Design Flood Estimation in Urban Areas in South Africa: Preliminary Results from Tshwane Case Studies

Deliverable 6: Final Report

KSA 1 – Water Resource Management
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I Loots & JC Smithers

Department of Civil Engineering
Engineering 1
University road
0001

&

Bioresources Engineering
School of Engineering
College of Agriculture, Engineering and Science
University of KwaZulu-Natal
Pietermaritzburg

WATER RESEARCH COMMISSION

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

UNIVERSITY OF KWAZULU-NATAL

Obtainable from:
Water Research Commission
Private Bag X03
Gezina
0031

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EXECUTIVE SUMMARY

Globally, more people now reside in cities than ever before, with more than half of the world's population living in urban areas since 2005 (UNDP, 2019). 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 (UNDP, 2019).

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 systems, 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 many South African urban areas. 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 South African 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 the range of South African 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 significant amounts of input data which are often not available, especially for consultants working 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 found in South Africa. Many of the methods currently applied in urban areas in South Africa were not developed specifically for the range of urban areas found in the country and the input parameters used for urban areas used are derived from studies in other countries, without considering the unique circumstances and conditions in present-day South Africa. The need has therefore arisen for the development of a validated and verified estimation procedure to accurately estimate design floods from both formal and informal urban settlements in South Africa, especially in areas with little or no reliable streamflow data.

The major aims of this project, as stated in the contract, consisted of major objectives related to design flood estimation for urban areas in South Africa including the following:

(i) To improve the understanding of hydrological processes in the South African urban and sub-urban environments.
(ii) To develop a calibrated design flood estimation method for urban and sub-urban areas, either by updating existing methods, or developing a new method, by focussing on two case studies in urbanised areas of South Africa.
(iii) To disseminate any new-found knowledge through scientific papers and at conferences.

The above aims were achieved by firstly conducting a detailed literature review focussing on urbanisation trends, the impacts of urbanisation on hydrological responses, challenges with hydrological modelling in developing countries, and models used in urban runoff modelling. The literature review was used to inform the methodology used to develop calibrated design flood estimation method parameters associated with each of the urban land use types on the Department of Environmental Affairs (DEA) land use maps (Geoterraimage, 2015) using the Storm Water Management Model (SWMM) software developed by the Environmental Protection Agency (EPA).

A small catchment in Tshwane was selected to use as a pilot study area in order to establish an applicable methodology for the model configuration and calibration applied in this project. After the SWMM parameters for the catchment configuration using the Modified Green-Ampt infiltration method were calibrated by adjusting the infiltration and imperviousness parameters, the adjusted parameters were verified on an adjacent catchment.

The calibration and verification process showed that the parameters currently used for runoff modelling in South African urban areas do not provide accurate results in gauged catchments. The need for updated parameters was therefore confirmed.

The SCS-SA method was identified as a method that could be used more widely in urban design flood estimation if the curve numbers were adapted and/or estimated for urban development types found in South Africa. Since SWMM also has the option to use an SCS infiltration method for urban models, the calibrated and verified catchment configurations were used to derive applicable SCS Curve Numbers for urban land use types in the calibration and verification catchments. The verified parameters for the study area catchments were used as basis for the extrapolation of preliminary parameter values for urban design flood estimation in ungauged catchments in South Africa. Further verification of the use of the preliminary parameter values on more catchments with a wider range of urban types of development is recommended.

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Mr C Brooker	:	CBA Specialist Engineers
Mr S Dunsmore	:	Fourth Element Consulting
Mr D van der Spuy	:	Department of Water and Sanitation
Dr S Lorentz	:	SRK Consulting
Dr OJ Gericke	:	Central University of Technology
Mr M Braune	:	BioEng
Mr JP Calitz	:	University of KwaZulu-Natal
Mr T Rowe	:	JG Afrika
Mr P Rademeyer	:	Department of Water and Sanitation
Prof JA du Plessis	:	Stellenbosch University
Prof JG Ndiritu	:	University of Witwatersrand
Mr M van Dijk	:	University of Pretoria
Mr JPJ Pietersen	:	Central University of Technology
Mr M Parak	:	SANRAL
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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
DEA	Department of Environmental Affairs
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
SA	South Africa
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.

Term	Description
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 55% of approximately 7.63 billion people, living in urban areas in 2018 (UNDP, 2019). 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 settlements on the city outskirts.

Many authors agree that all the impacts of urbanisation on runoff are still not properly understood and therefore the current methods used 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) recommended that, amongst others, "(t)he influence of urban development on catchment response (runoff peaks and runoff volume) be reviewed".

Braud *et al.* (2013b) state that, although progress has been made in recent years to better understand the hydrology of complex environments on urban fringes, 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 is 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.

From the literature reviewed it is clear that there is a need for the development of a validated and verified estimation procedure for urban runoff that will be applicable to the range of development types that are present in South Africa, but that may also be applicable to similar developments in other countries.

The major aims of this project, as stated in the contract, consisted of major objectives related to design flood estimation for urban areas in South Africa including the following:

i. To improve the understanding of hydrological processes in the South African urban and sub-urban environments.
ii. To develop a calibrated design flood estimation method for urban and sub-urban areas, either by updating existing methods, or developing a new method, by focussing on two case studies in urbanised areas of South Africa.
iii. To disseminate any new-found knowledge through scientific papers and at conferences.

The aims were achieved by firstly conducting a detailed literature review focussing on urbanisation trends (Chapter 2); the impacts of urbanisation on hydrological responses (Chapter 3); challenges with hydrological modelling in developing countries (Chapter 4); and models used in urban runoff modelling (Chapter 5). The literature review was used to inform the methodology used to develop calibrated design flood estimation method parameters associated with each of the urban land use types on the Department of Environmental Affairs (DEA) land use maps (Geoterraimage, 2015) using the Storm Water Management Model (SWMM) software originally developed by the Environmental Protection Agency (EPA). The commercial package, PCSWMM, was used for catchment configuration and analysis.

The second objective of this research project was to obtain calibrated catchment parameters that are associated with each of the urban land use types contained in the DEA land use maps for use in deterministic design flood estimation. The literature review was used to inform the methodology used to develop a calibrated design flood estimation method for South African urban and sub-urban areas using the Storm Water Management Model (SWMM) software developed by the Environmental Protection Agency (EPA), which was selected from a number of models reviewed. As detailed in Chapters 6 and 7, a small catchment was selected to use as a pilot study area in order to establish an applicable methodology for the catchment configuration and calibration applied in this project. After the SWMM parameters for the catchment configuration using the Modified Green-Ampt method were calibrated by adjusting the infiltration and imperviousness parameters, the adjusted parameters were verified with a configuration of an adjacent catchment area.

The calibration and verification process showed that the parameters currently used for runoff modelling in South African urban areas do not provide accurate results in gauged catchments. The need for updated parameters was therefore confirmed.

The SCS-SA method was identified as a method that could be used more widely in urban design flood estimation if the curve numbers were verified for urban development types in South Africa. SWMM also has the option to use an SCS infiltration method for urban models. After the SWMM parameters for the catchments using the Modified Green-Ampt method were calibrated and verified, the calibrated catchment configurations were used to derive applicable SCS Curve Numbers for the urban land use types in the calibration and verification catchments, as described in Chapter 8. It should, however, be noted that the derived CN values are generally conservative for large flood events, but underestimate small events.

The verified parameters for the study area catchments were used as a basis for the preliminary extrapolation of applicable parameter values for urban design flood estimation and storm water infrastructure design in South Africa, as described in Chapter 9. Parameters were calibrated for use in urban SWMM modelling and the SCS-SA deterministic design flood estimation method. Chapter 10 provides a discussion and draws conclusions from the study and provides recommendations for future research.

2 TRENDS IN URBANISATION

As urbanisation increases around the world, the occurrence of flooding and subsequent damage to infrastructure and social structures in urban areas are also rising. The background to the need for accurate urban runoff modelling, specifically considering the range of urban environments in developing countries, is discussed in this chapter.

2.1 Global Trends in Urbanisation

Since 2005, more than half of the world's population live in urban areas, with the proportion of urban dwellers set to rise to about 60% by 2030, as shown in Figure 2.1 (UNDP, 2019). As urban areas continue to expand, significant pressure is imposed on the natural dynamics, availability of resources and ecological diversity (Niemczynowicz, 1999). This is particularly true in developing countries, especially in Africa and Asia, where urbanisation rates are growing the fastest (Cohen, 2006; UNDP, 2014; Zhang *et al.*, 2015) and often occur in an unbalanced and disorganised manner (Gogate and Rawal, 2015).

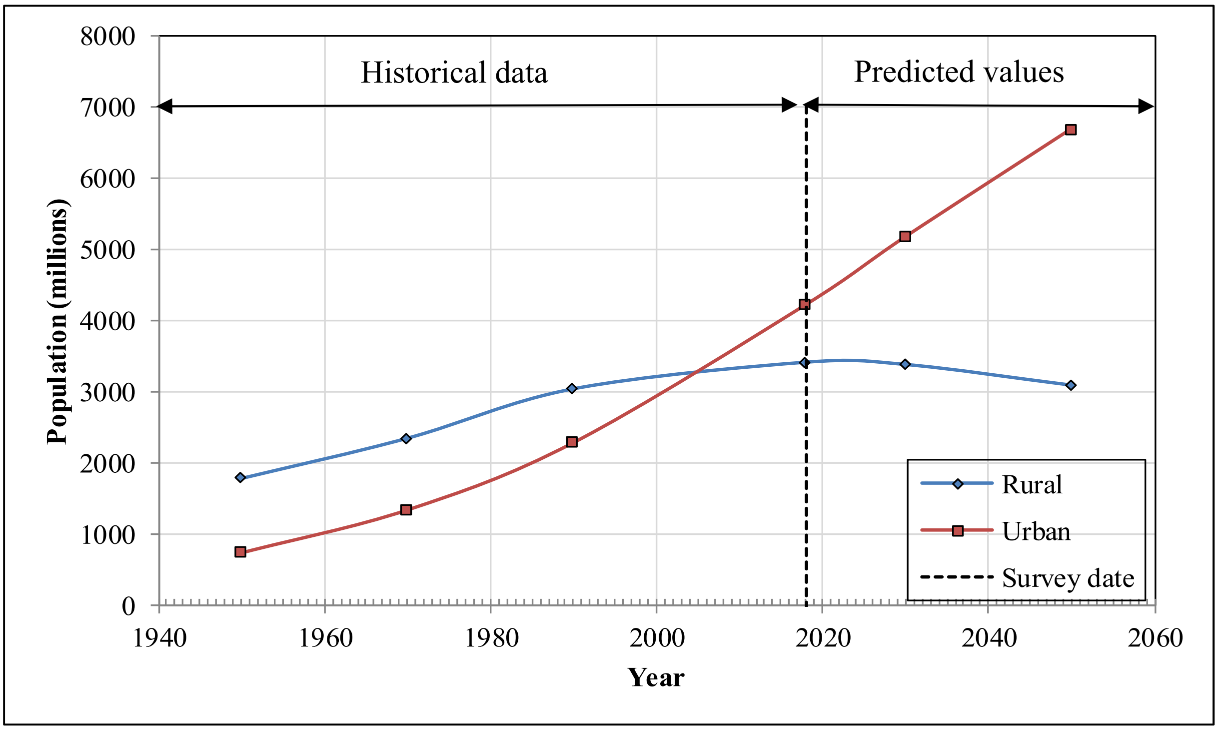

Figure 2.1 Global urbanisation trends from 1950 projected to 2050 (UNDP, 2019)

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 grow in the 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 and is where some of the poorest communities live in informal settlements on city outskirts (Geyer *et al.*, 2012) with no formal drainage and reticulation systems.

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 most 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).

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. This combination has led to significant development of 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 the nine provinces in South Africa, almost 20 % of the households resided in informal dwellings in 2013.

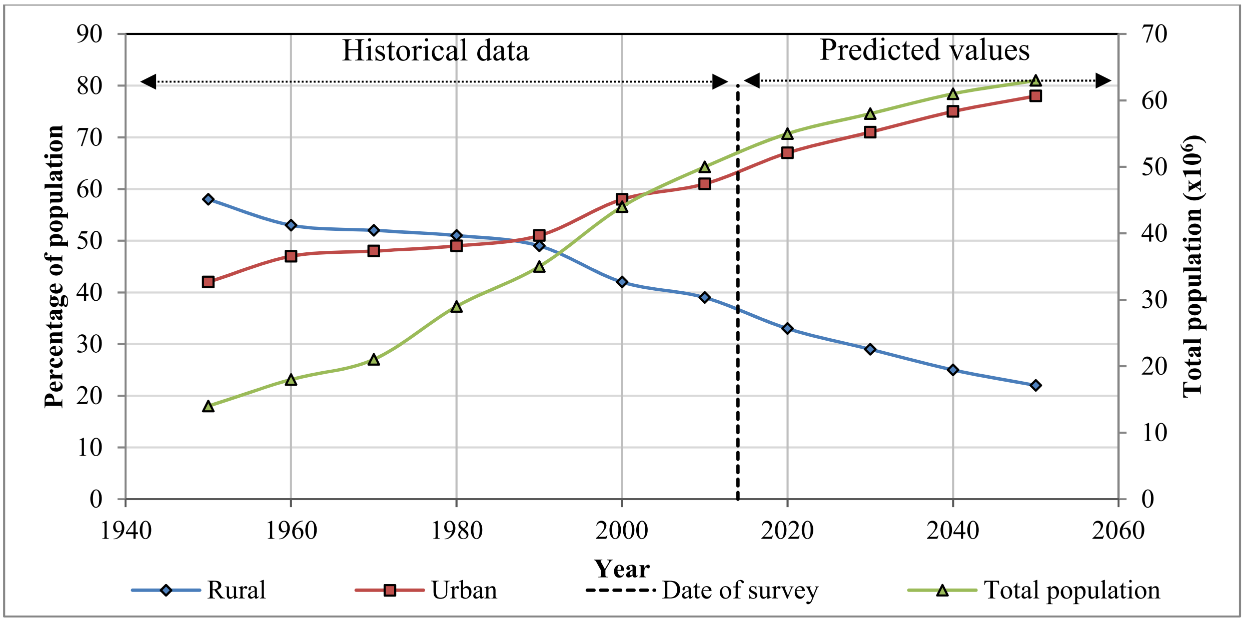

Figure 2.2 Proportion of urban and rural population in South Africa from 1950 projected to 2050 (UNDP, 2014)

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 rate of increase in 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 development has 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 quickly saturated, 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 have generally found increasing trends in hydrological responses in catchments as urbanisation occurred (Konrad, 2003; Putro *et al.*, 2016). These impacts are shown in Figure 3.1.

However, some studies suggest that not all aspects of storm water runoff are necessarily impacted by development (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). The materials, and types of infrastructure used in some developments, as well as local topography and changes in slopes, 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.

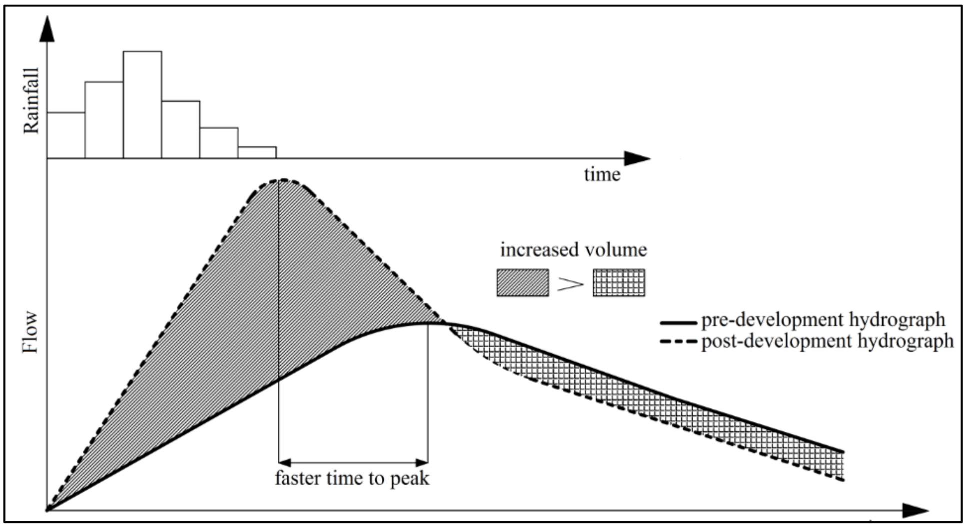

Figure 3.1 The perceived effect of urbanisation on runoff (Houghton-Carr, 1999)

3.1 The Influence of Development on Catchment Permeability

The percentage of impervious areas in an urban environment generally has a significant effect on the water environment (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* have 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 ranging 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 more 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, although there are various development features that would increase runoff, there are others that would have the opposite effect. Therefore, they concluded 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 larger 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 urban 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 base flow 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 on runoff from 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 on 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 next chapter will focus on the specific challenges of urban hydrological response modelling in developing countries.

4 CHALLENGES WITH HYDROLOGICAL MODELLING IN DEVELOPING COUNTRIES

Engineers and hydrologists face a number of challenges to accurately model urban runoff. The main factors that complicate urban modelling include heterogeneity of the catchment and the challenges with finding accurate and reliable input data, especially for complex models. This section contains a review of these challenges.

4.1 Heterogeneity in a Catchment

Heterogeneity in catchments can include: spatial variation in both soils and land-use, spatial and temporal rainfall variation, the effect of antecedent soil conditions on runoff, unpredictable flow path characteristics due to combined sewers, and uncertainties related to the operation and maintenance of infrastructure.

4.1.1 Land-use heterogeneity

Although the influence of truly impervious surfaces on runoff is relatively straightforward, the role of pervious areas within the urban environment is still not well understood (McGrane, 2016). Peri-urban areas generally consist of a mixture of land uses associated with assorted urban and rural conditions (Jia *et al.*, 2001; Parkinson and Tayler, 2003). In many cases, a clear distinction between urban and rural sections of a catchment could be elusive, as interactions between rural and urban components of a catchment can be difficult to separate (Andrieu and Chocat, 2004). In addition, peri-urban areas are prevalent both in affluent and poor communities (Geyer *et al.*, 2012), contributing to the significant heterogeneity of these areas. In poor communities, infrastructure provision tends to happen in a haphazard fashion, resulting in a lack of drainage infrastructure in many settlements (Parkinson and Tayler, 2003).

Braud *et al.* (2013b) have also noted that mixed natural and artificial catchments could cause major research challenges in peri-urban modelling. These catchments have a combination of fast and slow hydrologic responses, resulting from significantly different flow paths, mainly caused by the interaction between natural sections of the catchment and sections dominated, for example, by pipeflow. Fletcher *et al.* (2013) agree and state that, while the runoff from impervious areas can be predicted easily, the runoff in pervious areas can influence both surface and subsurface flow, which makes urban runoff modelling complex. The increased use of Low Impact Development (*LID*) infrastructure causes additional interaction between surface and subsurface runoff (McGrane, 2016), although poor maintenance and consequent hydraulic inefficiency is common in these systems (Janke *et al.*, 2011). This is especially true in developing countries where the rate of urbanisation combined with a lack of financing could lead to poor or non-existent maintenance of infrastructure (Bhawan, 2001). Even the materials used in roads (Ragab *et al.*, 2003), building facades and rooftops (Blocken *et al.*, 2013) could impact on the percentage runoff from storm events. This complexity remains an area of research.

4.1.2 Soil heterogeneity

There exists significant variation in soil properties in South Africa, even on areas smaller than one hectare (Dippenaar *et al.*, 2014; Heymann, 2016; Dippenaar, 2019). There also exists significant variation in the hydraulic conductivity, even for soils with similar classifications (Rawls *et al.*, 1983; Chow *et al.*, 1988; Heymann, 2016). Dippenaar *et al.* (2014) noted that the upper soil layers in South Africa are usually comprised of highly variable unconsolidated mineral and organic matter, which would complicate the classification of soil properties on a regional scale.

4.1.3 Spatial and temporal variation in rainfall

Land-use and soil properties not the only varying factors in urban hydrology. Although rainfall is often assumed to be evenly distributed, especially over small catchments, in reality significant discrepancies can occur between average and point rainfall (Beven, 2012; Makgopa, 2015). Qin *et al.* (2013) found that rainfall conditions (storm duration, magnitude and intensity) could significantly impact on the hydrological responses in a catchment.

Urban development could also have a local effect on rainfall patterns. Gero *et al.* (2006) used a climatic model to assess the impact of urbanisation in Sydney, Australia, on the local climate. Although some types of storms did not appear to be affected by urbanisation, dense urban areas could be responsible for severe convective storms in this study area. Lei *et al.* (2008) also modelled a severe storm event in Mumbai, India and found that urbanisation could have influenced the event by causing heterogeneity in surface temperatures. These and other studies show that urbanisation could well have an influence on future local rainfall patterns (Jacobson, 2011).

4.1.4 The effect of antecedent conditions

Antecedent soil moisture conditions can have a significant impact on runoff generated from certain storms. If a rainfall event occurs on an area with low soil moisture content at the start of the storm, infiltration will normally be larger than a few hours later, when the soil has become saturated (Van Dijk *et al.*, 2013). Konrad (2003) found that the effects of urban development could be best seen after moderate storms following dry periods, where less saturation would occur than in natural catchments. Boyd *et al.* (1993) have found that the antecedent soil moisture conditions play a more significant role for larger storms, with rainfall depth exceeding 50 mm, in pervious catchments. Perhaps due to this, various studies (Konrad, 2003; Wheater and Evans, 2009) have found that the relative increase in peak discharge after urbanisation was larger for frequent, small events than low-probability, large events.

4.2 Parameter Estimation, Prediction Uncertainty and Model Validation

Many uncertainties, ranging from unreliable input data, to unknown future conditions, could have a significant influence on hydrological modelling. The following sections investigate challenges related to input data; climate change and reliability of data.

4.2.1 Input data for complex models

As the databases in many cities develop, urban hydrological modelling is becoming more and more sophisticated with spatially distributed continuous simulation models becoming more common. This, together with the growing integration of all aspects of water management, is causing increasing complexity in models. The methods for assessing model uncertainties are therefore also becoming more complex. However, the validation and uncertainty evaluation of these models are lagging behind their application (Fletcher *et al.*, 2013).

Grayson and Bloschl (2001) also found that a major challenge with complex modern models is to obtain and verify all the necessary input parameters. On the other hand, they also warn against the oversimplification of hydrological modelling in catchments where a lot of data is available. This is illustrated in Figure 4.1.

