	A	A/B	B	B/C	C	C/D	D
Open spaces, parks, cemeteries (95% grass cover)	39	51	61	68	74	78	80
Open spaces, parks, cemeteries (75% grass cover)	49	61	69	75	79	82	84
Commercial/business area (85% impervious)	89	91	92	93	94	95	95
Industrial districts (72% impervious)	81	85	88	90	91	92	93
Residential: lot size 500 m^2 (65% impervious)	77	81	85	88	90	91	92
Residential: lot size 1000 m^2 (38% impervious)	61	59	75	80	83	85	87
Residential: lot size 1350 m^2 (30% impervious)	57	65	72	77	81	84	86
Residential: lot size 2000 m^2 (25% impervious)	54	63	70	76	80	83	85
Residential: lot size 4000 m^2 (20% impervious)	51	61	68	75	78	82	84
Paved parking lots, roofs, etc.	98	98	98	98	98	98	98
Streets/roads: tarred, with storm sewers, curbs	98	98	98	98	98	98	98
Streets/roads: gravel	76	81	85	88	89	90	91
Streets/roads: dirt	72	77	82	85	87	88	89
Streets/roads: dirt-hard surface	74	79	84	88	90	91	92

4.2.1.4 The Revitalised Flood Hydrograph (ReFH) model

The FSR/FEH rainfall-runoff method has been widely used in the UK since publication of the Flood Studies Report (FSR) by the Natural Environment Research Council in 1975 (NERC, 1975). The Revitalised Flood Hydrograph (ReFH) model was developed in 2006 as a lumped event-based rainfall-runoff model with the FSR/FEH model as a basis (Kjeldsen *et al.*, 2006). It is widely used in the UK for design flood estimation, but is also possibly applicable to other countries (Kjeldsen *et al.*, 2013). The ReFH model consists of three components: (a) a loss model where the input hyetograph is transformed into the excess rainfall hyetograph, dependent on the antecedent soil moisture conditions, (b) a unit hydrograph-based model for runoff routing, and (c) a baseflow model (Kjeldsen *et al.*, 2013). It was developed with few parameters to allow spatial generalisation and the consequent applicability to ungauged catchments. The original model was not designed specifically for use in urban catchments (Kjeldsen *et al.*, 2006). Urban design floods were estimated using a hyetograph based on high intensity summer storms, with a threshold of 12.5 % of urban area in a catchment used to define a catchment as urban (Kjeldsen, 2007). However, the mathematical expressions were recently extended to better incorporate impacts of urban development into the model (Kjeldsen *et al.*, 2013).

The loss model was adapted to include weighted averages of the contributions of runoff from rural and urban areas. The percentage runoff can be calculated as shown in Equation 4.8 (Kjeldsen *et al.*, 2013):

$$PR = (1 - 1.576URBEXT_{2000})PR^{(rural)} + 1.576URBEXT_{2000}PR^{(urban)} \tag{4.8}$$

where

PR = percentage runoff [%],

$URBEXT_{2000}$ = index of urban extents in the UK derived using satellite imagery from the year 2000,

$PR^{(rural)}$ = percentage runoff from the rural part of the catchment [%], and

$PR^{(urban)}$ = percentage runoff from the urban part of the catchment [%].

with

$$PR^{(urban)} = 0.3PR^{(imp)} + 0.7PR^{(rural)} \tag{4.9}$$

where

$PR^{(imp)}$ = percentage runoff [%] from impervious areas, usually taken as 70 %.

The assumptions of 30 % imperviousness and 70 % runoff in Equation 4.9 were taken from Packman (1980), but could be adapted where better information is available (Kjeldsen *et al.*, 2013).

The routing model was adapted by applying separate unit hydrographs for runoff routing from rural and urban sections of the catchment, with the time-to-peak (T_p) parameter of the urban area expressed as a ratio of the T_p for the rural area.