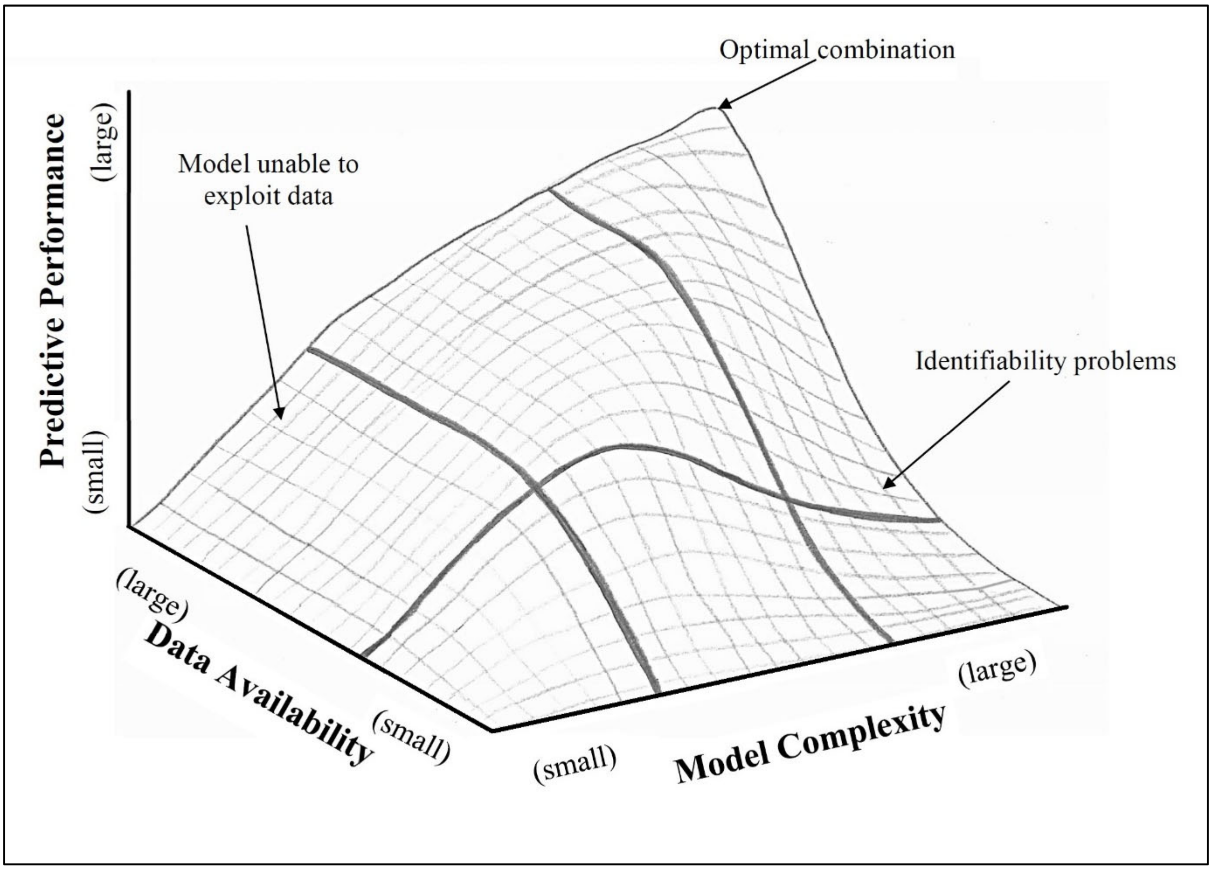

Figure 4.1 An illustration of the relationship between model complexity, data availability and predictive performance (Grayson and Bloschl, 2001)

According to Jacobson (2011), there are few clear guidelines on urban catchment model calibration. However, it seems that detailed and accurate information on land cover is an important parameter in effective urban catchment calibration. Although, no two catchments are the same, calibration parameters are not necessarily transferable between catchments. Therefore, Jacobson (2011) suggested that further research in this area should be conducted.

With increasing model complexity, increasing modeller skills are required to obtain accurate results (Parkinson *et al.*, 2007; Jacobson, 2011; Fletcher *et al.*, 2013). Fletcher *et al.* (2013) therefore suggest that model estimates, as well as an indication of the uncertainties, be provided to model users, so that these uncertainties could be taken into account in management processes.

4.2.2 Access to reliable data

Many of the models currently used for urban hydrological modelling require a significant amount of input data (Parkinson *et al.*, 2007). This data will not always be available (McIntyre *et al.*, 2014), especially when considering informal settlements in developing countries. Smithers *et al.* (2013) observed that it was difficult to apply a continuous simulation model in a catchment where observed data was not reliable, rain gauges were relatively sparse, water was transferred between catchments and various land cover changes occur over time.

Jacobson (2011) warns that short streamflow records, for example 10 years of record, can generally not be assumed as reliable, especially when gauging the influence of urbanisation, as other factors, like climate variability, could also significantly impact streamflow variability. Additionally, Smithers *et al.* (2013) have noted that in South Africa, the flow gauging data gathered by the Department of Water and Sanitation (DWS) may be inconsistent and unreliable, especially for large events. In the absence of reliable data, many modellers revert to using default values, which were not necessarily derived in areas with similar characteristics to the catchment being modelled. This could lead to inaccurate and unreliable models (Parkinson *et al.*, 2007). This situation would be more pronounced in developing countries where financial constraints could prevent authorities from maintaining gauging stations and constructing new gauging stations.

Once the input data for the catchment has been derived, then a model must be selected and configured for the urban areas under study. The following chapter contains a review of modelling approaches and models typically used in urban catchments.

5 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.

5.1 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.

5.2 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.

5.2.1 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 5.1. 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 5.1 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)

5.2.1.1 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 applicable to 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).

5.2.1.2 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 more complex 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):

$$Q = \frac{CIA}{3.6} \tag{5.1}$$

where

Q = flow [m^3/s],

C = runoff coefficient [dimensionless],

I = design storm intensity [mm/h], and

A = contributing catchment area [km^2].

and

$$C = \alpha(C_1 \times F_t) + \beta C_2 + \gamma C_3 \tag{5.2}$$

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 5.2. The values have been adapted from Horner and Flynt (1936), Vorster (1940) and 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 5.3.

Table 5.2 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 5.3 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 5.4.

Table 5.4 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:

$$C_{10} = 0.9 \times f + C_{10}^{1} \times (1 - f) \quad (5.3)$$

and

$$C_{10}^{1} = 0.1 + 0.0133 \times ({}^{10}I_1 - 25) \quad (5.4)$$

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:

$$C_{y0} = F_y \times C_{10} \quad (5.5)$$

where

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

F_y = frequency factor as given in Table 5.5.

Table 5.5 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 performance of the SDF method have been performed, with varying results (Gorgens, 2002; Van Bladeren, 2005; Gericke, 2010), but none of the evaluations considered urban catchments specifically.

5.2.1.3 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), as summarised in Table 5.6. 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 generation. 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):

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \text{ for } P > I_a \tag{5.6}$$

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:

$$S = \frac{25400}{CN} - 254 \tag{5.7}$$

where

S = potential maximum soil water retention [mm] and

CN = Curve Number, as given in Table 5.6 (Schulze *et al.*, 2004) [dimensionless].

Table 5.6 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

5.2.1.4 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 base flow 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, 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):

$$PR = (1 - 1.576URBEXT_{2000})PR^{(rural)} + 1.576URBEXT_{2000}PR^{(urban)} \qquad (5.8)$$

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

$$PR^{(urban)} = 0.3PR^{(imp)} + 0.7PR^{(rural)} \qquad (5.9)$$

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

$$r_t = BRq_t^{(rural)} \qquad (5.10)$$

where

r_t = recharge [m^3/s],

BR = model parameter controlling base flow reservoir recharge [unit less], 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 base flow (Kjeldsen *et al.*, 2013).

5.2.2 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: (a) 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), (b) 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 (c) 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 widely used model by consultants in South Africa. Other models that are widely used internationally include MUSIC in Australia (Dotto *et al.*, 2015), HSPF in the USA (Gebremariam *et al.*, 2014); TOPMODEL in the UK and Europe (Furusho *et al.*, 2013), and HEC-HMS in various countries and climates worldwide (Halwatura and Najim, 2013; Zema *et al.*, 2016). 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 reviewed in more detail in the following sections.

5.2.2.1 Agricultural Catchment Research Unit (ACRU) model

The ACRU model is a physically-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 (Schulze, 1995). 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 (Schulze, 1995).

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 the Thukela 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.

5.2.2.2 Hydrologic Engineering Center Hydrologic Modelling System (HEC-HMS)

HEC-HMS was developed by the US Army Corps of Engineers and is designed to simulate rainfall-runoff processes in a wide range of geographical areas, from large river basins to small urban or natural catchments. It contains components for precipitation, evapotranspiration, vegetation interception, infiltration, storage, runoff, base flow, channel routing, losses, reservoir storage and routing, and diversions (USACE, 2013). It can be used for event-based or continuous modelling of water balance, urban drainage, future flow and impact assessments, reservoir spillway design, flood risk mitigation, and system operation (USACE, 2013).

According to Texas A&M University (2010), the reliability of the model is dependent on the accuracy of the input data, especially boundary conditions like precipitation. The programme is more reliable for medium to large catchments.

5.2.2.3 Hydrological Simulation Program – Fortran (HSPF)

HSPF was developed by the USGS and is used for the simulation of hydrological (and associated water quality) processes in a variety of environments. It was developed in the 1960s as the Stanford Watershed model and was developed over subsequent years to now include many aspects of rainfall-runoff quantity and quality modelling. HSPF can simulate soil moisture, surface runoff, base flow, evapotranspiration, groundwater recharge, channel and reservoir routing, as well as various quality and snow-related parameters. It can be used for event-based or continuous modelling to simulate the impacts of land use changes, reservoir operation, flow diversion and quality aspects (USGS, 2014).

The model utilises process algorithms developed from theory, laboratory experiments and relationships derived from gauged catchments in the USA (USGS, 2014). It has been designed to be applied to almost any catchment in the USA, using existing meteorological input data required for a hydrological quantity-based analysis including: precipitation records, evapotranspiration potential, land area description, channel measurements and reservoir properties, as well as calibration data for stream flow (Texas A&M University, 2007a).

5.2.2.4 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). It’s 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 for low impact development applications, and design and optimisation of control systems (DHI, 2015).

5.2.2.5 Model for Urban Stormwater Improvement Conceptualisaton (MUSIC)

The Model for Urban Stormwater Improvement Conceptualisation (MUSIC) was developed in Australia and is one of the most widely used stormwater models in Australia (Dotto *et al.*, 2015). MUSIC can be used as a continuous model to generate runoff from impervious and pervious areas in a catchment. It also simulates flow in pipes and channels (Dotto *et al.*, 2015). One of the major focus areas in MUSIC is the prediction of pollution loads and the assessment of stormwater treatment devices (Fletcher *et al.*, 2013). The model generally needs a significant amount of calibration (Dotto *et al.*, 2009), but is widely used, especially where low impact development or similar interventions are included to minimise the potential environmental risk of new developments (Elliot and Trowsdale, 2007).

5.2.2.6 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 SCS 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, to evaluate LID infrastructure, to model combined sanitation and storm water conditions, and to model flood control in urban areas and natural systems (Texas A&M University, 2007b). 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 SWMM engine.

SWMM is a lumped model that uses the principle of the conservation of mass to calculate runoff from a sub-catchment. The sub-catchment 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 sub-catchment 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):

$$\frac{\delta d}{\delta t} = i - e - f - \frac{1.49WS^{1/2}}{An}(d - d_s)^{5/3} \tag{5.11}$$

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 = sub-catchment width [m],

S = sub-catchment slope [m/m],

A = sub-catchment 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):

$$q = \frac{1.49WS^{1/2}}{An}(d - d_s)^{5/3} \tag{5.12}$$

where

q = runoff rate [m/s], and

$$Q = \frac{1.49WS^{1/2}}{n}(d - d_s)^{5/3} \tag{5.13}$$

where

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

According to Texas A&M University (2007b), 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.

Two of the largest metropolitan municipalities in South Africa recommend the use of SWMM modelling for stormwater infrastructure design and runoff modelling for all new developments. The City of Cape Town has recommended it since 2002 (City of Cape Town Development Service, 2002) and The City of Johannesburg is currently in the process of developing a stormwater design manual with recommendation to use SWMM modelling for the analysis of stormwater management systems in the municipality (Barnard *et al.*, 2019). The City of eThekwini uses SWMM models in operational planning and disaster management.

5.2.2.7 TOPMODEL

As digital terrain models (DTMs) become more readily available, they also get incorporated into more hydrological models. TOPMODEL (a TOPography based hydrological MODEL), is an easy to use model structures that utilises Digital Terrain Model (DTM) data. It has therefore been used for various different applications. In this model, all points with similar topographic indices are assumed to behave in a similar way. This simplifies calculations in that the only necessary calculations are for areas with different index values (Beven, 1997).

Although it was originally developed for use in large rural basins, Furusho *et al.* (2013) recently used a coupled ISBA-TOPMODEL system to simulate an urban catchment in the city of Nantes, France. The model was modified by introducing impervious areas with lower infiltration rates and maximum storage capacity in order to reproduce the initial losses in an urban area. Groundwater infiltrations into the sewer network were also represented.

5.3 Comparative Summary of Urban Models

This section provides a summary of the models reviewed, indicating their categorisation (Table 5.7) and factors that were considered in model selection for this study (Table 5.8). Only the methods that are applicable to South African circumstances, and with a focus on design flood estimation, were considered in Table 5.8. In Table 5.8 green cells denote desirable characteristics, orange cells denote acceptable, but not desirable characteristics and red cells denote undesirable characteristics. From Table 5.8 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 proprietary software cost implications of MIKE URBAN.

As SWMM is also recommended for use by a number of the large municipalities in South Afirca and is a widely used tool for the analysis of stormwater management systems, the SWMM model was selected for use in this study.

Table 5.7 Characterisation of applicable urban models (after Zoppou, 2001)

Model	**Modelling Philosophy**	**Model Results**			**Modelling Time 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	✓	✓			✓
ACRU	SCS (Green-Ampt)	✓	✓		✓	
HEC-HMS	SCS (Hortonian flow) or Green-Ampt	✓	✓	✓	✓	✓
HSPF	SCS (Hortonian flow)	✓	✓		✓	
MIKE URBAN	SCS (Hortonian flow) or Green-Ampt	✓	✓	✓	✓	✓
MUSIC	SCS	✓	✓		✓	✓
SWMM	SCS (Hortonian flow) or Green-Ampt	Flow balance only	✓	With EXTRAN module	✓	✓
TOPMODEL	Green-Ampt	✓	✓		✓	✓

Table 5.8 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
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
HEC-HMS	Not currently calibrated for SA urban areas	Significant (Texas A&M University, 2010)	Lumped model (USACE, 2000)	Time steps from 1 minute to daily (USACE, 2013)	Hydrologic routing using the Muskingum Method (USACE, 2013)	Pipe flow (non-pressurised) and open channel flow (USACE, 2000)	Reliable stream flow prediction with accurate input data, accuracy is better for medium to large catchments (Texas A&M University, 2010)	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
SWMM	Not currently calibrated for SA urban areas	Significant (Texas A&M University, 2007b)	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

6 CATCHMENT CONFIGURATION AND CALIBRATION: PILOT STUDY

A pilot study was undertaken in order to establish an applicable methodology for the model setup and calibration applied in this project. A small catchment in North Gauteng was selected for this purpose. In the review of literature in Chapter 5, the Storm Water Management Model (SWMM) was selected as the best model to use in this study. In order to set up a representative model for the pilot study catchment, the data and catchment information required for model setup had to be collated. This chapter contains a discussion of the data collation, model setup and model calibration for the pilot study area.

6.1 Catchment Description: A2H063

The catchment used for the pilot study is a 30 km^2 catchment situated north-east of the City of Tshwane's central business district. The area is situated between Meintjieskop in the south and the Magaliesberg in the north and is known as the Moot. The DWS flow gauging station used for this catchment is Station A2H063, on the Wonderboom Spruit. The catchment area and position of the gauging station are shown in Figure 6.1. This figure also shows that no rainfall stations measuring sub-daily data are situated in the catchment, but the Eendracht, Pretoria University and Wonderboom Airport stations are all less than 5 km from the catchment. Thiessen polygons were used to assign sub-catchments to the closest rain gauge. The catchment was chosen due to its small size and relative homogeneity in terms of urban development types in the catchment.

The land use development coverage was obtained from the 2013/2014 South African National Land-Cover Dataset (Geoterraimage, 2015), as shown in Figure 6.2. One of the aims of this research project was to obtain calibrated catchment parameters that could be associated with each of the urban land use types on the DEA land use maps. In some cases the land type classifications may differ from traditional land use classifications for certain parameters in order to associate with the 72 land use types as described by the DEA. This catchment comprises mainly of residential areas of middle class income, with small areas of industrial and business use. The green areas are mainly grassland with some bushes and trees.

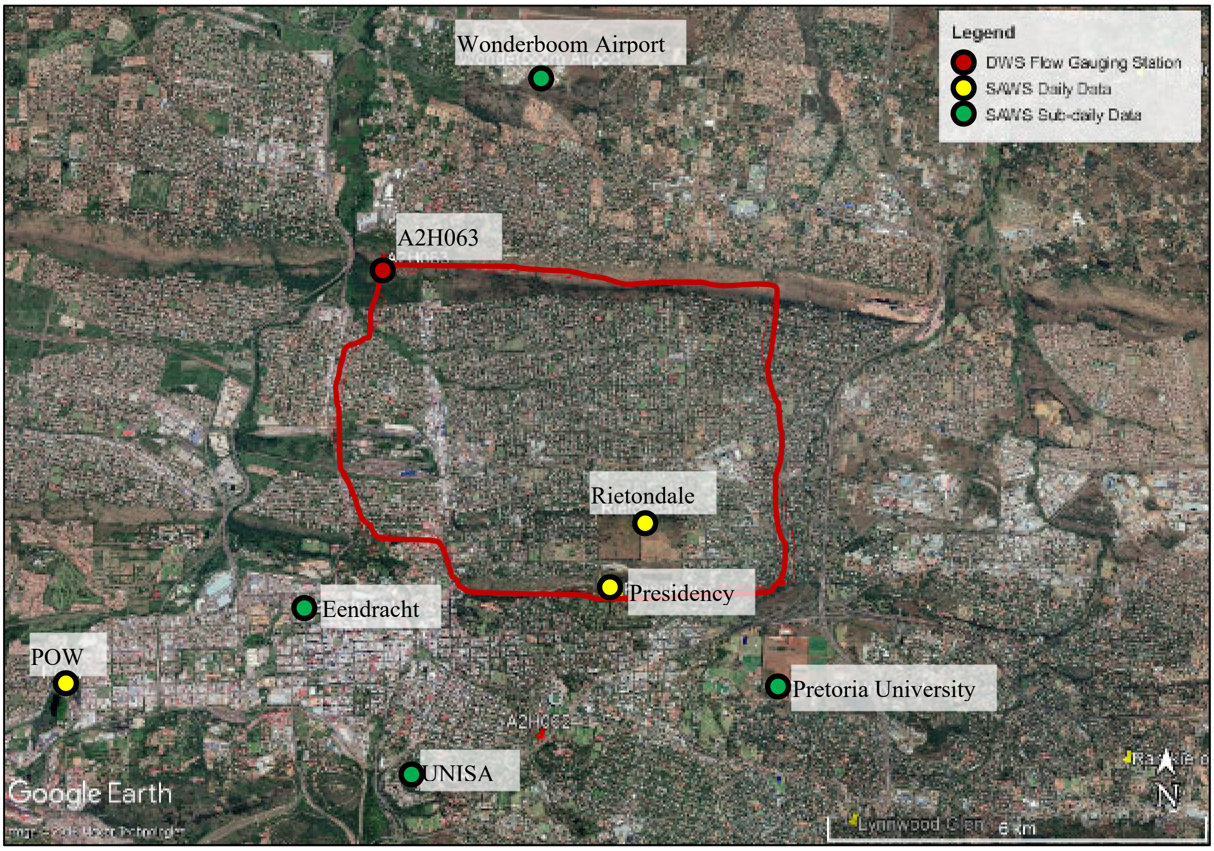

Figure 6.1 Wonderboom Spruit catchment and outlet at Weir A2H063

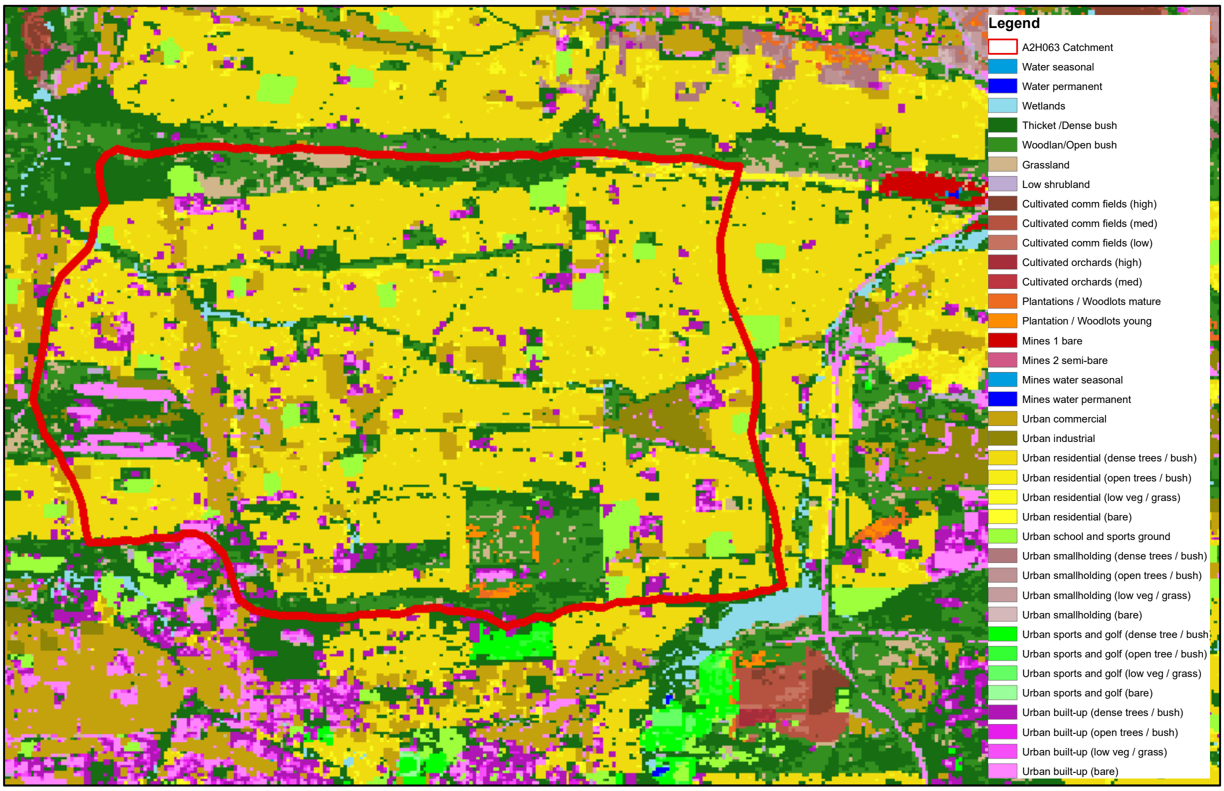

Figure 6.2 Land use of Wonderboom Spruit catchment

The soil classification was done using the SCS map by Schulze and Schütte (2018), using the Agricultural Research Council (ARC) Terrain unit database, that produced SCS values averaged by terrain units (Figure 6.3). The SCS Terrain units were related to the SCS soil groupings as summarised in Table 6.1.

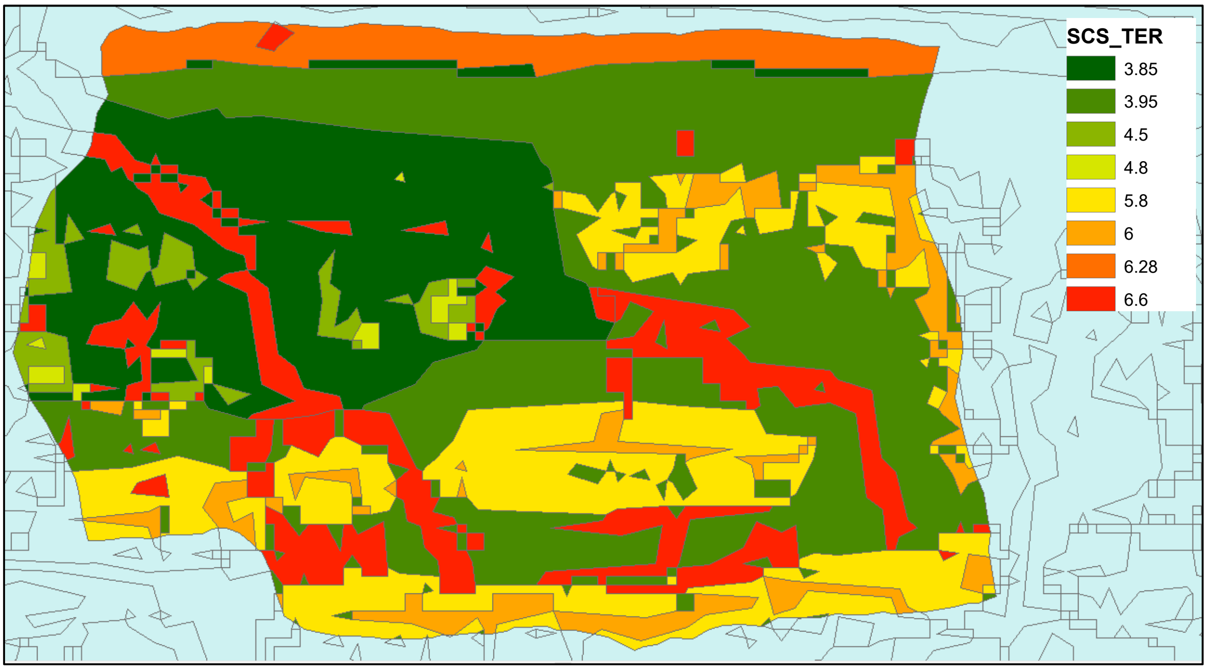

Figure 6.3 Soil classification based on the updated SCS map (Schulze and Schütte, 2018)

Table 6.1 Soil classification association

SCS Terrain unit	SCS soil grouping	United States Department of Agriculture (USDA) soil classification
1	A	Sand
2	A/B	Loamy sand
3	B	Sandy loam
4	B/C	Loam, silt loam
5	C	Sandy clay loam, clay loam
6	C/D	Silty clay loam, sandy clay, silty clay
7	D	Clay

6.2 Observed Rainfall

Multiple rainfall stations were used for the study to simulate the spatial variation of rainfall within a catchment. Historical rainfall was obtained from the South African Weather Services (SAWS). As shown in Figure 6.4, there are only two daily rainfall gauges within the catchment area, namely, SAWS Rietondale and Presidency. Wonderboom, Eendracht, Unisa and University of Pretoria sub-daily rain gauges are not in the catchment, but measure rainfall in 5-minute intervals, and were thus used for the catchment configuration. All rainfall gauges around the catchment and their Thiessen polygons are shown in Figure 6.4.

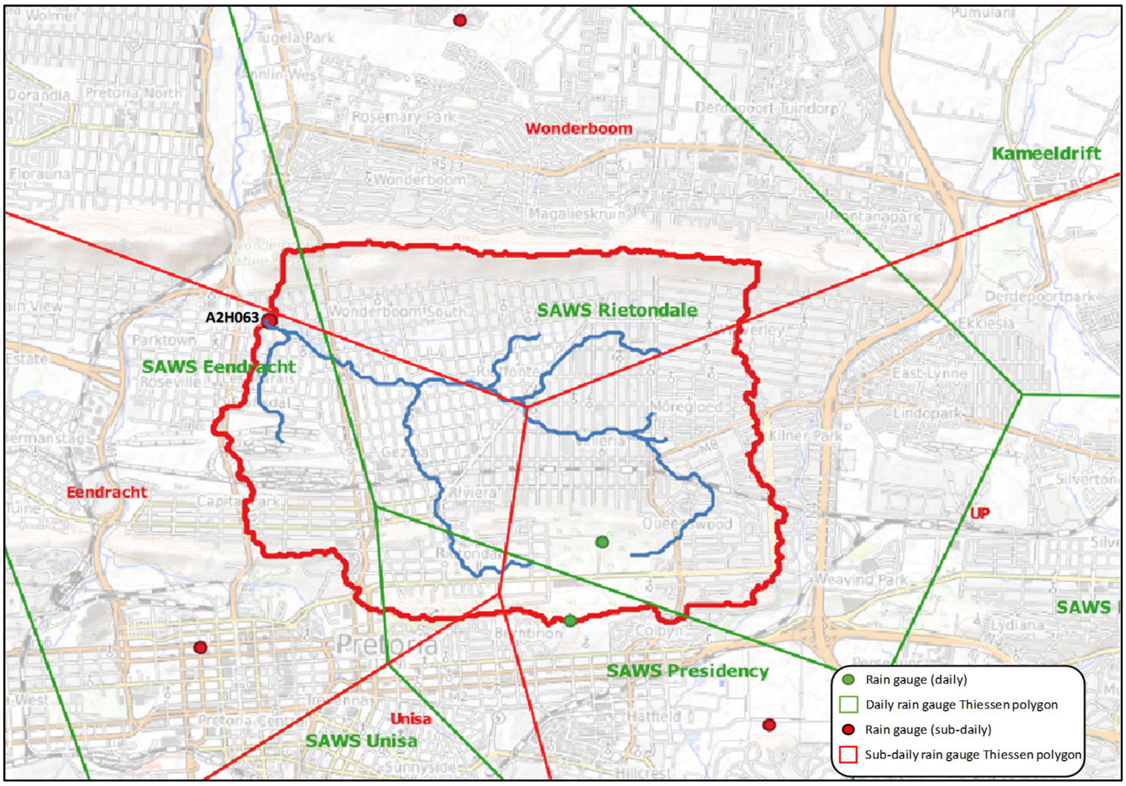

Figure 6.4 Rainfall gauges across the study area

The historic rainfall records for Wonderboom, Eendracht, Unisa and University of Pretoria, received from the SAWS covered periods of between 8 and 25 years, as shown in Table 6.2. Although a small part of the catchment falls within Unisa's Thiessen rainfall polygon, the likely impact of this record was disregarded and this record was only used to patch the other records. All the records were patched and lengthened with the records of the adjacent rainfall stations, including the Unisa gauge to form three complete records of 8 898 days (almost 25 years), each with 5-minute rainfall intervals.

Table 6.2 Rainfall gauges used for A2H063

Rainfall gauge	Date	Length of rainfall record
Wonderboom	19/06/2008 to 9/02/2019	Approximately 11 years
Pretoria Eendracht	19/10/1994 to 18/03/2014	Approximately 20 years
Pretoria University	24/02/2011 to 9/02/2019	Approximately 8 years
Pretoria Unisa*	19/10/1994 to 11/02/2019	Approximately 25 years

* *Rainfall record used for patching of other records.*

6.3 Observed Streamflow

Streamflow records for A2H063 were acquired from the DWS. DWS flow gauging station A2H063 with its catchment area is shown in Figure 6.1. The primary data were mostly of good quality, with one flood event reaching a peak stage above the DWS rating curve and with some minor gaps in the data (Table 6.3). The DWS rating curve was only exceeded once and this rating curve was extended to estimate flows for measured stages greater than 2.73 m (75.67 m^3/s) as shown in Figure 6.5. Although it is recognised that this method would not provide an accurate result, for the flood event of 4 February 2009, it was used to provide a first order estimate of flood peaks with annual exceedance probability of less than 5%, as described in Chapter 6.5.

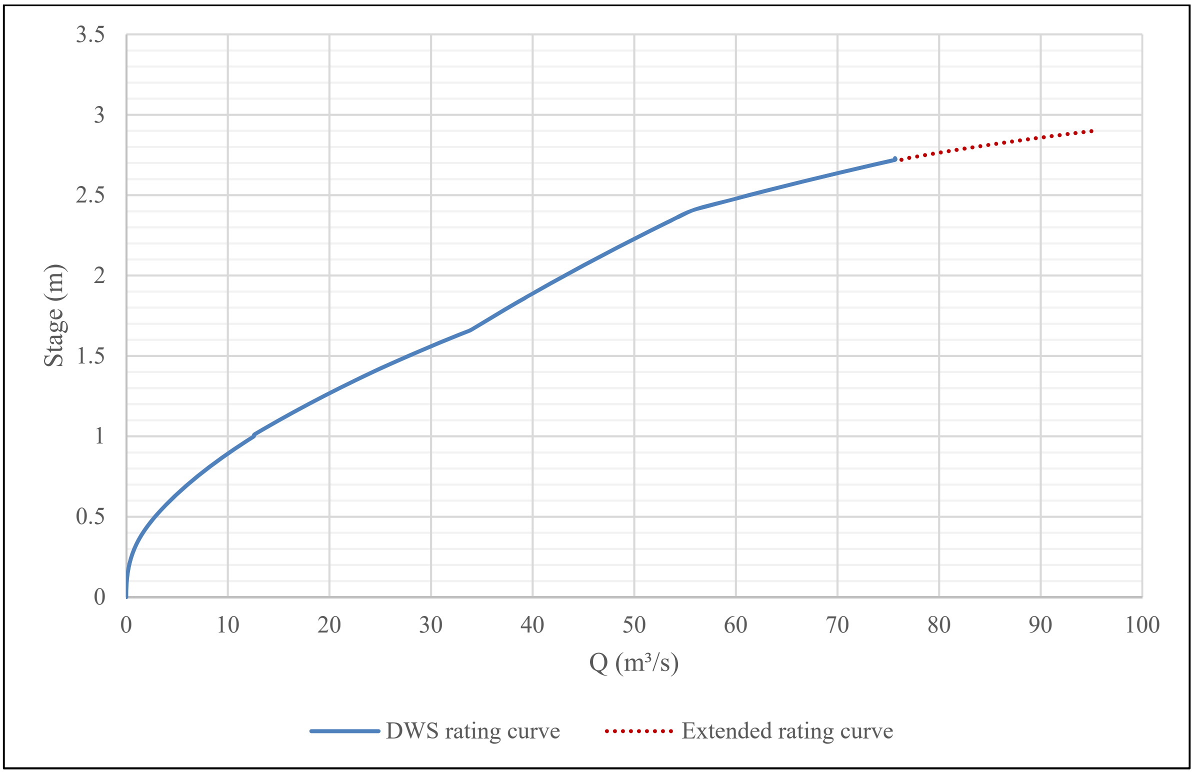

Figure 6.5 Extended flow rating curve for calibration of A2H063

Primary flow data was obtained for measuring Station A2H063 from DWS for the period from 1984 to 2018. There were some gaps in the data, the most notable gap being between July and August of 2001, which is in the dry season. A summary of all the data gaps in the observed streamflow data is provided in Table 6.3.

Table 6.3 Data gaps A2H063

Hydrological year	Date from	Date to	Adjustment made
1985/1986	2 January	8 January	Not included, as rainfall record started in 1994
1994/1995	2 May	4 May	Not included, as rainfall record started in 1994
1999/2000	2 February	4 February	Base flow used, as no major storms were recorded
2000/2001	17 July	23 August	Base flow used, as no major storms were recorded
2001/2002	12 July	14 July	Base flow used, as no major storms were recorded

6.4 Rainfall-runoff Comparison

The patched rainfall records from the three stations were compared with the patched streamflow data, as shown in Figure 6.6. This figure shows that significant rainfall events were not always followed by significant runoff events and that significant runoff events were not always preceded by significant rainfall events, even after gaps in the data were excluded. Frequency distribution, for periods with both rainfall and flow records, was therefore used for calibration of the SWMM catchment configuration. The catchment configuration and calibration will be discussed in the next sections.

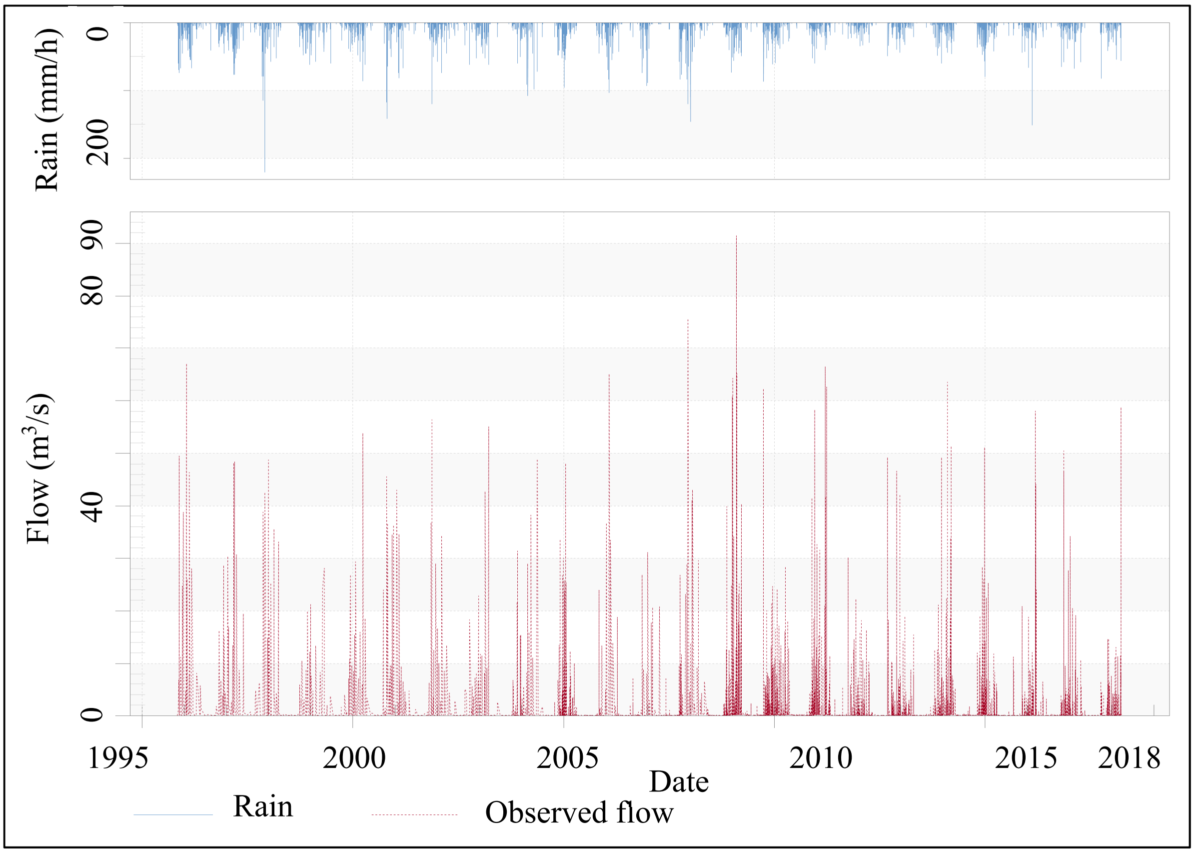

Figure 6.6 Patched rainfall records compared with streamflow for A2H063

6.5 Design Flood Estimation using Statistical Analyses

A first order design flood estimation was performed using statistical analyses as design floods were used to identify significant events during the calibration process. The statistical analyses for the Extreme Value Type 1 (EV1), Log-Extreme Value (LEV), Log-Pearson Type 3 (LP3), and Log-Normal (LN) distributions of this catchment were done using the UPD software (Sinotech cc, 2009). The General Extreme Value (GEV) analysis was done manually, as this distribution was not available on the UPD software. The statistical properties for the natural and transformed data are provided in Table 6.4.

The LP3 (Figure 6.7) distribution and the GEV (Figure 6.9) distribution fit the historical AMS data reasonably well for most return periods larger than the 1:2 year recurrence interval, with the GEV overestimating the flow rates, plotted using the XX plotting position, for the 1:20 recurrence interval and larger. It should be noted that, since the gauging station has only been operational for 33 years, it would be difficult to accurately extrapolate a reasonable 1:100 year recurrence interval flood peak from the data.

Table 6.4 Statistical properties of A2H063 observed annual peaks

Statistical Property	Natural Data	Log Transformed Data
Mean Annual Peak	42.94	1.63
Standard Deviation	20.52	0.34
Skewness Coefficient	-0.03	-2.27

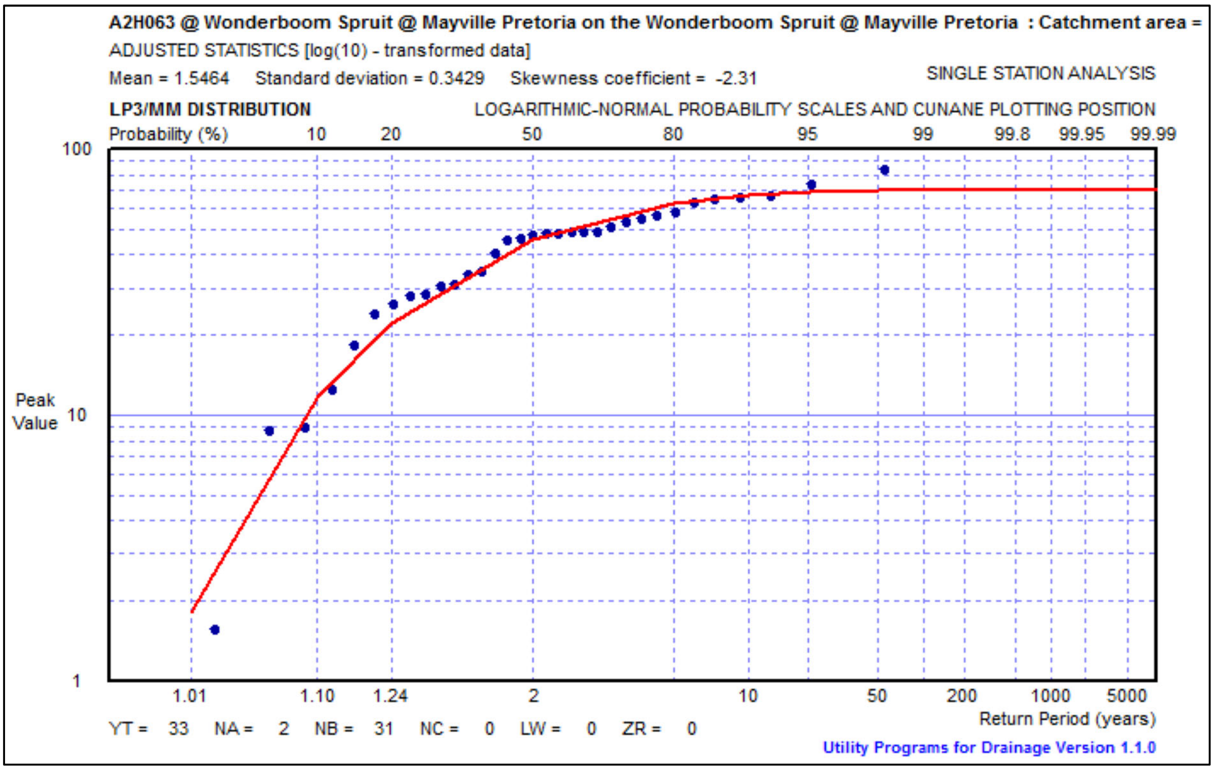

Figure 6.7 Design peak discharges estimated using the LP3 distribution and observed AMS values plotted using the Cunnane plotting position at Station A2H063