For the baseflow model, recharge of the catchment is related to the direct runoff from the rural area as shown in Equation 4.10:

$$r_t = BRq_t^{(rural)} \tag{4.10}$$

where

r_t = recharge [m^3/s],

BR = model parameter controlling baseflow reservoir recharge [unitless], and

$q_t^{(rural)}$ = direct runoff from the rural area [m^3/s].

Only runoff from the rural area is considered, as it is assumed that urbanisation will decrease baseflow (Kjeldsen *et al.*, 2013).

4.2.2 Continuous rainfall-runoff modelling

Estimation of future floods with an acceptable risk, quantified as the probability of exceedance, can be performed by continuous simulation of a long period of streamflow in order to extract the necessary flood statistics. In continuous simulation models, losses from rainfall and streamflow generation are simulated by a water budget of hydrological fluxes into and out of a catchment, computed in predetermined time steps. Most continuous simulation systems have a loss model for determining runoff from rainfall and a flood hydrograph model for simulating the temporal distribution of that runoff at the downstream end of the catchment (Boughton and Droop, 2003; Smithers *et al.*, 2013).

The first hydrological computer modelling software, the Stanford Watershed Model, was developed in the 1960s (James, 1965, cited by Boughton and Droop, 2003) and numerous models have been subsequently developed to simulate storm water quantity and/or quality and many of these can be used for both urban and rural hydrological simulation.

Many of the models were developed by US government agencies, most prominent of which is the Environmental Protection Agency (USEPA) and the Army Corps of Engineers. The USEPA developed: the Hydrologic Simulation Program – Fortran (HSPF), which is an updated version of the Stanford Watershed Model that uses the Green-Ampt model for infiltration (Bicknell *et al.*, 1993); the Storm Water Management Model (SWMM), which can be used for continuous simulation or event-based modelling using either Hortonian flow or Green-Ampt (Huber and Dickinson, 1988); and the Quantity-Quality Simulator (QQS), which simulates both water quality and flow volumes (Geiger and Dorsch, 1980). The HEC-HMS Hydrologic Modelling System, which uses curve numbers to calculate infiltration (Kumar and Bhattacharjya, 2011), was developed by the US Army Corps of Engineers (Charley *et al.*, 1995).

The Danish Hydraulic Institute (DHI) have also developed a number of software packages to assist engineers and hydrologists with urban water modelling, with MIKE URBAN used for urban runoff modelling. It runs on the SWMM engine and can be used to model water distribution systems, storm water drainage systems and combined or separate sewer systems (DHI, 2015). There are several other academic institutions, government departments and consulting firms that have also developed, and are continuing to develop, hydrological models (Jacobson, 2011). Many of the software programmes now include functionality for digital terrain mapping and some programmes even support the interaction between sewer flows and surface flooding, thereby enabling new approaches to urban flood management (Wheater and Evans, 2009; Fletcher *et al.*, 2013). Other continuous models that can be used for urban hydrological quantity modelling include DR_3M, MUSIC, STORM and the Wallingford Model (Zoppou, 2001; eWater, 2016). The Agricultural Catchment Research Unit (ACRU) model (Schulze, 1995) which is a conceptual agrohydrological continuous simulation model that uses a modified SCS approach to generate stormflow (Smithers *et al.*, 2013) has also been used successfully in an urban study (Schmitz and De Villiers, 1997). MUSIC was originally developed mainly for water sensitive urban design planning, but can be utilised for a wide range of urban stormwater scenario modelling. It is used mainly in Australian urban areas (eWater, 2016). Despite the range and availability of programmes for urban storm water modelling, research in the field is still continuing (Fletcher *et al.*, 2013).

At present, the most-used models for continuous urban hydrological quantity modelling found in recently published journal papers are SWMM and MIKE URBAN (Zoppou, 2001; Elliot and Trowsdale, 2007; Jacobson, 2011; Yao *et al.*, 2015; Zhang *et al.*, 2015; Bisht *et al.*, 2016; Faust and Dulcy, 2016), with SWMM probably being the most-used model by consultants in South Africa. ACRU has also been used successfully in South Africa (Schulze, 1995; Schmidt *et al.*, 2009; Kienzle, 2011; Kienzle *et al.*, 2012; Smithers *et al.*, 2013). Therefore these models will be discussed in the following sections.

4.2.2.1 Storm Water Management Model (SWMM)

The Storm Water Management Model (SWMM) is one of the most widely used storm water models (Elliot and Trowsdale, 2007; Fletcher *et al.*, 2013) When it was released in 1971, it was an event-based model, but it has developed to include the functionality of a continuous runoff quantity and quality model (Fletcher *et al.*, 2013). Time steps of between 1 minute and a number of days can be used, depending on the application and desired detail of the model (Rossman and Huber, 2016). The Green-Ampt model, Horton model or curve numbers can be used to account for losses due to infiltration. Routing can be simulated using steady wave routing, kinematic wave routing or dynamic wave routing (Bisht *et al.*, 2016).

SWMM is generally used to design storm water drainage, but it can also be used to track non-point source pollutant loadings; evaluate Low Impact Development (LID) infrastructure; model combined sanitation and storm water conditions; and model flood control in urban areas and natural systems (Texas A&M University, 2007). In addition to its wide range of uses, the SWMM engine is open source software and therefore widely accessible (Elliot and Trowsdale, 2007). Various companies have built modelling software that offer sophisticated user interfaces around the engine.

SWMM is a lumped model that uses the principle of the conservation of mass to calculate runoff from a subcatchment. The subcatchment is assumed to be a rectangular, non-linear reservoir with a uniform slope and a width that drains to a single outlet. Inflow is generated by precipitation and losses by evaporation and infiltration. The net excess water will form a pond of depth d on the subcatchment surface. Depression storage, d_s, is included to account for surface ponding on flat areas and vegetation. The Manning equation is used to express the runoff volumetric flow rate, Q (Rossman and Huber, 2016). Combining these principles, Equation 4.11 is used to compute the mass balance over a time step (Rossman and Huber, 2016):

$$\frac{\delta d}{\delta t} = i - e - f - \frac{1.49 W S^{1/2}}{An}(d - d_s)^{5/3} \tag{4.11}$$

where

$\frac{\delta d}{\delta t}$ = net change in depth per unit of time [m/s],

i = rate of rainfall plus snowmelt [m/s],

e = surface evaporation rate [m/s],

f = infiltration rate [m/s],

W = subcatchment width [m],

S = subcatchment slope [m/m],

A = subcatchment surface area [m^2],

n = Manning’s surface roughness coefficient,

d = net ponding depth [m], and

d_s = depression storage depth [m].

Equation 4.11 can be solved numerically over each time step to find the ponded depth *d*. Once d is known, the runoff rate q can be found using Equation 4.12 and Equation 4.13 (Rossman and Huber, 2016):

$$q = \frac{1.49WS^{1/2}}{An}(d - d_s)^{5/3} \qquad (4.12)$$

where

q = runoff rate [m/s], and

$$Q = \frac{1.49WS^{1/2}}{n}(d - d_s)^{5/3} \qquad (4.13)$$

where

Q = runoff rate [m^3/s].

According to Texas A&M University (2007), the percentage of impervious areas and infiltration parameters have the largest influence on runoff volumes. The peak flow is influenced by the length and slopes of flow paths and the accuracy of flow routing is dependent on the time step used. The model is deemed to have reliability levels of approximately 10 % for volumes and 20 % for flow peaks.

4.2.2.2 MIKE URBAN

DHI have developed a number of software packages to assist engineers and hydrologists with urban water modelling, with the main product currently promoted for urban runoff modelling being MIKE URBAN. This product can be used to model water distribution systems, storm water drainage systems and combined or separate sewer systems (DHI, 2015).