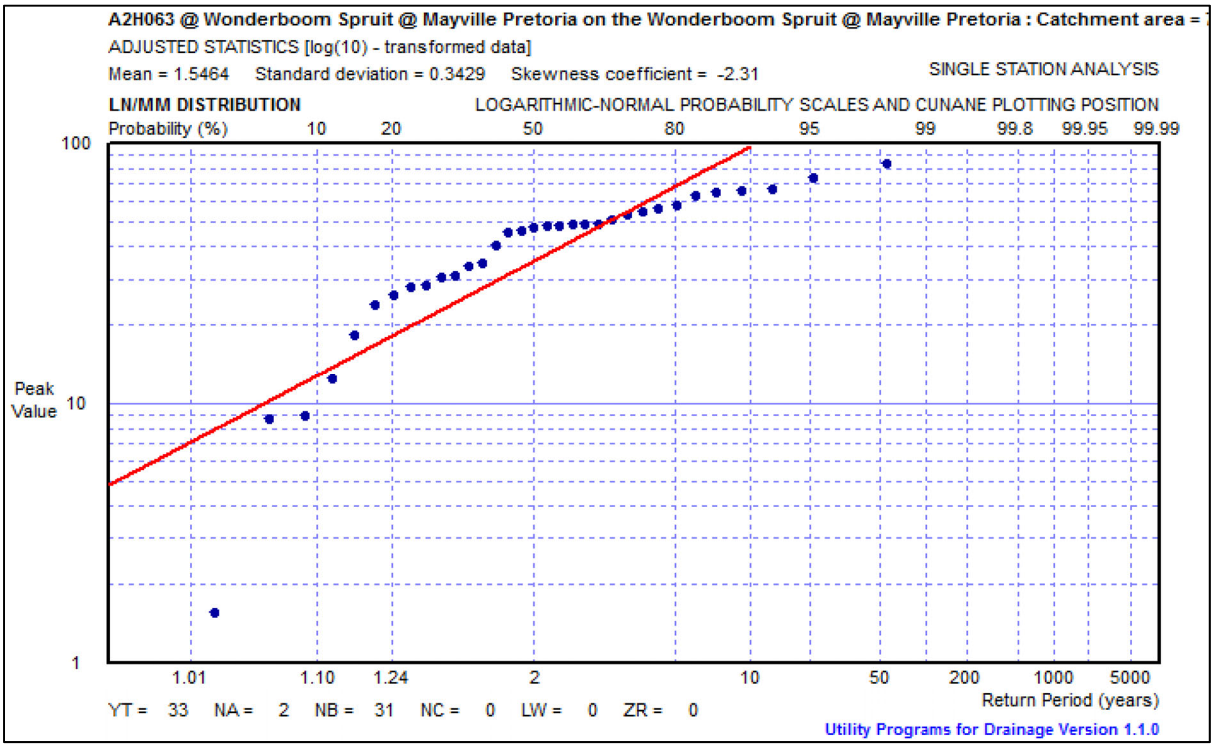

Figure 6.8 Design peak discharges estimated using the LN distribution and observed AMS values plotted using the Cunnane plotting position at Station A2H063

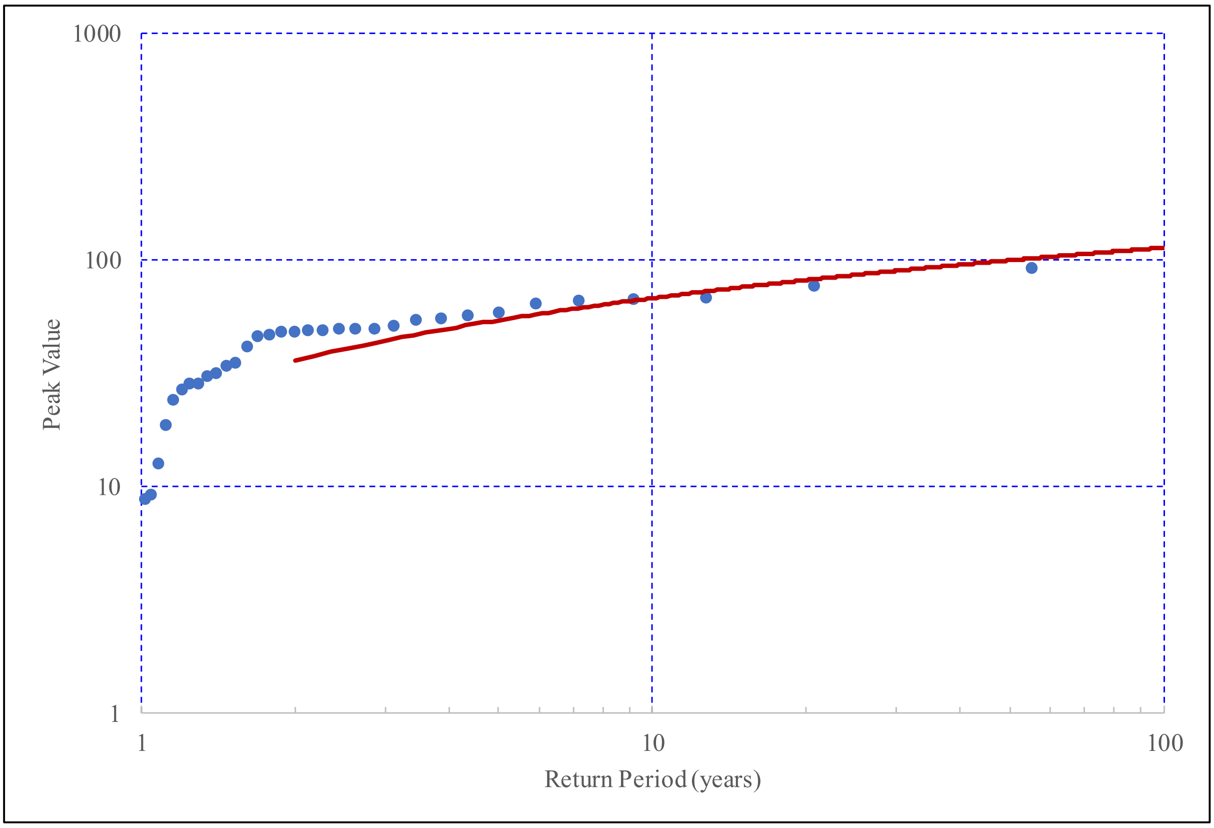

Figure 6.9 Design peak discharges estimated using the GEV distribution and observed AMS values plotted using the Cunnane plotting position at Station A2H063

The results for all applied methods are summarised in Table 6.5. As the GEV distribution showed good correlation with the measured flows lower than the 1:20 recurrence interval flood peak, does not flatten out like the LP3 distribution for larger return periods, and is often used in South Africa, this distribution was used for design flood estimation of this catchment.

Table 6.5 Design peak discharges estimated for Wonderboom Spruit at A2H063 using different probability distributions

Method	**Calculated Peak Flows (m^3/s) for Return Periods**					
	2	**5**	**10**	**20**	**50**	**100**
LN	35	84	97	129	178	222
LEV	31	62	99	154	273	419
LP3	46	61	67	69	70	70
EV1	39	60	69	80	94	105
GEV	38	54	66	79	99	116

6.6 Model Configuration

The SWMM model was configured to simulate runoff from the A2H063 catchment. A continuous simulation model was run with sub-daily rainfall (5-minutes time step) to better simulate antecedent soil moisture conditions and the short durations of flood events in the catchment.

SWMM uses a distributed cell/sub-catchment modelling system. PCSWMM is a commercial product that runs off the SWMM engine. This product was used as it includes superior user interaction capability to the Environmental Protection Agency's open-source version of EPASWMM.

Two hundred sixty-three sub-catchments were selected based on the land use as delineated in the Department of Environmental Affairs (DEA) land use maps (Figure 6.2) (Geoterraimage, 2015), as shown in Figure 6.10. One of the aims of this research project was to obtain calibrated catchment parameters that could be associated with each of the urban land use types included in the DEA land use maps. In some cases the land type classifications may therefore differ from traditional land use classifications for certain parameters in order to associate with the 72 land use types as described by the DEA. It should be noted that areas with similar land use characteristics, as well as small land use areas like trees lining roads, were incorporated into larger sub-catchments.

As the catchment configuration had 263 sub-catchments, it was not practical to model each stormwater pipe as obtained from the Tshwane as-built drawings. Only pipes that drain the sub-catchments were included. Streams and rivers were added based on satellite imagery.

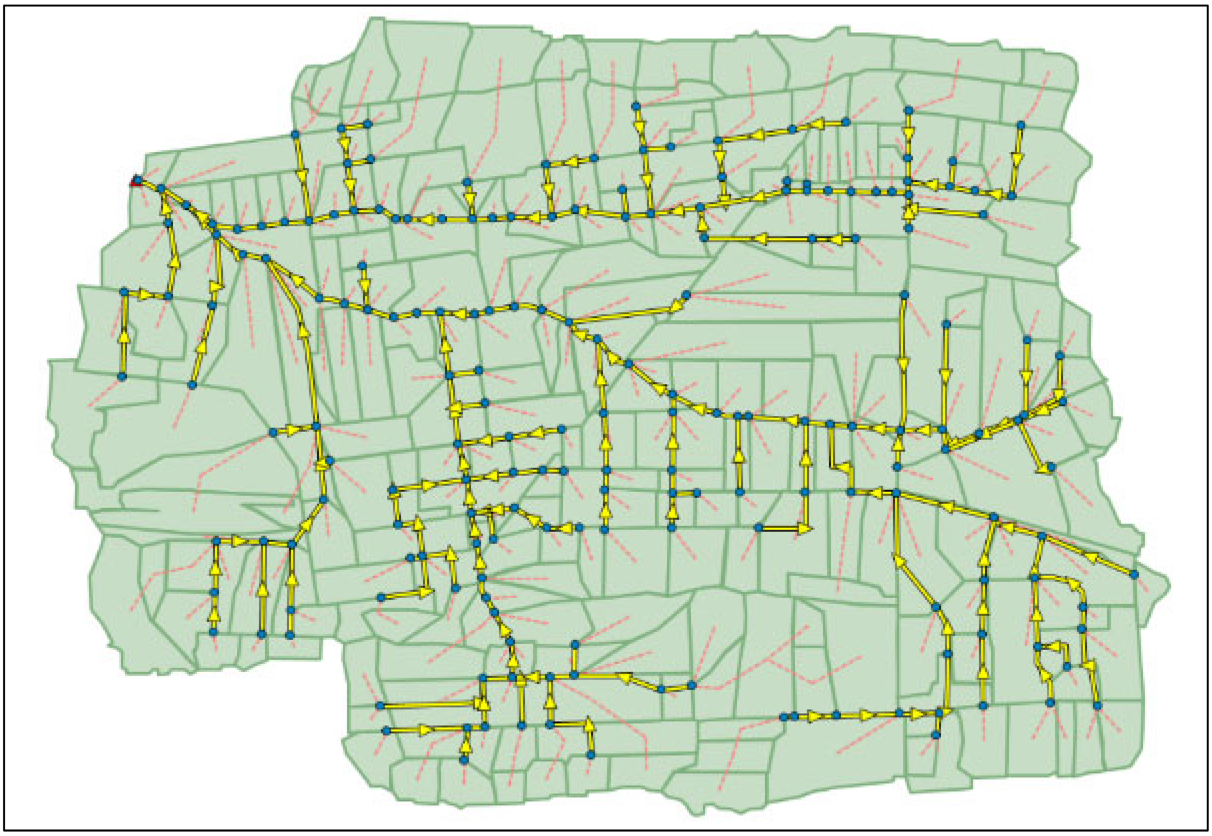

Figure 6.10 SWMM configuration for A2H063

6.7 Uncalibrated SWMM Input Parameters for the Modified Green-Ampt Infiltration Model

For the initial catchment configuration, parameter values were chosen according to the available information and values indicated in literature. The uncalibrated values for all parameters that could not be measured directly are discussed below.

6.7.1 Soil infiltration parameters

The Modified Green-Ampt infiltration method was chosen for the initial setup in order to ensure that the SWMM configuration reflected physical infiltration parameters as closely as possible. Infiltration parameters required for this infiltration method includes the saturated hydraulic conductivity, the suction head on the wetting front and the initial soil moisture deficit (or effective porosity). Various sources (Rawls *et al.*, 1983; Chow *et al.*, 1988; Barnard *et al.*, 2019) recommend similar infiltration values. The infiltration values listed in Rawls *et al.* (1983) were used for the initial catchment configuration, as shown in Table 6.6. These values were associated with SCS Terrain units as described in Table 6.1.

Table 6.6 Infiltration parameter values for the Green-Ampt method (Rawls *et al.*, 1983)

Texture	**Initial deficit (fraction)**	**Wetting front soil suction head ψ (mm)**	**Hydraulic conductivity K (mm/h)**
Sand	0.413	49.02	120.34
Loamy Sand	0.390	60.96	29.97
Sandy Loam	0.368	109.98	10.92
Loam	0.347	88.90	3.30
Silt Loam	0.366	169.93	6.60
Sandy Clay Loam	0.262	219.96	1.52
Clay Loam	0.277	210.06	1.02
Silty Clay Loam	0.261	270.00	1.02
Sandy Clay	0.209	240.03	0.51
Silty Clay	0.228	290.07	0.51
Clay	0.210	320.04	0.25

6.7.2 Imperviousness parameters

Impervious area percentages were assigned to developed sub-catchments based on the impervious percentages for similar land uses in Schulze *et al.* (2004), and adjusted based on impervious area measurements of representative sections for each land use type in the catchment area. All undeveloped areas on hills or steep slopes were assigned 10% imperviousness to account for the rock outcrops prevalent in this catchment. Undeveloped areas on flat slopes were assigned 5% imperviousness to account for shallow rock expected in this catchment.

SWMM has the ability to model directly connected versus unconnected impervious areas by routing a portion of the runoff generated on impervious areas over pervious areas before reaching the sub-catchment outlet. A portion of the pervious area could also be routed over the impervious area in a sub-catchment if necessary. These values were estimated based on development types and typical stormwater configurations on individual stands in the catchment. The impervious area percentages, as well as routing estimates, are shown in Table 6.7.

Table 6.7 Imperviousness used in the SWMM configuration (adapted from (Schulze *et al.*, 2004)

Land Use Type	**Associated SCS Land Use Class**	**Impervious Percentage (%)***	**Subarea Routing°**	**Percent Routed# (%)**
Grassland	Veld/pasture in fair condition	**5-10**	Pervious	100
Low shrubland	Brush – Winter rainfall region	**5-10**	Pervious	100
Plantation/Woodlots young	Forests and plantations – Humus depth 25 mm; compactness: loose/friable	**5-10**	Pervious	100
Plantations/Woodlots mature	Forests and plantations – Humus depth 100 mm; compactness: moderate	**5-10**	Pervious	100
Thicket/Dense bush	Woods, low stormflow potential	**5-10**	Pervious	100
Urban built-up (bare)	Commercial/business areas	85	Impervious	90

Land Use Type	Associated SCS Land Use Class	Impervious Percentage (%)*	Subarea Routing°	Percent Routed# (%)
Urban built-up (dense trees/bush)	Commercial/business areas	85	Impervious	90
Urban built-up (low veg/grass)	Commercial/business areas	85	Impervious	90
Urban built-up (open trees/bush)	Commercial/business areas	85	Impervious	90
Urban commercial	Commercial/business areas	**95**	Impervious	90
Urban industrial	Industrial districts	**95**	Impervious	90
Urban residential (dense trees/bush)	Residential: lot size 1350 m^2 (30% impervious)	30	Pervious	80
Urban residential (open trees/bush)	Residential: lot size 1000 m^2 (38% impervious)	38	Pervious	80
Urban school and sports ground	Open spaces, parks, cemeteries (75% grass cover)	**20**	Pervious	80
Urban sports and golf (bare)	Veld/pasture in poor condition	**5-10**	Pervious	100
Urban sports and golf (dense trees/bush)	Open spaces, parks, cemeteries (95% grass cover)	5	Pervious	100
Urban sports and golf (low veg/grass)	Woods, low stormflow potential	**5-10**	Pervious	100
Urban sports and golf (open trees/bush)	Woods, high stormflow potential	**5-10**	Pervious	100
Wetlands	Irrigated pasture	**0**	Outlet	100
Woodland/Open bush	Woods, high stormflow potential	**5-10**	Pervious	100

*Values in bold were not based on Schulze *et al.* (2004), but were measured on typical examples of the land use types in the study catchment.

°Subarea routing legend:

Impervious	Runoff from pervious area flows to impervious area
Pervious	Runoff from impervious flows to pervious area
Outlet	Runoff from both areas flows directly to outlet

#The percentage of sub-area runoff to be routed over other downstream sub-area before reaching the outlet

6.7.3 Depression storage

Urban catchments typically contain various pits and depressions that retain water. SWMM models these small storage areas as impervious and pervious depression storages. These parameters carry a significant degree of uncertainty when modelling (James, 2003). The uncertainty range for impervious depressions storages is could be between 25 and 50% while the range for pervious depressions storages is 50 to 100% (James (2003) and CHI (2019)).

Depression storage depths proposed by ASCE (1992) (Table 6.8) were adapted and used as shown in Table 6.9 for the initial setup. Urban areas that typically include large parking areas were assigned larger depression storage values, as these relatively flat areas usually have more depressions than natural slopes or steeper areas.

Table 6.8 Depression storage depths (ASCE, 1992)

Surface	Depression storage (mm)
Impervious surfaces	1.25 – 2.5
Lawns	2.5 – 5.0
Pasture	5.0
Forest litter	8.0

Table 6.9 Depression storage depths used in the SWMM configuration (adapted from ASCE, 1992)

Land Use Type	Depression Storage for Impervious Areas (mm)	Depression Storage for Pervious Areas (mm)
Grassland	5.0	5.0
Low shrubland	8.0	8.0
Plantation/Woodlots young	8.0	8.0
Plantations/Woodlots mature	8.0	8.0
Thicket/Dense bush	8.0	8.0
Urban built-up (bare)	2.0	2.5
Urban built-up (dense trees/bush)	2.0	8.0
Urban built-up (low veg/grass)	2.0	2.5

Land Use Type	Depression Storage for Impervious Areas (mm)	Depression Storage for Pervious Areas (mm)
Urban built-up (open trees/bush)	2.0	2.5
Urban commercial	2.0	2.5
Urban industrial	2.0	2.5
Urban residential (bare)	2.0	2.5
Urban residential (dense trees/bush)	2.0	8.0
Urban residential (open trees/bush)	2.0	2.5
Urban school and sports ground	2.0	5.0
Urban sports and golf (bare)	2.5	2.5
Urban sports and golf (dense trees/bush)	8.0	8.0
Urban sports and golf (low veg/grass)	2.5	5.0
Urban sports and golf (open trees/bush)	2.5	2.5
Wetlands	5.0	5.0
Woodland/Open bush	2.5	2.5

6.7.4 Manning roughness values for overland flow

The Manning roughness values proposed in SWMM and other literature for overland flow are significantly larger than the Manning roughness values traditionally used for defined watercourses. For the initial catchment configuration, the overland flow Manning roughness values, as first proposed by the United States Department of Agriculture (USDA, 1986) and later extended by McCuen *et al.* (2002) as shown in Table 6.10, were used for impervious and pervious roughness values, as shown in Table 6.11. The land use types were again categorised according to the DEA classification to achieve consistency.

Table 6.10 Manning roughness values for sheet flow (McCuen *et al.*, 2002)

Surface Description	Manning n-value
Smooth asphalt	0.011
Smooth concrete	0.012
Concrete lining	0.013
Gravelled surface	0.020
Good wood	0.014
Brick with cement mortar	0.014
Vitrified clay	0.015
Cast iron	0.015
Corrugated metal pipe	0.024
Cement rubble surface	0.024
Fallow (no residue)	0.050
Cultivated soils:	
Residue cover ≤20%	0.060
Residue cover >20%	0.170
Range (natural)	0.130
Grass:	
Short grass prairie	0.150
Dense grasses (including weeping lovegrass, bluegrass, buffalo grass, blue grama grass, and native grass mixtures)	0.240 0.410
Bermuda grass	
Woods:	
Light underbrush	0.400
Dense underbrush	0.800

Table 6.11 Manning roughness values used for overland flow in the SWMM configuration (adapted from McCuen, 2002)

Land Use Type	**Associated surface description**	**Manning N-value for Impervious Areas**	**Associated surface description**	**Manning N-value for Pervious Areas**
Grassland	Dense grasses	0.240	Dense grasses	0.240
Low shrubland	Light underbrush	0.400	Light underbrush	0.400
Plantation/Woodlots young	Light underbrush	0.400	Light underbrush	0.400
Plantations/Woodlots mature	Dense underbrush	0.800	Dense underbrush	0.800
Thicket/Dense bush	Dense underbrush	0.800	Dense underbrush	0.800
Urban built-up (bare)	Ordinary concrete lining	0.013	Gravelled surface	0.020
Urban built-up (dense trees/bush)	Ordinary concrete lining	0.013	Dense underbrush	0.800
Urban built-up (low veg/grass)	Ordinary concrete lining	0.013	Short grass prairie	0.150
Urban built-up (open trees/bush)	Ordinary concrete lining	0.013	Light underbrush	0.400
Urban commercial	Ordinary concrete lining	0.013	Short grass prairie	0.150
Urban industrial	Ordinary concrete lining	0.013	Short grass prairie	0.150
Urban residential (bare)	Cement rubble surface	0.024	Gravelled surface	0.020
Urban residential (dense trees/bush)	Cement rubble surface	0.024	Dense underbrush	0.800
Urban residential (open trees/bush)	Cement rubble surface	0.024	Light underbrush	0.400
Urban school and sports ground	Cement rubble surface	0.024	Short grass prairie	0.150

Land Use Type	Associated surface description	Manning N-value for Impervious Areas	Associated surface description	Manning N-value for Pervious Areas
Urban sports and golf (bare)	Cement rubble surface	0.024	Gravelled surface	0.020
Urban sports and golf (dense trees/bush)	Cement rubble surface	0.024	Dense underbrush	0.800
Urban sports and golf (low veg/grass)	Cement rubble surface	0.024	Short grass prairie	0.150
Urban sports and golf (open trees/bush)	Cement rubble surface	0.024	Light underbrush	0.400
Wetlands	Dense grass	0.24	Dense grass	0.24
Woodland/Open bush	Light underbrush	0.400	Light underbrush	0.400

6.7.5 Manning roughness values for conduits

Manning roughness values used for pipes, canals and rivers were based on the materials typically used or found in these conduits and associated Manning roughness values as proposed by the American Society of Civil Engineers (ASCE, 2007). The Manning roughness values used for conduits in this configuration are shown in Table 6.12.

Table 6.12 Manning roughness values for conduits (based on (ASCE, 2007))

Material	Manning n-value for Pervious Areas
Concrete pipe	0.015
Concrete canal	0.018
Grass-lined channel	0.030
Natural river	0.040-0.100

6.7.6 Evaporation rates

SWMM accounts for the evaporation of standing water on sub-catchment surfaces, for water being conveyed through open channels and water held in storage units (Rossman, 2010). Given that these simulations were conducted using a continuous simulation, SWMM simulates the soil saturation levels and drying period using the Green-Ampt infiltration method (Chen *et al.*, 2008). Therefore, daily evaporation rates for the catchments were required (CHI, 2019).