MIKE URBAN incorporates GIS components to provide a user-friendly interface for the SWMM engine (Elliot and Trowsdale, 2007). It therefore has all the functionality of SWMM, with the additional capability to simulate 2D overland flow and GIS integration (Bisht *et al.*, 2016). Its storm water functionality can be applied in many engineering and planning processes, including: master planning; operational and maintenance planning; wet weather management; planning for urban flooding risk mitigation; evaluation of storm water designs and low impact development (LID) applications; and design and optimisation of control systems (DHI, 2015).

4.2.2.3 Agricultural Catchment Research Unit (ACRU) model

The Agricultural Catchment Research Unit (ACRU) model is a physical based conceptual continuous simulation model that was originally developed for agricultural applications, but has also been successfully applied to urban catchments (Tarboton and Schulze, 1992; Schmitz and De Villiers, 1997). It uses daily time steps and uses input rainfall, land cover and soil characteristics (Schulze, 1995) in a modified SCS Curve Number model and soil moisture deficit is used to replace the curve number (Boughton and Droop, 2003). Triangular-shaped unit hydrographs are either used to calculate the peak discharge from the daily runoff, or daily rainfall is disaggregated into shorter time intervals and the excess routed through the catchment to calculate the flood hydrograph (Boughton and Droop, 2003).

The model was developed in South Africa, but has been used successfully in various other countries, including: Swaziland, Zimbabwe, Germany, the USA, Canada and New Zealand (Schulze, 1995; Schmidt *et al.*, 2009; Kienzle, 2011; Kienzle *et al.*, 2012).

The ACRU model was successfully used by Smithers *et al.* (2013) as a continuous simulation model in a catchment in South Africa. However, they have noted that the lack of reliable data was a challenge in the use of ACRU. Smithers *et al.* (2013) recommended further improvement and verification of a continuous simulation modelling methodology for use in design flood estimation in South Africa.

4.2.3 Comparative summary of urban models

This section provides a summary of the models reviewed, indicating their categorisation (Table 4.7) and factors that were considered in model selection for this study (Table 4.8). In Table 4.8 green cells denote desirable characteristics, orange cells denote acceptable, but not desirable characteristics and red cells denote undesirable characteristics. From Table 4.8 it is clear that the SCS method and the ReFH model present the most desirable characteristics of event-based models and SWMM presents the most desirable characteristics of a continuous model, considering the cost implications of MIKE URBAN.

Table 4.7 Characterisation of applicable urban models (after Zoppou, 2001)

Model	Modelling Philosophy	Model Results			Time Modelling Scale	
		Flood Peak	Flood Hydrograph	Hydraulic Routing	Continuous	Event
Rational method	Conservation of mass	✓				✓
SCS-SA method	Hortonian flow and Unit hydrographs	✓	✓			✓
ReFH model	Unit hydrograph	✓	✓			✓
SWMM	SCS (Hortonian flow) or Green-ampt	Flow balance only	✓	With EXTRAN module	✓	✓
MIKE URBAN	SCS (Hortonian flow) or Green-ampt	✓	✓	✓	✓	✓
ACRU	SCS (Green-ampt)	✓	✓		✓	✓

Table 4.8 Summary of applicable urban models

Model	Applicability to Urban Areas	Data Requirements	Spatial Modelling	Temporal Scale	Runoff Routing to Outlet	Hydraulic Modelling Capability	Accuracy of Results	Simulation Time	Cost
Rational method	High	Little (Van Dijk *et al.*, 2013)	None	None, only flood peak is calculated	None	None	Coefficient selection is subjective, so accuracy can be poor (Smithers, 2012)	Short	Low
SCS method	Not currently calibrated for SA urban areas	Little (Van Dijk *et al.*, 2013)	None	None	Flood hydrograph is calculated from unit hydrograph	None	Less subjective than Rational method (Smithers, 2012), but CN-value is approach-dependent (Randusova *et al.*, 2015)	Short	Low
ReFH model	Not currently calibrated for SA urban areas	Moderate (Kjeldsen *et al.*, 2006; Kjeldsen *et al.*, 2013)	Lumped model	None	Flood hydrograph is calculated from unit hydrograph	None	Further testing on urban catchments is recommended, but initial results are promising (Kjeldsen *et al.*, 2013)	Short	Low
SWMM	Not currently calibrated for SA urban areas	Significant (Texas A&M University, 2007)	Lumped model	Time steps from 1 minute to a number of days (Rossman and Huber, 2016)	Steady wave, kinematic wave or dynamic wave (Bisht *et al.*, 2016)	Pipe flow and open channel flow	Relatively accurate, but cannot simulate 2D flow (Bisht *et al.*, 2016)	Moderate	Software is free, but time is required for model setup
MIKE URBAN	High	Significant (Texas A&M University, 1999)	Distributed model	Time steps of less than 1 second to a number of days	Diffusive wave (DHI, 2007)	2D overland flow, pipe flow and open channel flow	Seen as most accurate, as 2D and 1D flow can be simulated (Bisht *et al.*, 2016)	Significant	Software cost is high and time is required for model setup
ACRU	Calibration done for certain areas (Tarboton and Schulze, 1992)	Significant (Schulze, 1995)	Distributed model	Time steps from 30 minutes (for flood routing) to daily time steps	Hydrologic routing using the Muskingum Method	Open channel flow	Relatively accurate, but further verification was recommended (Smithers *et al.*, 2013)	Moderate	Software is free, but time is required for model setup

5 DISCUSSION AND CONCLUSIONS

Globally, more people now reside in cities than ever before, with more than half of the world's population living in urban areas in 2014. As more people move to cities, the sustainable development of urban areas will have to be improved, especially in developing countries, where urbanisation rates are the fastest.

It is widely accepted that urban development results in a decrease in the permeability of a catchment and will therefore result not only in larger flood peak discharges with faster catchment response times, but also in larger total flood volumes. However, this assumption does not take into account the possibility of retention and attenuation in urban systems due to property boundary fences and/or the levelling of naturally sloping areas, which are typical in South African formal peri-urban developments. In addition and in contrast with the perceived effects of urban development in first-world countries, runoff from informal settlements could be lower than expected when compared to formal urban areas, although this has not yet been researched thoroughly.

Various recent studies suggest that development does not affect all aspects of storm water runoff as generally perceived. The results from many studies indicate that all the effects of urbanisation on runoff are still not properly understood and therefore the current methods to quantify runoff from peri-urban catchments are still under development. Based on the findings published in a South African WRC report, it was recommended that the effect of urban and peri-urban development on storm water runoff be reviewed.

The international trend in urban hydrological modelling is currently leaning towards models that can better simulate the spatial and temporal distribution of urban storm water runoff. However, some of the software packages currently available are relatively expensive, especially for consultants in developing countries. Additionally, many of the models currently used for urban storm water modelling require a significant amount of input data. This data will generally not be available when considering settlements in developing countries. It also becomes more difficult to assess the accuracy of models with increasing complexity. Although the Rational method is seen as subjective and inaccurate, it is still one of the most widely applied methods, especially in developing countries where practitioners often cannot use more sophisticated methods due to the cost, data requirements and skills necessary in application of these methods.

Many design flood estimation procedures are currently in use in South Africa, but not all are applicable to urban areas. The methods that can be used in urban areas, including the Rational method and SCS-SA method, have not necessarily been calibrated for South African urban and peri-urban conditions, considering the unique development characteristics of these in South Africa. The ReFH method was recently updated for urbanised catchments in the UK, and some of the modelling procedures may be applicable to South African models.