There are several ways to define evaporation rates on SWMM (Rossman, 2010). For this study, monthly average evaporation rates (mm/day) were utilized. The Class A evaporation pan's (A-pan) Mean Annual Equivalent Potential Evaporation as documented by Schulze and Maharaj (2007) of 2 178 mm for the region and was used. The Monthly A-pan Equivalent Potential Evaporation, expressed as a percentage of the annual A-pan Equivalent Potential Evaporation, E_{apan} (Schulze, 1997), was obtained for Region 4. Finally, the average daily evaporation rates for each month was estimated as shown in Table 6.13. It is important to note that the evaporation rates input to SWMM are potential rates and that the actual amount of water evaporated depends on the amount of water available (Rossman, 2010).

Table 6.13 Monthly and daily A-pan evaporation rates for Pretoria (based on Schulze, 1997)

Month	**Average Monthly evaporation (mm/month)**	**Average Daily evaporation (mm/day)**
January	230	7.4
February	188	6.7
March	183	5.9
April	144	4.8
May	130	4.2
June	105	3.5
July	118	3.8
August	161	5.2
September	207	6.9
October	239	7.7
November	231	7.7
December	239	7.7

6.8 Uncalibrated SWMM Results for the Modified Green-Ampt Infiltration Model

The results of the SWMM modelling for the period from 1995 to 2018 are shown in Figure 6.11. From this analysis, it is clear that the SWMM configuration overestimated flood peaks for most events, but that there were also a number of events where the simulated runoff was significantly lower than observed flow. The data was checked for phasing and total volume simulated. No phasing issues were evident, as shown in Figure 6.12 and Figure 6.13, but from these figures it is clear that some disparity exists between rainfall and runoff for certain events, as Figure 6.12 shows under-simulation of flow volume and peak discharge and Figure 6.13 shows over-simulation of flow volume and peak discharge. As none of the rain gauges are situated inside the catchment area, it is possible that the flow gauging station might sometimes register run-off from rainfall events that were not recorded at any of the rainfall stations, and vice versa. However, as the rainfall stations are all in the vicinity of the catchment and experience the same type of weather patterns, frequency distribution could be used to compare the exceedance probabilities of the simulated flow generated versus observed data for the continuous simulation period. The total simulated flow volume (1.564×10^8 m^3) is 17% larger than the observed flow volume (1.337×10^8 m^3). It may therefore be assumed that the catchment configuration tends to over-simulate total flow volume.

As the purpose of the catchment configuration was to calibrate for significant flows, the frequency distributions of the simulated and observed flows were compared to assess if high flow rates were over- or underestimated. This comparison eliminates the possible inconsistences in the data at a time step or event level due to the spatial variation of rainfall.

Figure 6.14 shows the frequency distribution curve for flows of larger than the 1:1 year recurrence interval flood peak of 9 m^3/s, as estimated using the GEV distribution, compared with the frequency distribution curve for flow generated in the uncalibrated SWMM configuration. The flow ranginge from 9 m^3/s and larger was chosen as the purpose of the configuration was to calibrate for significant flows. From Figure 6.14 it is clear that the simulated values had a higher frequency of occurrence than the observed flows for flow rates larger than 9 m^3/s. The configuration was therefore calibrated for flow rates larger than 9 m^3/s. The calibration will be discussed in the next section.

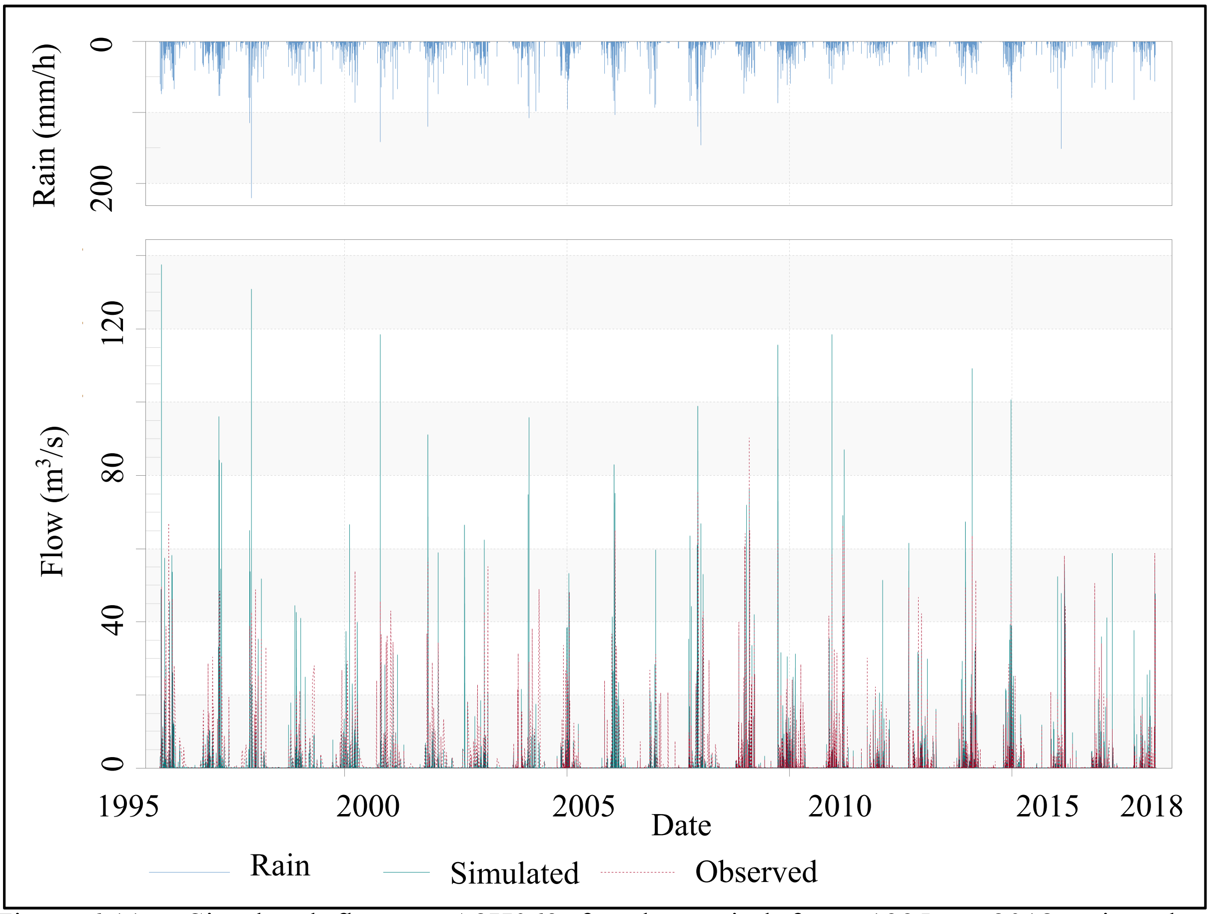

Figure 6.11 Simulated flow at A2H063 for the period from 1995 to 2018 using the uncalibrated SWMM and the modified Green-Ampt infiltration model

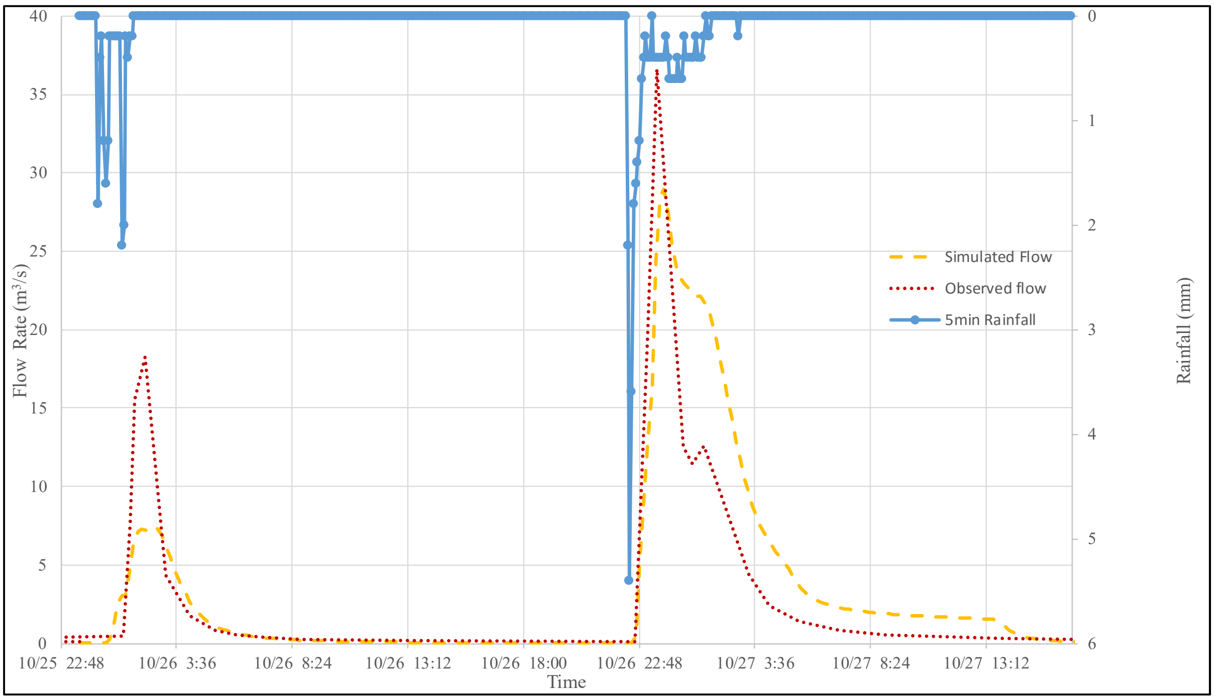

Figure 6.12 Simulated flow at A2H063 for the period from 25 to 27 October 2000 using the uncalibrated SWMM and the modified Green-Ampt infiltration model

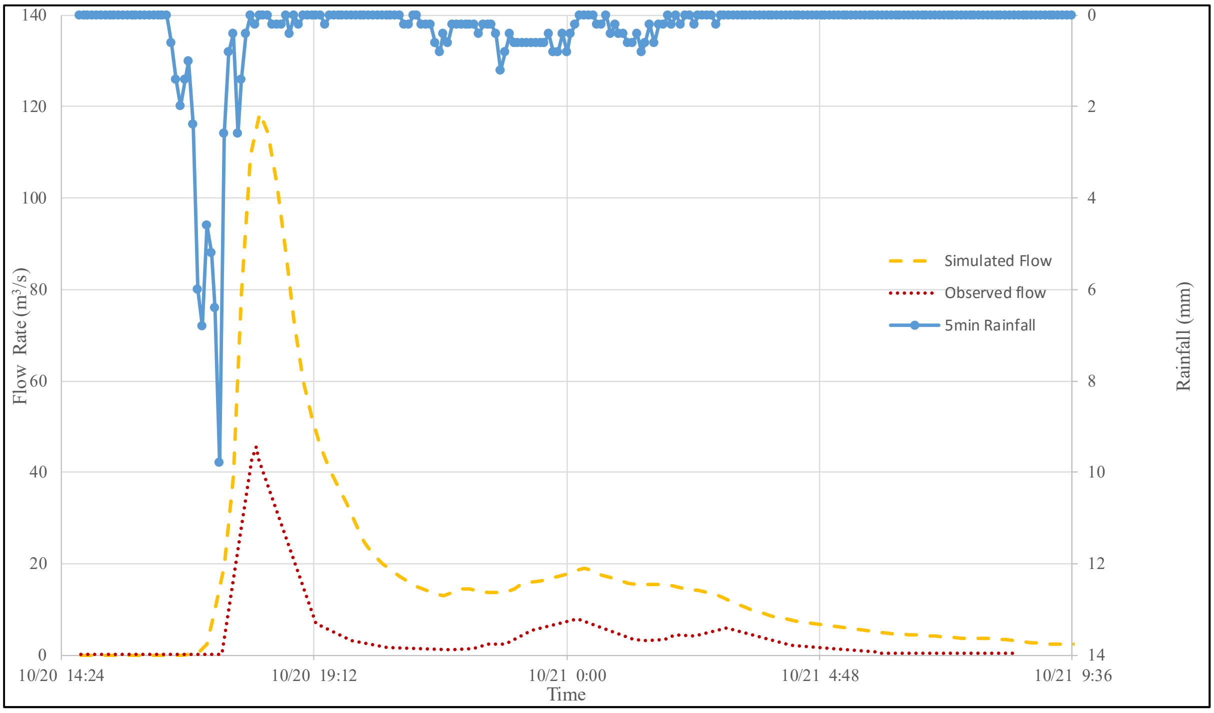

Figure 6.13 Simulated flow at A2H063 for the period from 20 to 21 October 2000 using the uncalibrated SWMM and the modified Green-Ampt infiltration model

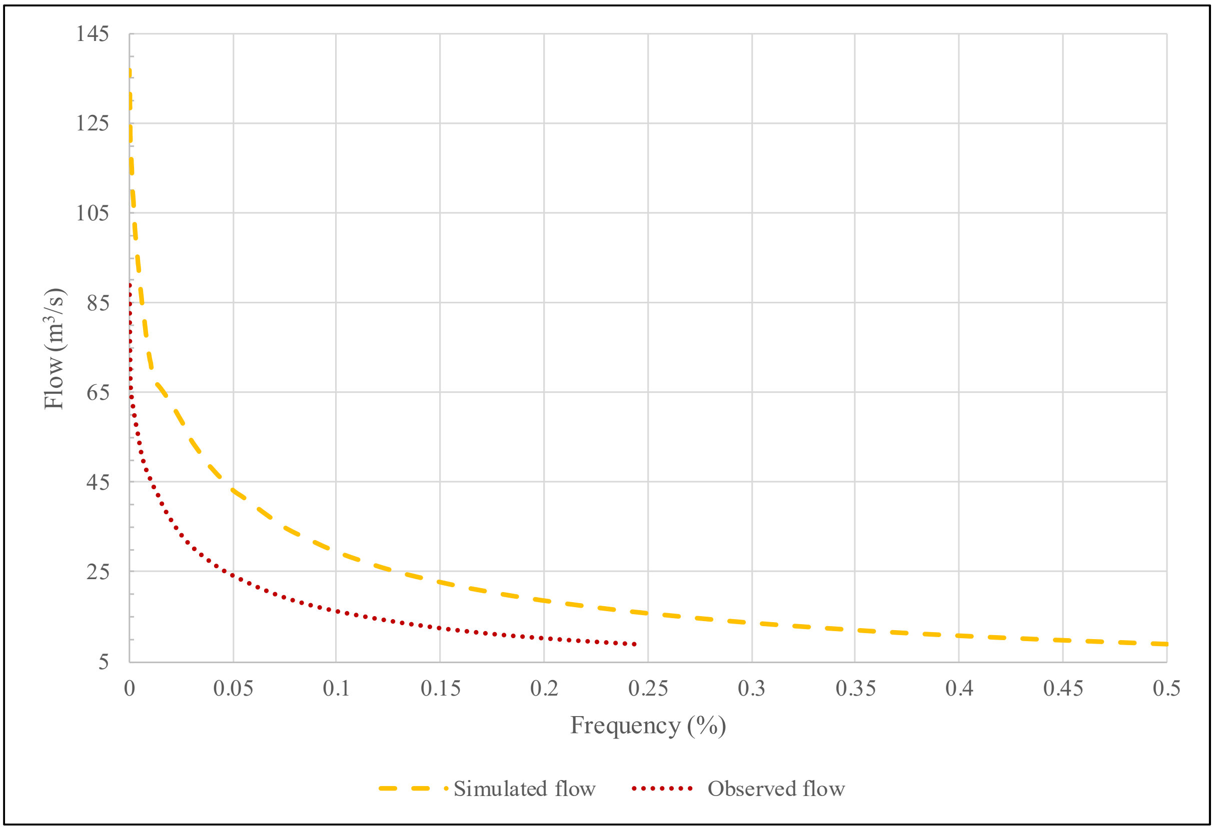

Figure 6.14 Frequency distribution curves for high flows at A2H063 in the uncalibrated SWMM and the modified Green-Ampt infiltration model

6.9 SWMM Calibration Parameters

As the results of the uncalibrated SWWM catchment configuration tended to overestimate the frequency distribution for flow rates above 9 m^3/s, which represents the 1:1 year recurrence interval flood peak, the configuratoin was calibrated to better simulate observed flood peaks and volumes. This section describes the parameter adjustment for calibration of the SWMM configuration at the gauging weir A2H063.

6.9.1 Calibrated soil infiltration parameters for the modified Green-Ampt infiltration model

SWMM is sensitive to changes in the infiltration parameters. There exists significant variation in the hydraulic conductivity, even for soils with similar classifications (Rawls *et al.*, 1983; Chow *et al.*, 1988; Schulze, 1995; Heymann, 2016). Consultation with Dippenaar (2019) and Heymann (2019) revealed that the variability of soil properties even on areas smaller than one hectare in the study area meant that physical infiltration testing over the catchment area would be unfeasible. Dippenaar *et al.* (2014) noted that the upper soil layers in South Africa are usually comprised of highly variable unconsolidated mineral and organic matter. The infiltration rates for soil groupings A, B, C and D proposed by Schulze *et al.* (2004) were measured for soils with a short grass cover. As this would imply conditions similar to most of the permeable areas in the catchment, and as the purpose of the model was simulate infiltration into the upper layers of the soil profile, without accounting for interflow or recharge, the values proposed for soil groupings A to D were used and linearly interpolated between SCS terrain numbers one to seven for the calibration, as shown in Table 6.14 . These values were associated with SCS Terrain units as described in Table 6.1.

Table 6.14 Infiltration values used for the calibrated SWMM configuration (adapted from Schulze *et al.*, 2004)

Texture	SCS Soil Grouping	SCS Terrain Number	Hydraulic Conductivity K (mm/h)*
Sand	A	1	**25**
Loamy Sand	A/B	2	19
Sandy Loam	B	3	**13**
Loam	B/C	4	9.5
Silt Loam	B/C	4.5	7.7
Sandy Clay Loam	C	5	**6**
Clay Loam	C	5.5	5.3
Silty Clay Loam	C/D	6	4.5
Sandy Clay	C/D	6.3	4.1
Silty Clay	D	6.6	3.6
Clay	D	7	**3**

*Values in bold print were obtained from (Schulze *et al.*, 2004) and other values were derived using interpolation

These adjustments resulted in significant improvement to the calibration, but the calibration needed to be improved further. The next step in the calibration was to adjust imperviousness parameters for each land use type in the catchment area.

6.9.2 Imperviousness parameters

The greatest uncertainty in the impervious parameters centred on the percentage of unconnected imperviousness on residential properties and at schools. The percentage of runoff routed from impervious subareas in sub-catchments with these land covers was therefore adjusted to achieve better calibration of the model. The adjusted impervious area percentages, as well as calibrated routing estimates, are shown in Table 6.15.

Table 6.15 Imperviousness and routing used in the calibrated SWMM configuration

Land Use Type	Associated SCS Land Use Class	Impervious Percentage (%)	Subarea Routing°	Percent Routed*# (%)
Grassland	Veld/pasture in fair condition	5-10	Pervious	100
Low shrub land	Brush – Winter rainfall region	5-10	Pervious	100
Plantation/Woodlots young	Forests and plantations – Humus depth 25 mm; compactness: loose/friable	5-10	Pervious	100
Plantations/Woodlots mature	Forests and plantations – Humus depth 100 mm; compactness: moderate	5-10	Pervious	100
Thicket/Dense bush	Woods, low stormflow potential	5-10	Pervious	100
Urban built-up (bare)	Commercial/business areas	85	Impervious	90
Urban built-up (dense trees/bush)	Commercial/business areas	85	Impervious	90
Urban built-up (low veg/grass)	Commercial/business areas	85	Impervious	90
Urban built-up (open trees/bush)	Commercial/business areas	85	Impervious	90
Urban commercial	Commercial/business areas	95	Impervious	90
Urban industrial	Industrial districts	95	Impervious	90
Urban residential (dense trees/bush)	Residential: lot size 1350 m^2 (30% impervious)	30	Pervious	**82** (80)
Urban residential (open trees/bush)	Residential: lot size 1000 m^2 (38% impervious)	38	Pervious	**82** (80)

Land Use Type	Associated SCS Land Use Class	Impervious Percentage (%)	Subarea Routing°	Percent Routed*# (%)
Urban school and sports ground	Open spaces, parks, cemeteries (75% grass cover)	20	Pervious	**82** (80)
Urban sports and golf (bare)	Veld/pasture in poor condition	5-10	Pervious	100
Urban sports and golf (dense trees/bush)	Open spaces, parks, cemeteries (95% grass cover)	5	Pervious	100
Urban sports and golf (low veg/grass)	Woods, low stormflow potential	5-10	Pervious	100
Urban sports and golf (open trees/bush)	Woods, high stormflow potential	5-10	Pervious	100
Wetlands	Irrigated pasture	0	Outl et	100
Woodland/Open bush	Woods, high stormflow potential	5-10	Pervious	100

*Values in bold were adjusted during the model calibration from the initial values shown in brackets ()..

°Subarea routing legend:

Impervious	Runoff from pervious area flows to impervious area
Pervious	Runoff from impervious flows to pervious area
Outlet	Runoff from both areas flows directly to outlet

#The percentage of sub-area runoff to be directed to the other sub-area before reaching the outlet

6.10 Calibrated Results for the Modified Green-Ampt Infiltration Model

Adjustment of the parameters discussed in Sections 6.9.1 and 6.9.2 achieved an adequately calibrated model for the study catchment. Figure 6.15 shows the frequency distribution curve for flows of more than the 1:1 year recurrence interval flood peak compared with the simulated flow in the calibrated SWMM configuration. The flow range from 9 m^3/s and larger was chosen as the purpose of the configuration is to calibrate for significant flows. Figure 6.14 shows that the simulation model slightly overestimated the frequency of flow rates larger than 45 m^3/s, but Figure 6.16 shows that that the calibrated simulation model fits the observed flow curve almost exactly for flow rates between 45 m^3/s and 1 m^3/s. The disparity at low flow rates is due to the fact that the model did not account for interflow or recharge of flow from the soil layers to the stream.