The United States Environmental Protection Authority's Storm Water Management Model (EPA SWMM) is available as open source software and has been used successfully in many urban hydrology studies. It has moderate data requirements and can be used as an event-based or continuous model. It is widely used, but there are currently no available calibrated coefficients for South African urban areas.

The ACRU model is a physical based conceptual continuous simulation model that was originally developed for agricultural applications, but has also been successfully applied to urban catchments. Previous studies have recommended further improvement and verification of a continuous simulation modelling methodology like ACRU for use in design flood estimation in South Africa.

There is clearly a need for the development of a properly calibrated, simplistic, estimation procedure for design flood estimation in peri-urban areas, specifically for South African peri-urban areas which include formal suburbs, informal settlements and traditional township areas.

6 PROJECT PROPOSAL

This chapter contains a proposal for the development and assessment of an approporiate method for estimating design floods in urban and peri-urban areas in South Africa by considering the need established in the previous chapters of this document. The project proposal includes the problem statement, hypothesis, objectives of the study, methodology, expected time frame, the proposed outcomes and contribution to new knowledge from this study.

From the above review of the literature it is clear that there is a need for the development of a properly validated and verified estimation procedure for estimating runoff from peri-urban areas, specifically for South African peri-urban areas, but that may also be applicable to more heavily urbanised areas in South Africa, as well as similar developments in other countries.

6.1 Problem Statement

South Africa is a developing country where people migrate to urban areas in search of employment and better service delivery. Studies have shown that the metropolitan and most intermediate sized cities in the country have experienced significant population increases in recent years, with approximately 65 % of South Africans currently living in urban areas. However, South African urban areas are somewhat unique in that during the post-Apartheid era, a large percentage of the white population has moved away from the urban centres towards urban fringes and smaller towns, while the traditional black townships on the outskirts of cities have experienced continued growth. The rate of urbanisation has also led to the establishment of many squatter camps on urban fringes. The combination has led to significant development of urban settlements on the outskirts of cities, referred to as peri-urban areas, most of which could be categorised as medium density and in many places formalised drainage systems are lacking.

The methods currently used for design flood estimation in urban areas do not necessarily provide for the unique range and combination of development types present in South Africa. Many of the methods to estimate floods in urban areas were not developed specifically for South African urban or peri-urban areas and the coefficients currently used were taken from studies in other countries, without considering the unique development types of present-day South Africa.

6.2 Hypotheses

It is hypothesised that the urban design flood estimation models currently used in South Africa can be improved by developing and/or adapting models used internationally for conditions in South Africa. It is believed that the SWMM model, and/or SCS-SA method, and/or Rational method can be improved to better account for runoff from a range of South African urban developments. As ACRU is often used in rural settings in South Africa, but has been used in the past to model runoff from urban areas, it is further hypothesised that a better calibration of ACRU for urban areas could be achieved that would be valuable for future design flood estimation in South African urban and peri-urban areas.

6.3 Research Aims

The aim of this study is to improve the understanding of hydrological processes in the South African urban and peri-urban environment and to develop a simple, calibrated model for design flood estimation that is applicable to South African urban and peri-urban areas. This will be achieved by developing and adapting urban runoff models to properly reflect the range of hydrological and hydraulic characteristics in South African urban areas.

6.4 Objectives of the Study

The objectives required to achieve the research aims and prove or disprove the hypotheses are the development, adaptation and calibration of urban runoff models for conditions in South Africa. The objectives required to achieve the research aims and prove or disprove the hypotheses are to:

(a) Review literature on the current methods and trends in hydrological modelling of urban and peri-urban areas in South Africa, as well as internationally. From these, applicable methods for urban and peri-urban modelling and design flood estimation will be selected.

(b) Determine the data requirements for runoff and design flood estimation in a range of urban areas and the availability of the data in South Africa.

(c) Collect data from municipalities, the South African Weather Services, the Department of Water and Sanitation and the Surveyor General.

(d) Set up models for various metropolitan areas in South Africa where data has been obtained.