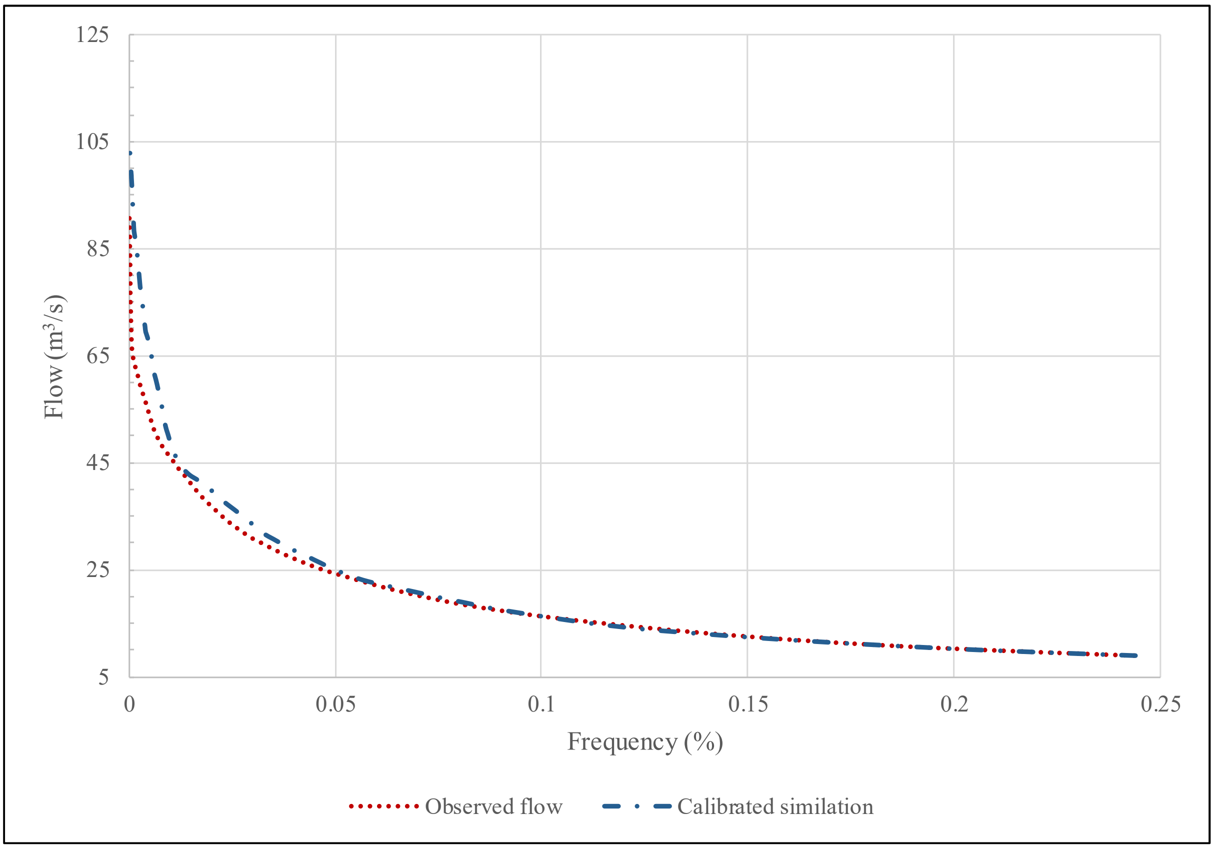

Figure 6.15 Frequency distribution curves for high flows at A2H063 in the calibrated SWMM and the modified Green-Ampt infiltration model

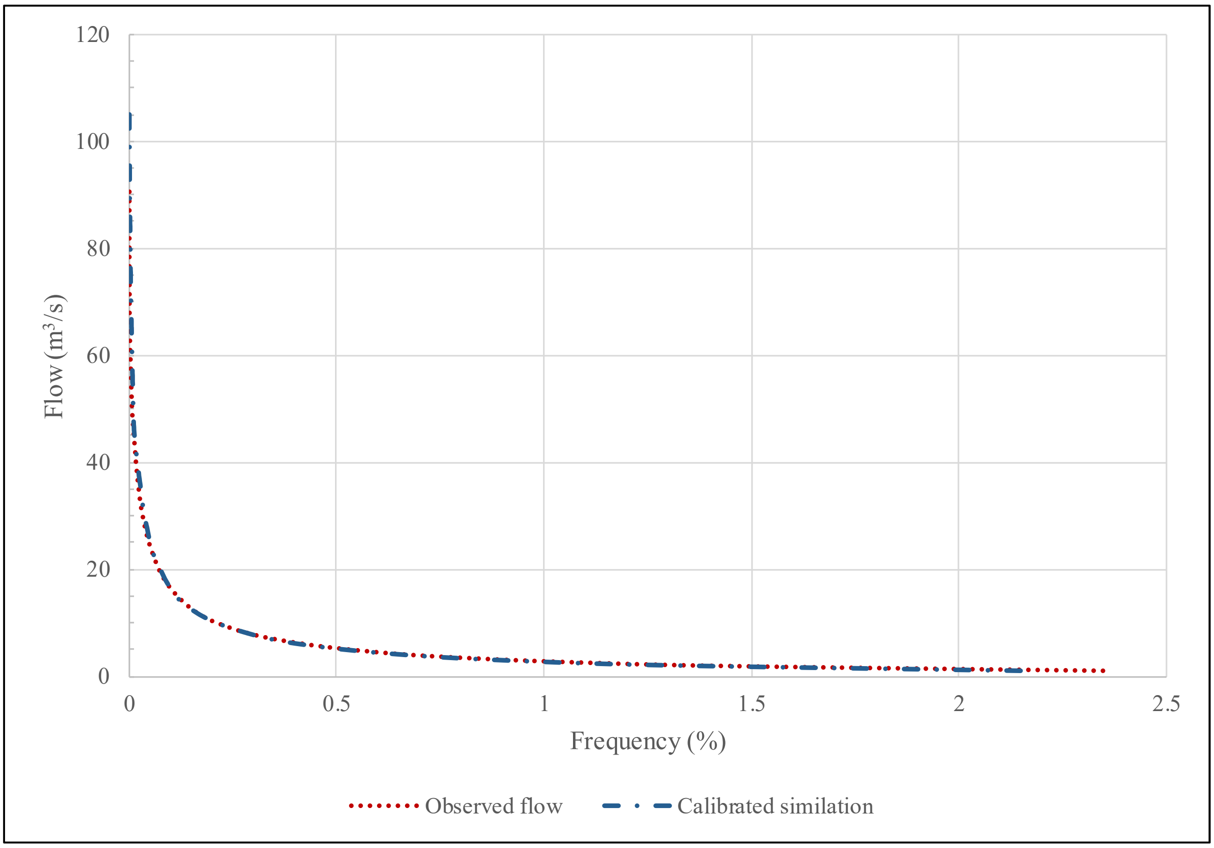

Figure 6.16 Frequency distribution curves for all flows at A2H063 in the uncalibrated SWMM and the modified Green-Ampt infiltration model

The calibrated parameters were independently verified using SWMM configured for an adjacent catchment, as described in the next chapter.

7 MODEL VERIFICATION

After the model was calibrated by adjusting the infiltration and imperviousness parameters as detailed in the previous chapter, the adjusted parameters were verified on an adjacent catchment. This chapter documents the verification of the SWMM parameters.

7.1 Catchment description: A2H054

The Hartebees Spruit drains an urban area in the East of Pretoria, comprising suburban areas, agricultural land, and some industrial and business areas, as shown in Figure 7.1. This figure also shows that the Pretoria University rain gauge is situated in the catchment, with the Eendracht and UNISA stations less than 5 km from the catchment. Thiessen polygons were used to assign sub-catchments to the closest rain gauge with 5 minute interval rainfall data.

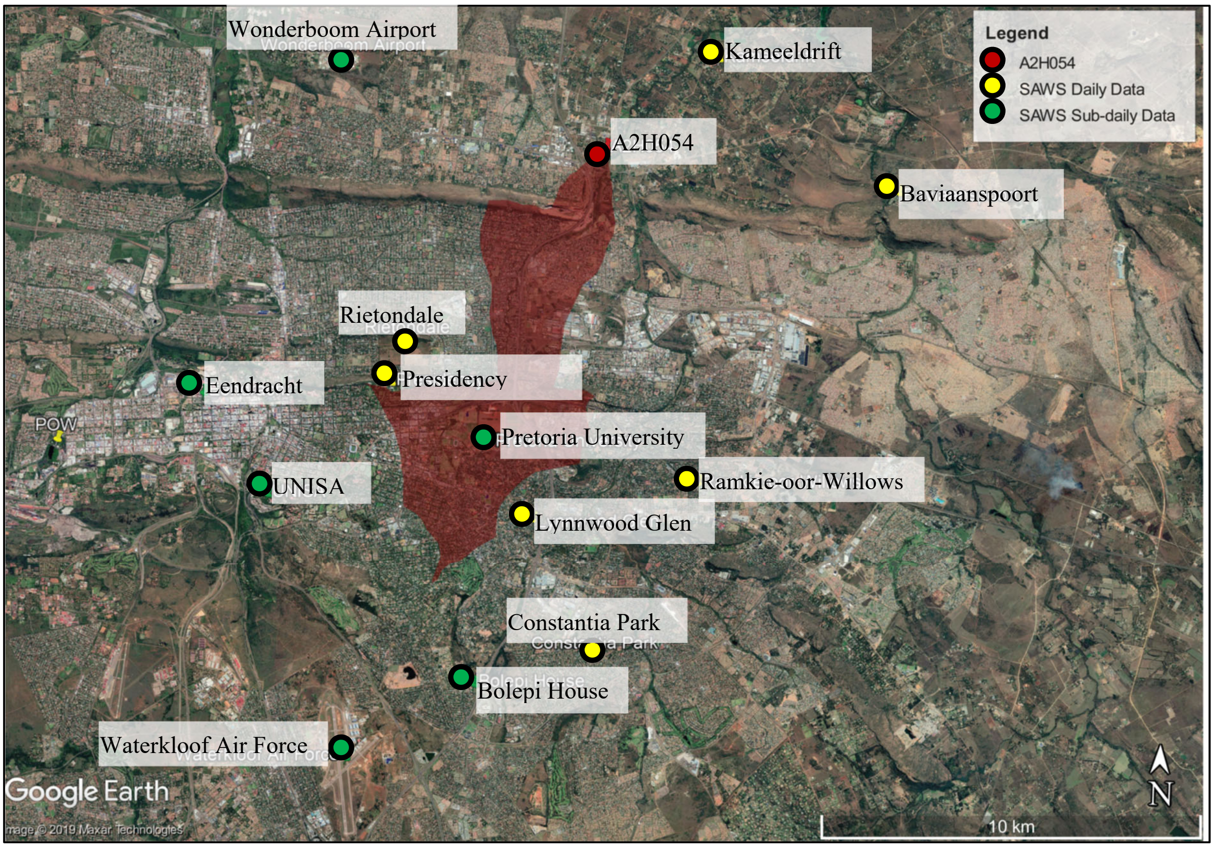

Figure 7.1 Hartbees Spruit catchment at Weir A2H054 and tributaries

The land use development levels were obtained from the 2013/2014 South African National Land-Cover Dataset (Geoterraimage, 2015), as shown in Figure 7.2. The catchment comprises mainly of residential areas, with sports grounds, agricultural areas, woodland areas and small areas of industrial and business use. The green areas are mainly grassland with some bushes and trees. All input values used in this catchment configuration were based on the calibrated catchment parameters used for the SWMM configuration of A2H063, specifically the values from Table 6.9, Table 6.11, Table 6.12, Table 6.13, Table 6.14, and Table 6.15.

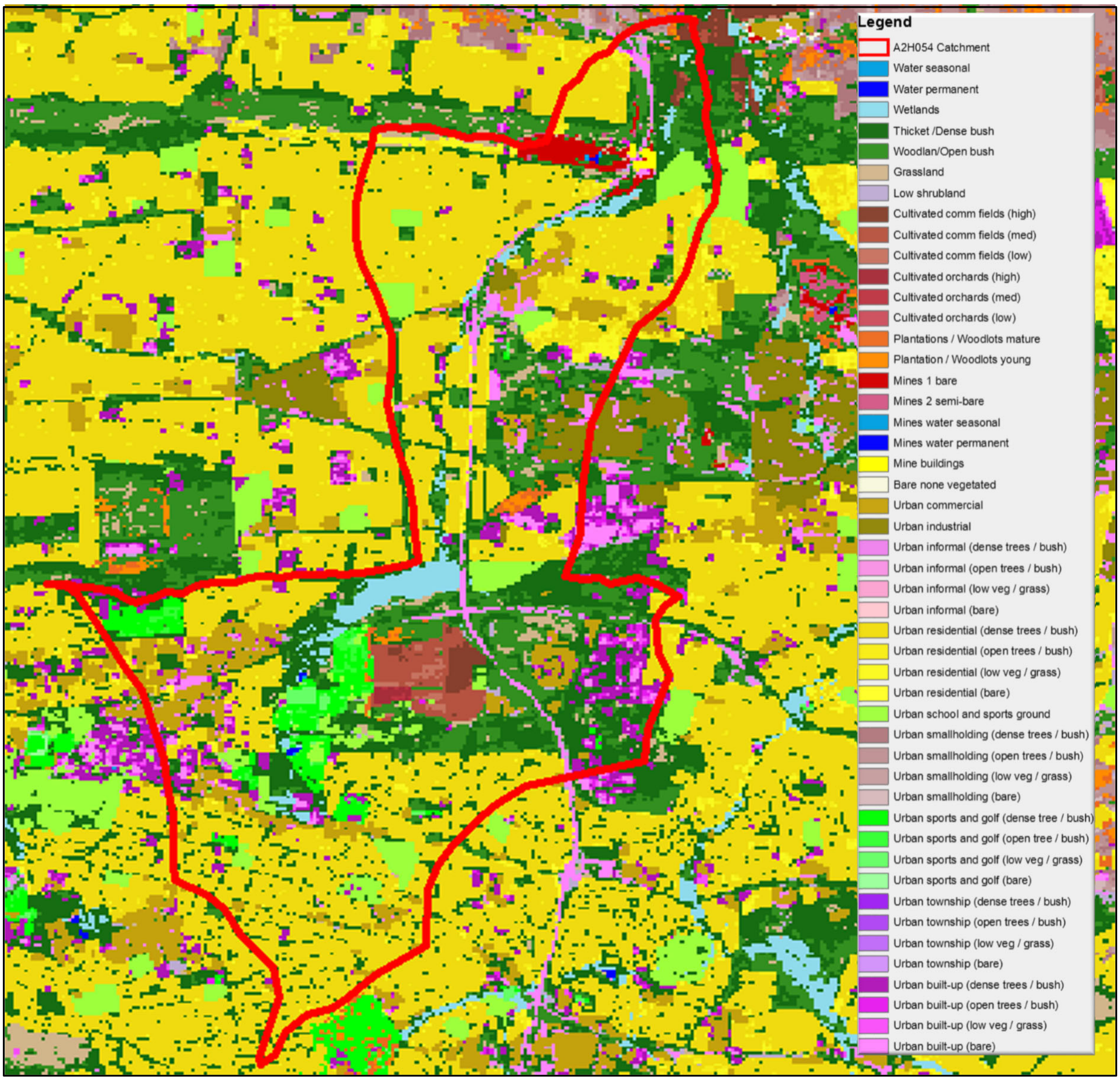

Figure 7.2 Land use of Hartbees Spruit catchment

The soil classification was done using the SCS map produced by Schulze and Schütte (2018), using the Agricultural Research Council (ARC) Terrain unit database, that produced SCS values averaged by terrain units (Figure 7.3). The SCS Terrain units were related to the SCS soil groupings as summarised in Table 6.1.

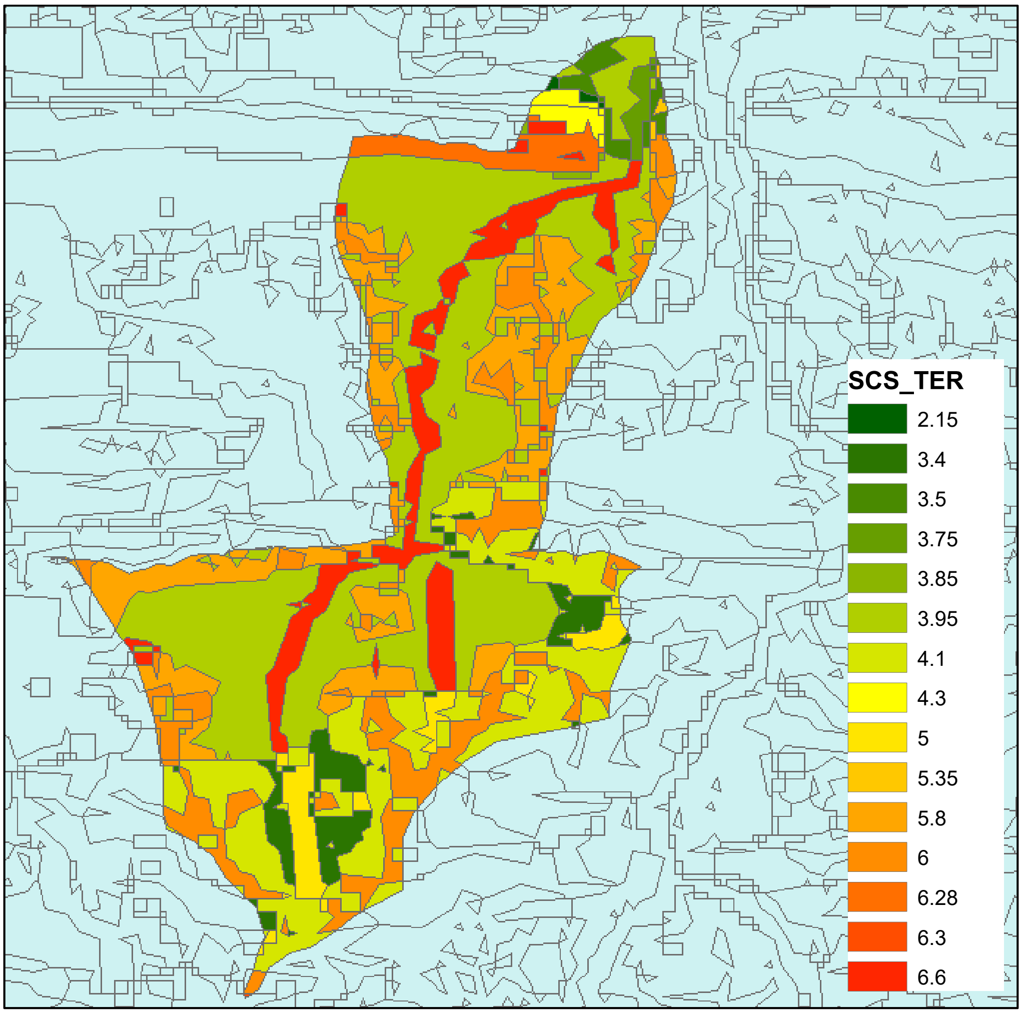

Figure 7.3 Soil classification based on the updated SCS map (Schulze and Schutte, 2018)

7.2 Observed Rainfall and Streamflow

Historical rainfall was obtained from the South African Weather Services (SAWS). The University of Pretoria rain gauge is the only station with sub-daily data in the catchment. The Wonderboom, Eendracht, and Unisa sub-daily rain gauges are not in the catchment, but also measure rainfall in 5-minute intervals, and were also used.

The historic rainfall records for Wonderboom, Eendracht, Unisa and University of Pretoria, received from the SAWS covered periods of between 8 and 25 years, as shown in Table 7.1. As the University of Pretoria station only has data from 2011, the Eendracht station's rainfall records were used to create a longer record. All the records were patched and lengthened with the records of the adjacent rainfall stations, including the Eendracht gauge to form three complete records of 8 898 days (almost 25 years) each with 5-minute rainfall intervals.

Table 7.1 Rainfall gauges used for A2H063

Rainfall Gauge	Date	Length of Rainfall Record
Wonderboom	19/6/2008 to 9/2/2019	Approximately 11 years
Pretoria Eendracht*	19/10/1994 to 18/3/2014	Approximately 20 years
Pretoria University	24/2/2011 to 9/2/2019	Approximately 8 years
Pretoria Unisa	19/10/1994 to 11/2/2019	Approximately 25 years

* *Rainfall record used for patching of other records.*

Streamflow records for A2H054 were acquired from the DWS. DWS flow gauging station A2H054 with its catchment area is shown in Figure 7.1.

The patched rainfall records from the three stations were compared with the patched streamflow data, as shown in Figure 7.4. This figure shows that significant rainfall events were not always followed by significant runoff events and that significant runoff events were not always preceded by significant rainfall events, even after gaps were excluded. Frequency distribution, of periods with both rainfall and flow data, was therefore used for verification of the SWMM model.

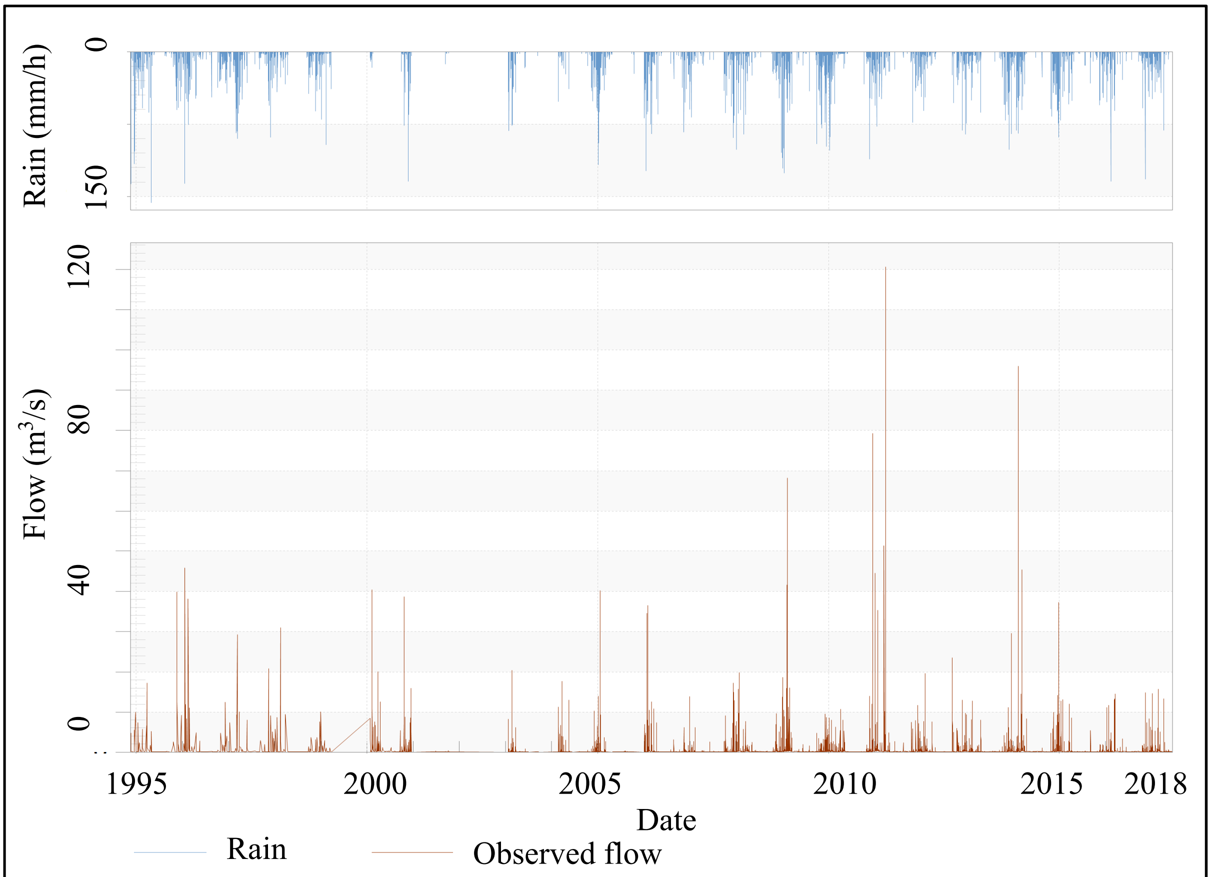

Figure 7.4 A2H054 rainfall-runoff patched data

7.3 Model Configuration

146 sub-catchments were selected following a similar methodology as for the pilot study and based on the land use as delineated by the Department of Environmental Affairs (DEA) land use maps (Figure 7.2) (Geoterraimage, 2015), as shown in Figure 7.5. It should be noted that land use areas with similar characteristics, as well as small land use areas like trees lining roads, were incorporated into larger sub-catchments.

As the catchment configuration had 146 sub-catchments, it was not practical to model each stormwater pipe as obtained from the Tshwane as-built drawings. Only major conduits that drain the sub-catchments were included. Streams and rivers were added based on satellite imagery.

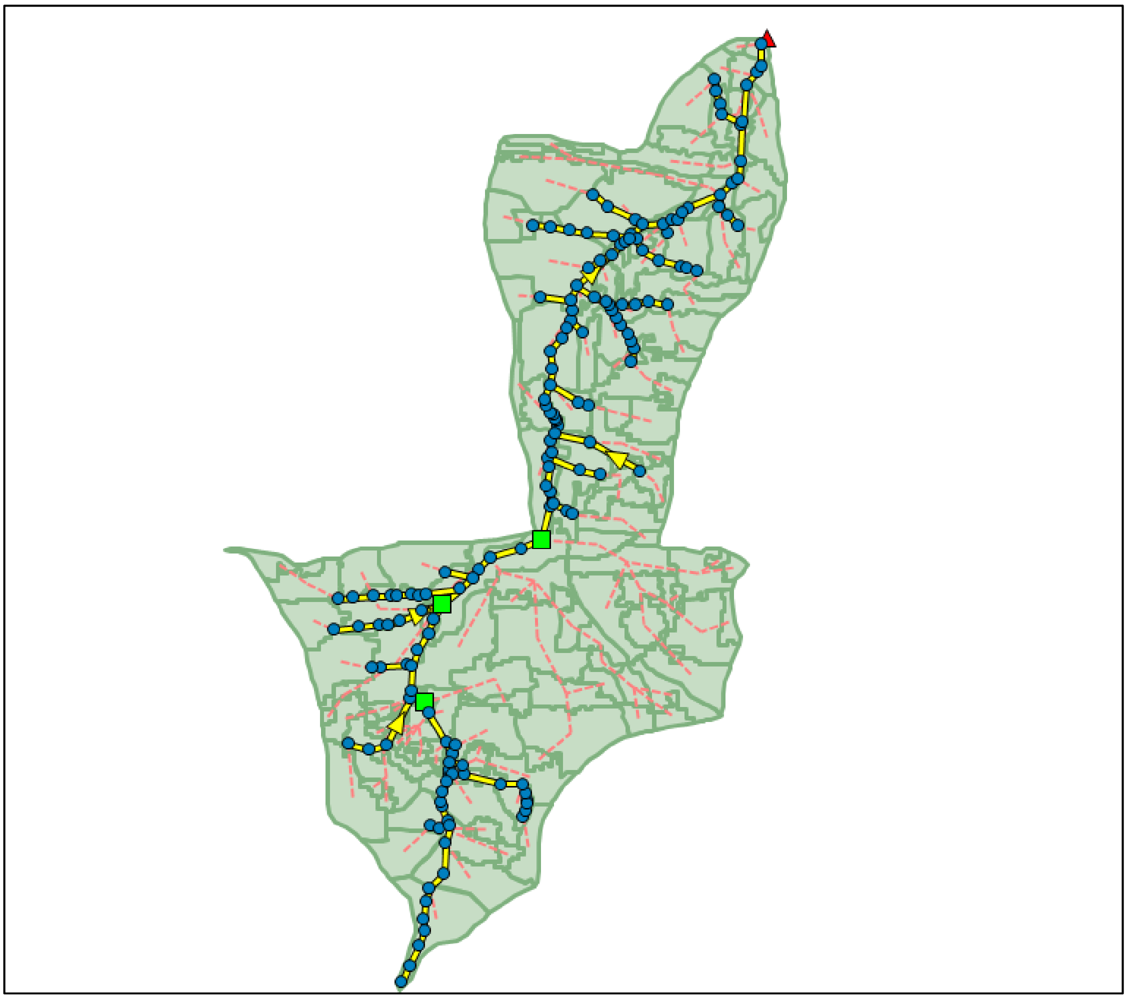

Figure 7.5 SWMM configuration for A2H054

7.4 SWMM Results for the Modified Green-Ampt Infiltration Model

When the calibrated parameters used for A2H063 were applied to A2H054, the total flow volume over the analysis period was underestimated by approximately 3%. The frequency distribution curve in Figure 7.6 shows that the simulated value generally slightly underestimated flow for flow rates above 8 m^3/s for this catchment, but that the correlation between simulated and observed flows is acceptable. The minimum flow of 8 m^3/s was used as it represents the 1:1 year flood peak as estimated using the GEV distribution, which provided the best distribution fit for the recorded data.

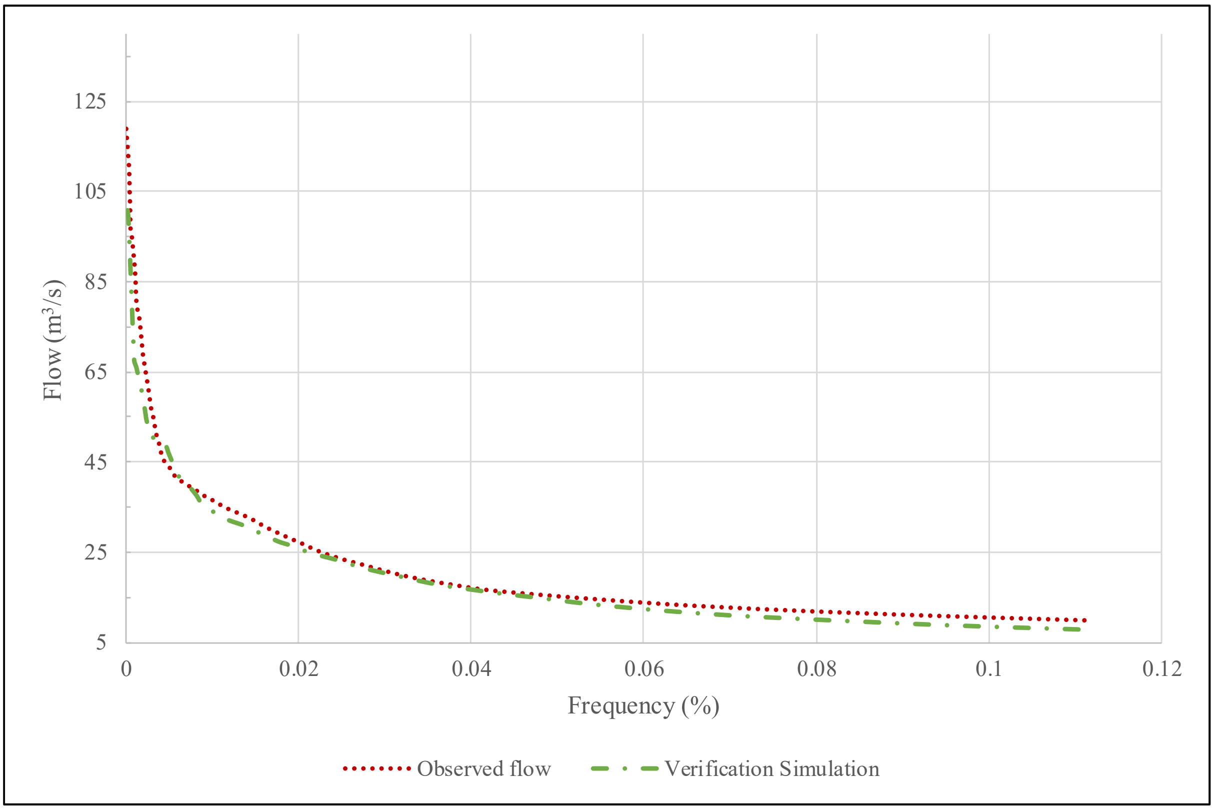

Figure 7.6 Frequency distribution curve for A2H054 using the calibrated modified Green-Ampt parameters of A2H063

The calibration and verification process showed that the parameters currently used for urban areas in South Africa do not provide accurate results in gauged catchments. The need for updated parameters was therefore confirmed.

After the model parameters were calibrated and verified for the Modified Green-Ampt method, the calibrated SWMM configurations were used to calibrate SCS Curve Numbers for use in urban catchments. The process is described in the next chapter.

8 SCS CURVE NUMBER CALIBRATION

One of the aims of this research project was to develop a calibrated design flood estimation method for urban and sub-urban areas, either by updating existing methods, or developing a new method. The SCS-SA method was identified as a method that could be used more widely in urban design flood estimation if the curve numbers were verified. SWMM also has the option to use an SCS infiltration method for urban models. Catchment parameters, that are associated with each of the urban land use types on the DEA land use maps (Geoterraimage, 2015), were therefore calibrated for the SCS-SA method to be used for deterministic design flood estimation. After the SWMM parameters for the catchment configurations using the Modified Green-Ampt method were calibrated and verified, the calibrated configurations were used to derive applicable SCS Curve Numbers for urban land use types in the calibration and verification catchments. This chapter documents the methodology followed and results obtained.

8.1 Using the SCS Method in SWMM

The SCS method is a simple method usually employed for estimating surface runoff from single event design storms for catchments dominated by Hortonian overland flow. It accounts for both land use and soil effects through a Curve Number (CN) variable. 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).

Although SWMM was not primarily designed for flood estimation using the SCS method, Rossman and Huber (2016) postulate that the software could be used to estimate the total runoff volume from a sub-catchment by doing the following:

a) Setting the percentage impervious areas of all sub-catchments to zero, as the CN accounts for the hydrological responses from impervious area.
b) Using CN values as would be used with the SCS method.
c) Selecting the Curve Number infiltration computation method.
d) Setting the pervious area depression storages equal to the initial abstraction depth is used in the SCS method.

e) Setting the pervious area roughness coefficients equal to zero to prevent any delay in runoff.

This method was attempted using the calibrated SWMM configuration for the pilot study area to confirm whether it could be used as an alternative to the Green-Ampt method.

8.2 Soil Infiltration Parameters for the CN Infiltration Model

The land cover classes traditionally used in the SCS method (Schulze *et al.*, 2004) (Table 5.6) differ from the 72 land use types as described by the DEA (Geoterraimage, 2015). In order to achieve conformity, curve numbers were estimated for the applicable DEA land use types found in the study A2H063 and A2H054 areas, based on the land use types and curve numbers used by Schulze *et al.* (2004), as shown in Table 8.1.

Table 8.1 Curve Numbers used in the SWMM configuration (adapted from Schulze *et al.*, 2004)

Land Use Type	Associated SCS Land Use Class	Curve Number						
		1	2	3	4	5	6	7
		A	A/B	B	B/C	C	C/D	D
Grassland	Veld/pasture in fair condition	49	61	69	75	79	82	84
Low shrubland	Brush – Winter rainfall region	28	36	44	53	60	64	66
Plantation/Woodlots young	Forests and plantations – Humus depth 25 mm; compactness: loose/friable	37	49	60	66	71	74	77
Plantations/Woodlots mature	Forests and plantations – Humus depth 100 mm; compactness: moderate	34	47	59	64	69	72	75
Thicket/Dense bush	Woods, low stormflow potential	25	47	55	64	70	74	77
Urban built-up (bare)	Commercial/business areas	89	91	92	93	94	95	95
Urban built-up (dense trees/bush)	Commercial/business areas	89	91	92	93	94	95	95
Urban built-up (low veg/grass)	Commercial/business areas	89	91	92	93	94	95	95

Land Use Type	Associated SCS Land Use Class	Curve Number						
		1	2	3	4	5	6	7
		A	A/B	B	B/C	C	C/D	D
Urban built-up (open trees/bush)	Commercial/business areas	89	91	92	93	94	95	95
Urban commercial	Commercial/business areas	89	91	92	93	94	95	95
Urban industrial	Commercial/business areas	89	91	92	93	94	95	95
Urban residential (bare)	Residential: lot size 500 m^2 (65% impervious)	77	81	85	88	90	91	92
Urban residential (dense trees/bush)	Residential: lot size 1350 m^2 (30% impervious)	57	65	72	77	81	84	86
Urban residential (open trees/bush)	Residential: lot size 1000 m^2 (38% impervious)	61	69	75	80	83	85	87
Urban school and sports ground	Open spaces, parks, cemeteries (75% grass cover)	49	61	69	75	79	82	84
Urban sports and golf (bare)	Veld/pasture in poor condition	68	74	79	83	86	88	89
Urban sports and golf (dense trees/bush)	Open spaces, parks, cemeteries (95% grass cover)	39	51	61	68	74	78	80
Urban sports and golf (low veg/grass)	Woods, low stormflow potential	25	47	55	64	70	74	77
Urban sports and golf (open trees/bush)	Woods, high stormflow potential	45	56	66	75	77	80	83
Woodland/Open bush	Woods, high stormflow potential	45	56	66	75	77	80	83

As proposed by Rossman and Huber (2016), the initial abstraction values were used as the depression storage for pervious areas. The initial abstractions were calculated according to method described for the SCS-SA, assuming that the initial abstraction would be equal to 10% of the potential maximum soil water retention (S), with S related to the CN (Schmidt and Schulze, 1984):

$$S = \frac{25400}{CN} - 254 \tag{8.1}$$

where

S = potential maximum soil water retention, and

CN = Curve Number.

SWMM uses the number of days it takes a fully saturated soil to dry in order to adjust the initial curve numbers during a continuous simulation. Drying times used in the SWMM configuration were based on the hydraulic conductivity and the equation proposed for calculating drying times in the Green-Ampt method (Rossman and Huber, 2016) and adapted for SI units:

$$T_{dry} = \frac{15.78}{\sqrt{(K)}} \tag{8.2}$$

where

T_{dry} = drying time [days], and

K = hydraulic conductivity [mm/h].

Table 8.2 Drying times used in the SWMM configuration (using infiltration values from Schulze *et* al., 2004)

SCS Soil Grouping	Hydraulic Conductivity K (mm/h)	Drying Time (days)
A	25.0	3.1
A/B	19.0	3.6
B	13.0	4.4
B/C	9.5	5.1
C	6.0	6.4
C/D	4.5	7.4
D	3.0	9.1

8.3 Uncalibrated SWMM Results for the CN Infiltration Model

The results of the uncalibrated SWMM configuration using CN infiltration parameters for Catchment A2H063 for the period from 1995 to 2018 are shown in Figure 8.1. From this analysis, it is clear that the SWMM configuration overestimated flood peaks for most significant events, but that there were a large proportion of events where no simulated runoff was generated. The catchment configuration was checked for phasing and total volume simulated. No phasing issues were evident, but the configuration only generated runoff for certain rainfall events. Figure 8.2 shows the simulated flow hydrographs for the CN analysis. The event is the same as shown for the Green-Ampt analysis in Figure 6.12, but the generated runoff is significantly lower than in the Green-Ampt analysis. Figure 8.3 shows an event where the uncalibrated CN configuration generated similar runoff to the uncalibrated Green-Ampt analysis (Figure 6.13). The second event was a larger rainfall event and occurred a few days after the first, which could contribute to the better correlation for the second event. The total simulated flow volume (9.71 x 10^7 m^3) is approximately 28% lower than the observed flow volume (1.337 x 10^8 m^3). The catchment configuration therefore over-estimated volumes for significant events, but severely underestimated runoff for events with peak flow rates lower than the 1:1 year recurrence interval peaks.

As the purpose of the catchment configuration was to calibrate for significant flows, the frequency distributions of the simulated and observed flows were compared next to see if high flow rates were being over- or underestimated. This comparison would eliminate the possible discrepancies encountered at specific events due to the spatial variation of rainfall, as well as runoff not generated in SWMM for smaller rainfall events.

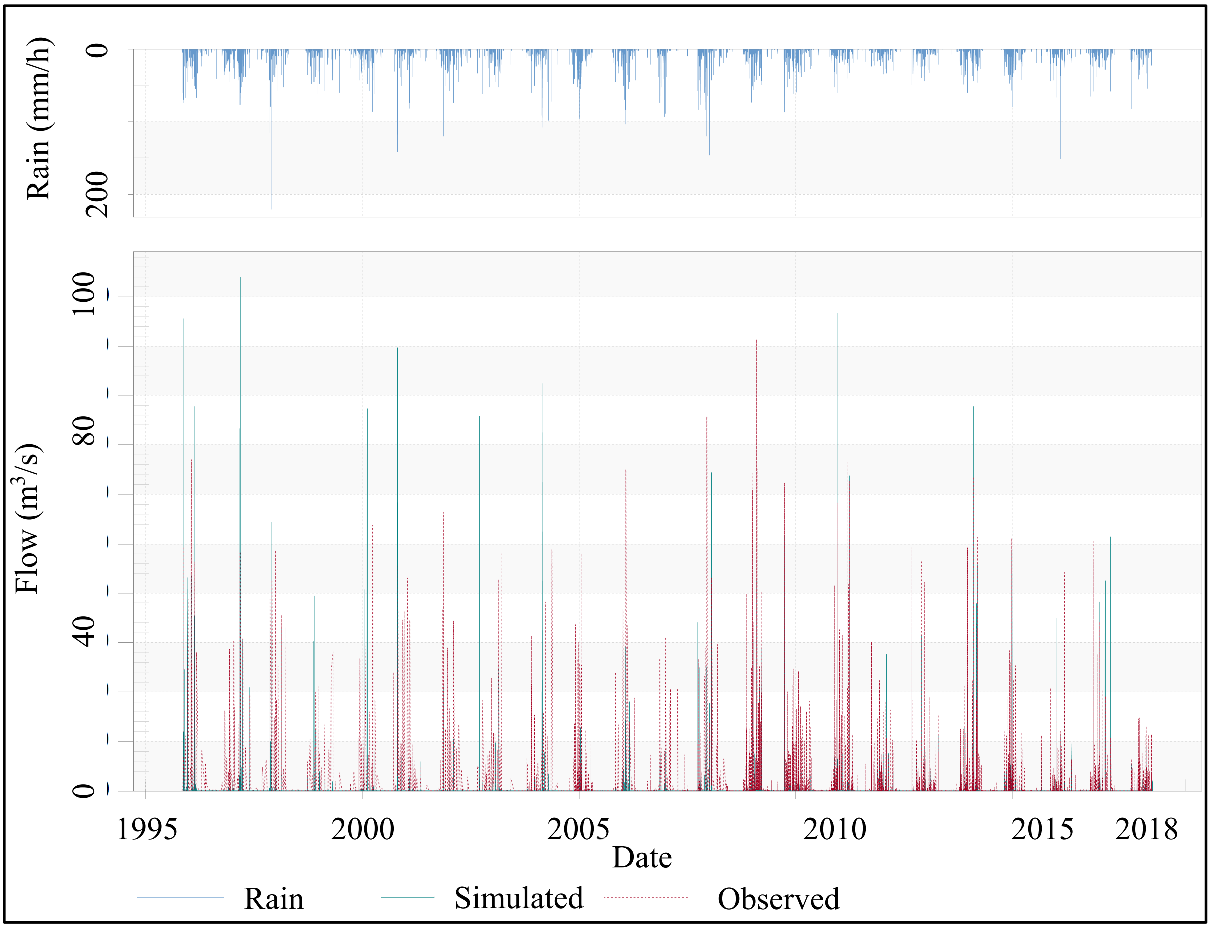

Figure 8.1 Simulated flow at A2H054 for the period from 1995 to 2018 using the uncalibrated SWMM and the modified Green-Ampt infiltration model