(e) Develop, adapt and calibrate the models using the collected data. This will include the assessment of the performance of the ACRU and SWMM continuous models, the selection and calibration of the most applicable model and the use of the selected model to simulate a range of events.

(f) Undertake hydrological and hydraulic modelling for the metropolitan study areas.

(g) Evaluate the modelling results and select the best model to use. The results from the modelled scenarios will then be used to refine the parameters of event based models including the SCS-SA and the Rational method for conditions in a range of South African urban areas.

(h) Use the selected model to simulate the hydrological effect of urbanisation on different metropolitan areas in South Africa.

(i) Set up a matrix with coefficients for different development types found in South African metropolitan areas.

6.5 Methods and Materials

This section discusses the methodology that will be used to achieve the aims and objectives of the study which includes a description of the research sites, the proposed methodology, and the required equipment and resources.

6.5.1 Research sites

The chosen metropolitan areas represent the major urbanised areas in South Africa. The research sites include urbanised areas across the country, including the metropolitan areas of Pretoria, Johannesburg and Ekurhuleni in Gauteng, Durban in KwaZulu-Natal and Cape Town in the Western Cape. The study will be limited to urban areas with sufficient available rainfall and flow data. The areas are also situated in a variety of climatic regions and will therefore provide a basis of understanding of other urbanised areas in these climatic regions.

6.5.2 Methodology

The proposed methodology includes a thorough review of relevant literature to determine the generally used urban design flood estimation methods and hydrological modelling software currently used in South Africa and internationally. The data requirements and successful calibration of the models in a variety of urban areas will be investigated and practically applicable methods and models identified. Potential improvements to the structure of the models will be investigated and implemented, if required.

The historical changes in urban runoff peaks and response times with increasing development of various urban areas in South Africa will be studied. This will be done by statistically analysing rainfall measured in urban areas, as well as flow gauging data in rivers within urban catchments, obtained from the Department of Water and Sanitation and from various metropolitan municipalities and comparing this data to development trends in the catchment areas, as obtained from the Surveyor General and various metropolitan municipalities.

Hydrological models will be set up and calibrated using historical rainfall data and flow data from gauged catchments in urban areas. Urbanised catchments with sufficient flow data and historical urbanisation records will be simulated using the ACRU model and the SWMM model. The models will be calibrated using the spatial and flow data for the catchment areas. It is proposed that a variety of areas are studied in order for the results to be used in the development of a calibrated procedure for design flood estimation in various types of urban and peri-urban development which are typical in South Africa. The degree to which this will be achieved will depend on the amount of reliable data that could be gathered. The result will be verified/calibrated models of the ACRU model and/or SWMM, incorporating SCS-SA adaptions, and the Rational method. The selected verified model will be used to simulate the range of urban areas and develop rules and calibration coefficients for application of the model in South Africa.

6.5.3 Equipment and resources

The model input will include flow data obtained from the Department of Water and Sanitation, Ethekwini Metropolitan Municipality and Cape Town Metropolitan Municipality. Rainfall data will be obtained from the South African Weather Services, Ethekwini Metropolitan Municipality and Cape Town Metropolitan Municipality. Spatial urbanisation data will be obtained from the Surveyor General, various metropolitan municipalities and geographical information system data from the Centre for Water Resources Research at the University of KwaZulu-Natal.

Statistical analyses of measured flow data will be analysed using Microsoft Excel software and Sinotech’s Utility Programme for Drainage. The hydrological models will be set up using Microsoft Excel for the SCS-SA and Rational methods; in the EPA SWMM software, version 5.1: and in the ACRU Model, version 4. Urbanisation areas and trends will be observed using ESRA’s ARCMap software.

6.6 Time Schedule

In order to complete the study timeously and effectively, all activities have to be properly scheduled. The list of required activities is shown in Table 6.1. The colour scales refer to different types of activities, including data acquisition, analysis, calibration, thesis writing and journal paper writing.

Table 6.1 Proposed time schedule

Proposed research activities, work plan and deliverables																																																	
		2015												**2016**												**2017**												**2018**											
Activity number	**Activity name**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
1a	Review of applicable literature				░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░																											
1b	Formulation of hypothesis																				░	░	░																										
1c	Review of applicable design flood estimation methods													░	░	░	░	░	░	░																													
2a	Finalisation of project proposal																	█	█	█	█	█	█	█	█																								
3a	Write review paper on urban and peri-urban design flood estimation procedures																		■	■	■	■	■	■	■																								
1d	Gather data (rainfall, flow and GIS urbanisation data)																	░	░	░	░	░	░	░	░	░	░																						
4a	Analyse GIS data and categorise development types																						▒	▒	▒	▒	▒	▒	▒	▒																			
4b	Configure models on SWMM and ACRU																							▒	▒	▒	▒	▒	▒																				
4b.1	Pretoria																							▒	▒	▒																							
4b.2	Cape Town																									▒	▒																						
4b.3	Johannesburg																										▒	▒																					
4b.4	Durban																											▒	▒																				
4b.5	Ekhurhuleni																												▒	▒																			
5a	Calibrate and verify model outputs																					▓	▓	▓	▓	▓	▓	▓	▓	▓	▓																		
5a.1	Pretoria																					▓	▓	▓	▓																								
5a.2	Cape Town																									▓	▓																						
5a.3	Johannesburg																										▓	▓																					
5a.4	Durban																											▓	▓																				
5a.5	Ekhurhuleni																													▓	▓																		
5b	Compare model outputs considering development types and climatic conditions																										▓	▓	▓	▓	▓	▓	▓																
3c	Write paper on the effect of urbanisation on runoff in South Africa																													■	■	■	■	■															
5c	Develop calibration coefficients for SWMM for the different development types																																▓	▓	▓														
3d	Write paper on SWMM calibration coefficients																																	■	■	■													
5d	Develop calibration coefficients for the SCS-SA and/or Rational method for different development types																																		▓	▓	▓												
3e	Write paper on SCS-SA calibration coefficients																																			■	■	■											
2b	Combine and synthesise papers into first draft thesis																																						█	█									
2c	Prepare final draft thesis																																								█	█	█	█					

Legend:
░ Information gathering
▒ Data analysis
▓ Calibration
█ Thesis writing
■ Paper writing

6.7 Intellectual Considerations

Form IP2 of the University of KwaZulu-Natal, dealing with intellectual property and proprietary information, was signed and submitted to the School of Engineering on the 2nd of February 2015.

It is evident from the literature review that the parameters currently used in South Africa were developed in other countries with development characteristics that differ from the typical range of South African development characteristics. The new contribution to knowledge will include a better understanding of the effect of urban development on runoff in and around South African cities. Calibrated parameters for South African conditions will be developed.

6.8 Expected Outcomes and Deliverables

The following outcomes and deliverables are planned for this study:

(a) The aim of the study is to provide calibration coefficients for the selected model which has been developed, adapted and calibrated for conditions in South African urban areas. The proposed outcome will be a matrix of calibrated model parameters for the range of different development types in different climatic regions in South Africa.

(b) Four to five papers relating to various elements of the study will be published in ISI-accredited journals. The preliminary titles of the envisaged journal articles are:
    (a) A review of urban and peri-urban design flood estimation procedures applicable to South Africa.
    (b) Analysis of urban development characteristics in South Africa and the effects thereof on runoff.
    (c) Proposed calibration coefficients for SWMM applied to a range of South African urban areas.
    (d) Proposed calibration coefficients for SCS-SA and the Rational method applied to a range of South African urban areas.
    (e) Recommended approaches for flood estimation in urban areas in South Africa.

(c) Two national and one international conference papers will be compiled and prepared for presentation.

(d) A PhD Engineering thesis will be produced by incorporating the journal articles.

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