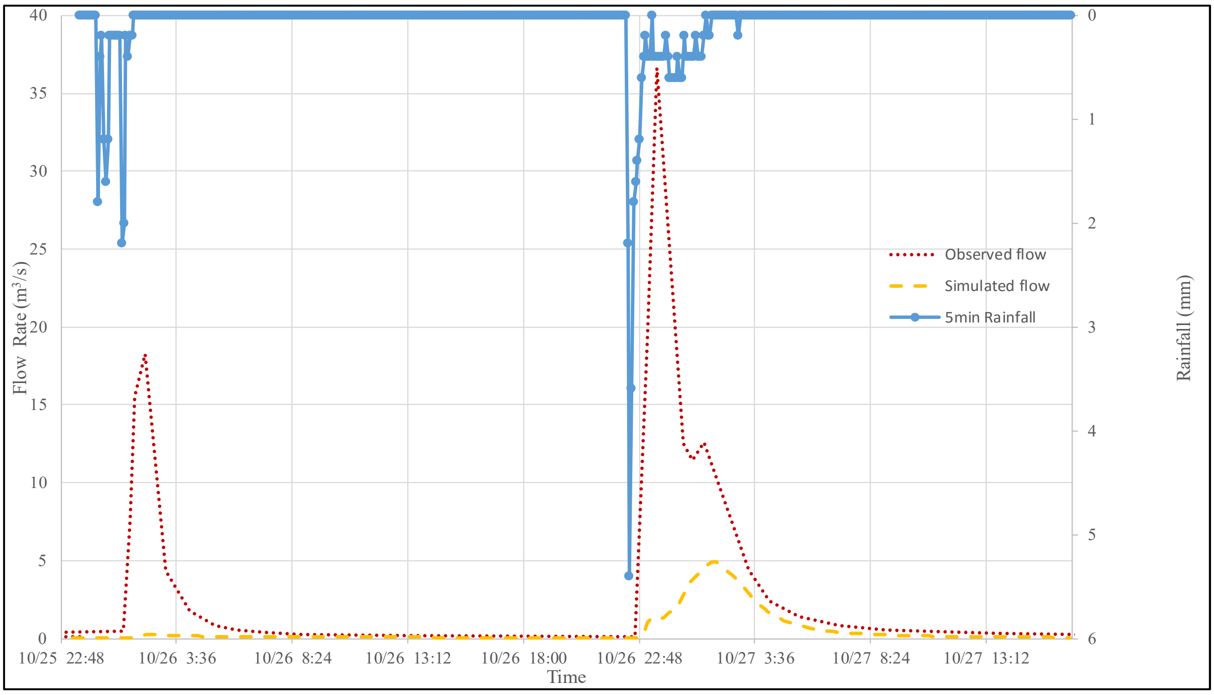

Figure 8.2 Simulated flow at A2H063 for the period from 25 to 27 October 2000 using the uncalibrated SWMM and the CN infiltration model

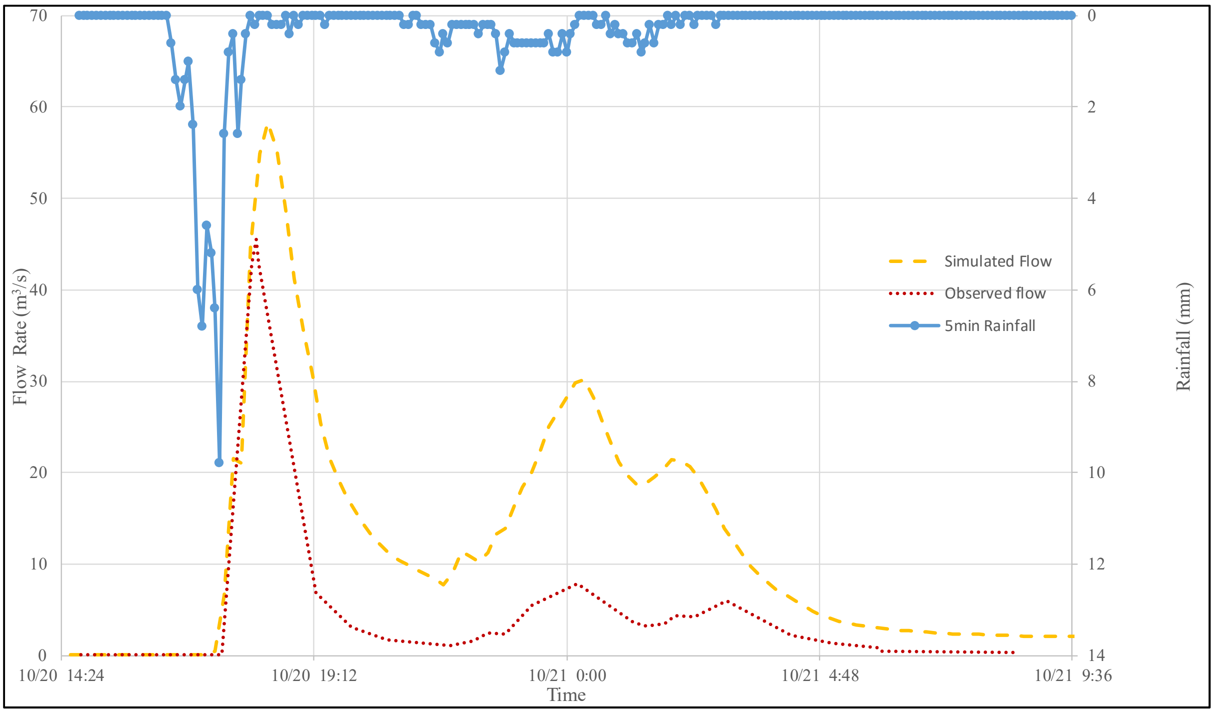

Figure 8.3 Simulated flow at A2H063 for the period from 20 to 21 October 2000 using the uncalibrated SWMM and the CN infiltration model

Figure 8.4 shows the frequency distribution curve for flows of more than the 1:1 year recurrence interval flood peak of 9 m^3/s, as estimated using the GEV distribution, compared with the distribution curve for the uncalibrated SWMM configuration. The flow range from 9 m^3/s and larger was chosen as the purpose of the catchment configuration is to calibrate for significant flows. From Figure 8.4 it is clear that the simulated values had a higher frequency of occurrence than the observed flows for flow rates larger than 9 m^3/s. The configuration was therefore calibrated for flow rates larger than 9 m^3/s. The calibration of the catchment configuration will be discussed in the next section.

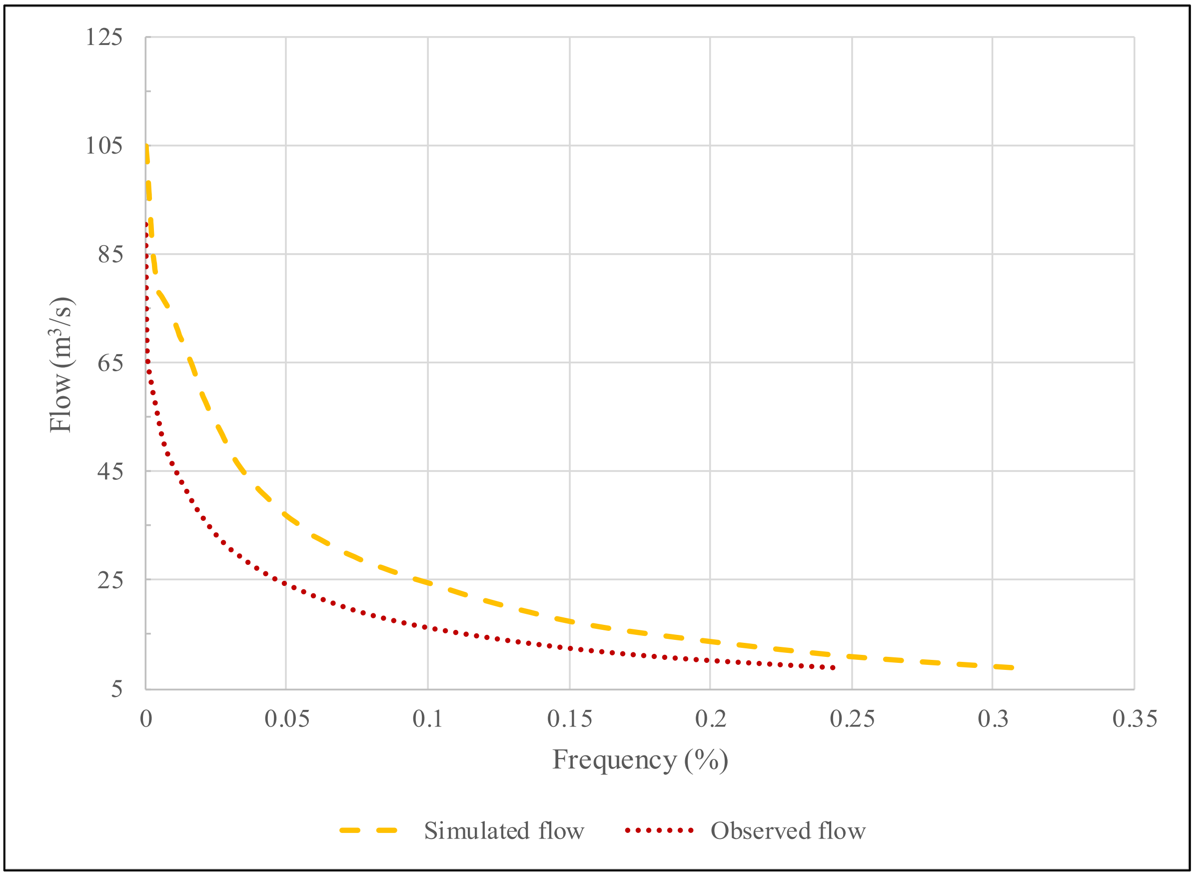

Figure 8.4 Frequency distribution curves for high flows at A2H063 in the uncalibrated SWMM and the CN infiltration model

8.4 SCS Curve Number Calibration Parameters

As all other parameter values had already been calibrated and verified, the only parameters that were calibrated for the CN model were the Curve Numbers, with associated depression storage values, and the drying times. A sensitivity analysis was run which showed that the high flow events in the configuration were not sensitive to drying time adjustments. Therefore, only the CN values were adjusted, which meant that the depression storage values were also adjusted accordingly, as shown in Section 8.2, since they are related. The CN values for residential sub-catchments were adjusted downwards by 10, as this was the development type with the highest uncertainty due to the connectedness percentages of the impervious areas. The calibrated CN values are shown in Table 8.3.

Table 8.3 Curve Numbers used in the calibrated SWMM configuration (adapted from Schulze *et al.*, 2004)

Land Use Type	**Associated SCS Land Use Class**	**Curve Number**						
		A	**A/B**	**B**	**B/C**	**C**	**C/D**	**D**
Grassland	Veld/pasture in fair condition	49	61	69	75	79	82	84
Low shrubland	Brush – Winter rainfall region	28	36	44	53	60	64	66
Plantation/Woodlots young	Forests and plantations – Humus depth 25 mm; compactness: loose/friable	37	49	60	66	71	74	77
Plantations/Woodlots mature	Forests and plantations – Humus depth 100 mm; compactness: moderate	34	47	59	64	69	72	75
Thicket/Dense bush	Woods, low stormflow potential	25	47	55	64	70	74	77
Urban built-up (bare)	Commercial/business areas	89	91	92	93	94	95	95
Urban built-up (dense trees/bush)	Commercial/business areas	89	91	92	93	94	95	95
Urban built-up (low veg/grass)	Commercial/business areas	89	91	92	93	94	95	95
Urban built-up (open trees/bush)	Commercial/business areas	89	91	92	93	94	95	95
Urban commercial	Commercial/business areas	89	91	92	93	94	95	95
Urban industrial	Commercial/business areas	89	91	92	93	94	95	95
Urban residential (bare)	Residential: lot size 500 m^2 (65% impervious)	**69**	**73**	**77**	**79**	**81**	**82**	**83**
Urban residential (dense trees/bush)	Residential: lot size 1350 m^2 (30% impervious)	**51**	**59**	**65**	**69**	**73**	**76**	**77**
Urban residential (open trees/bush)	Residential: lot size 1000 m^2 (38% impervious)	**55**	**60**	**68**	**72**	**75**	**77**	**78**

Land Use Type	Associated SCS Land Use Class	Curve Number						
		A	**A/B**	**B**	**B/C**	**C**	**C/D**	**D**
Urban school and sports ground	Open spaces, parks, cemeteries (75% grass cover)	49	61	69	75	79	82	84
Urban sports and golf (bare)	Veld/pasture in poor condition	68	74	79	83	86	88	89
Urban sports and golf (dense trees/bush)	Open spaces, parks, cemeteries (95% grass cover)	39	51	61	68	74	78	80
Urban sports and golf (low veg/grass)	Woods, low stormflow potential	25	47	55	64	70	74	77
Urban sports and golf (open trees/bush)	Woods, high stormflow potential	45	56	66	75	77	80	83
Woodland/Open bush	Woods, high stormflow potential	45	56	66	75	77	80	83

*Values in bold were adjusted during the model calibration.

8.5 Calibrated Results

Adjustment of the parameters discussed in Section 8.4 achieved a slightly better model response for the study catchment during significant rainfall events. Figure 8.6 shows the frequency distribution curve for flows of more than the 1:1 year recurrence interval flood peak compared with the simulated flow in the calibrated CN SWMM configuration. Figure 8.5 shows that the simulation still overestimated the frequency of flow rates larger than 15 m^3/s, but Figure 8.6 shows that that the calibrated simulation fits the observed flow curve better for flow rates larger than 10 m^3/s.

The calibrated results were used to estimate CN values for all other urban land use types. The proposed input parameters for urban run-off modelling in South Africa are described in the next chapter.

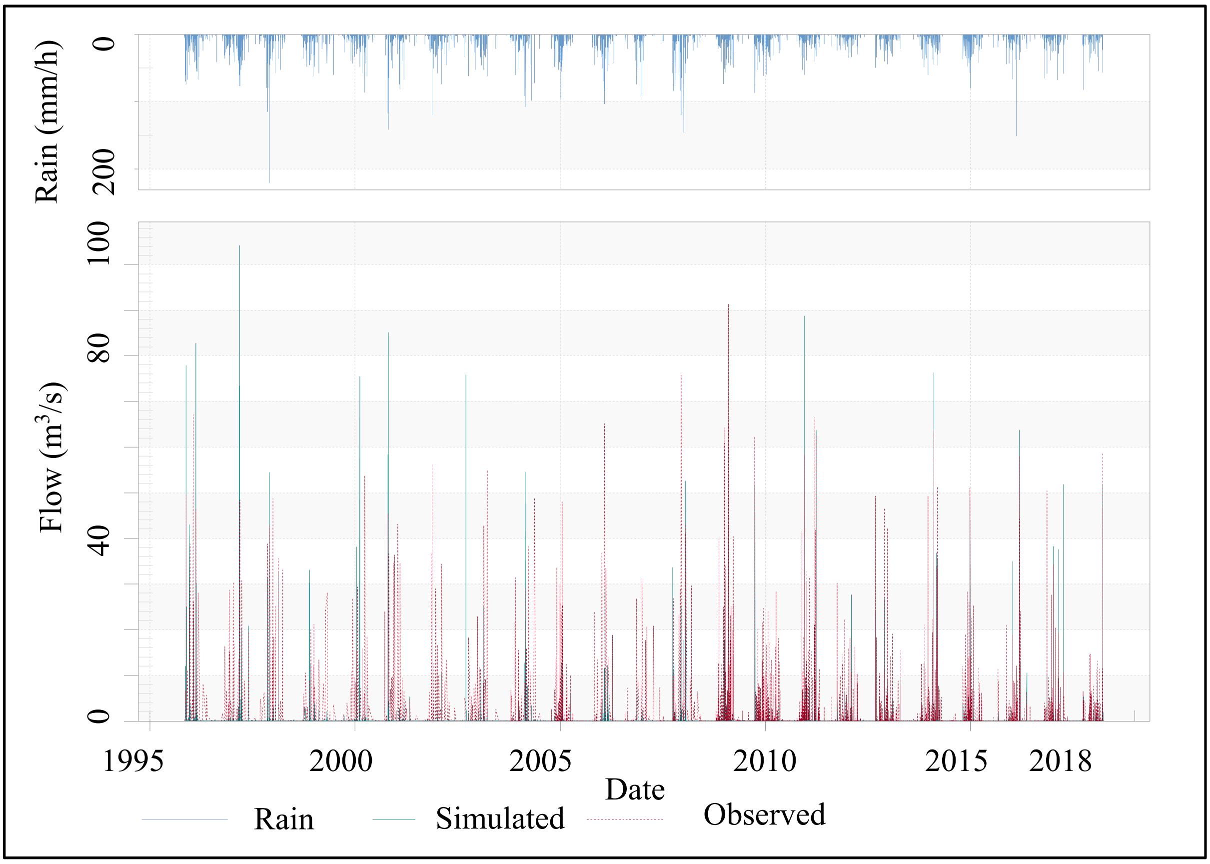

Figure 8.5 Calibrated SWMM CN analysis results for period from 1995 to 2018 for A2H063

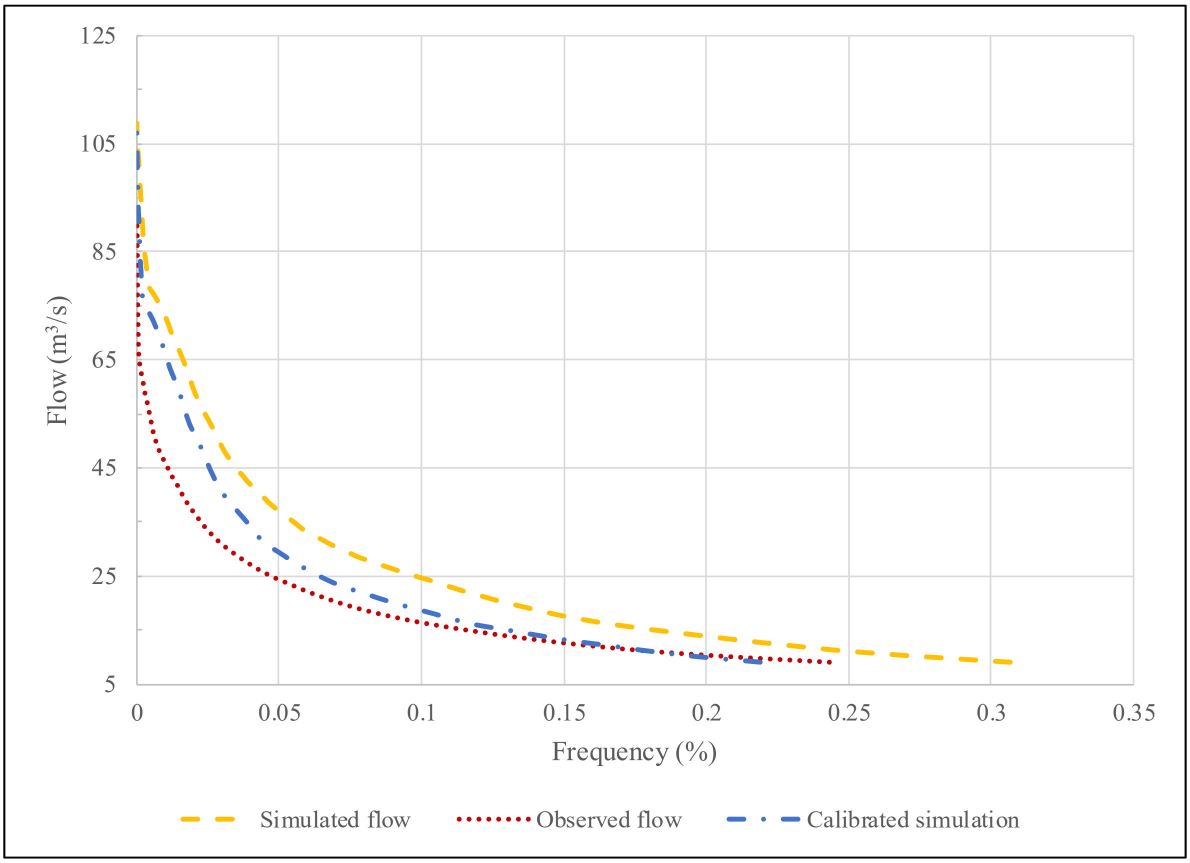

Figure 8.6 Frequency distribution curves for high flows at A2H063 in the calibrated SWMM and the CN infiltration model

9 PRELIMINARY INPUT PARAMETERS FOR URBAN RUNOFF MODELLING IN SOUTH AFRICA

The verified parameters for the study area catchments were used as basis for the extrapolation of applicable parameter values for urban design flood estimation and stormwater infrastructure design in South Africa. Parameters were calibrated for use in urban SWMM modelling and the urban application of the SCS-SA deterministic design flood estimation method. Emphasis is placed on the fact that the proposed parameters in this chapter can only be seen as preliminary parameters, and further verifications using catchments with different types of development is required.

9.1 Green-Ampt Parameters

The Green-Ampt method considers routing in the sub-catchments, as well as the different types of connections between pervious and impervious areas. The preliminary parameters for the Green-Ampt method are therefore discussed separately from the CN method.

9.1.1 Green-Ampt infiltration parameters

It is proposed that soil classification for South African urban areas be done using the SCS map by Schulze and Schütte (2018) that produced SCS values averaged by terrain units, unless measured soil texture data is available for the study area. The SCS Terrain units are related to the SCS soil groupings as summarised in Table 9.1.

Table 9.1 Soil classification association

SCS Terrain unit	SCS soil grouping	United States Department of Agriculture (USDA) soil classification
1	A	Sand
2	A/B	Loamy sand
3	B	Sandy loam
4	B/C	Loam, silt loam
5	C	Sandy clay loam, clay loam
6	C/D	Silty clay loam, sandy clay, silty clay
7	D	Clay

Dippenaar *et al.* (2014) note that the upper soil layers in South Africa are usually comprised of highly variable unconsolidated mineral and organic matter. As the final infiltration rates for soil groupings A, B, C and D proposed by Schulze *et al.* (2004) were proposed for conditions similar to most of the permeable areas in South African urban catchments, and as the purpose of SWMM catchment configurations are generally to simulate infiltration into the upper layers of the soil profile, without accounting for interflow or recharge, it is suggested that the values proposed for soil groupings A to D be used and interpolated between SCS terrain numbers one to seven, as shown in Table 9.2. These values have been associated with SCS Terrain units as described in Table 9.1.

Table 9.2 Infiltration values used for the calibrated SWMM (adapted from Schulze *et al.*, 2004)

Texture	**SCS Soil Grouping**	**SCS Terrain Number**	**Hydraulic Conductivity K (mm/hr)***
Sand	A	1	**25**
Loamy Sand	A/B	2	19
Sandy Loam	B	3	**13**
Loam	B/C	4	9.5
Silt Loam	B/C	4.5	7.7
Sandy Clay Loam	C	5	**6**
Clay Loam	C	5.5	5.3
Silty Clay Loam	C/D	6	4.5
Sandy Clay	C/D	6.3	4.1
Silty Clay	D	6.6	3.6
Clay	D	7	**3**

*Values in bold print were obtained from (Schulze *et al.*, 2004) and other values were derived using interpolation

9.1.2 Imperviousness parameters

The greatest uncertainty in the impervious parameters centred on the percentage of unconnected imperviousness on residential properties and at schools. The percentage of runoff routed from impervious subareas in sub-catchments with these descriptions was therefore adjusted to achieve better calibration of the model. The impervious area percentages, as well as calibrated, verified and preliminary extrapolated input routing values for all urban land use types according to the DEA classification, are shown in Table 9.3. As the focus of this study was on urban land uses, only applicable DEA land use numbers are shown in Table 9.3.

Table 9.3 Preliminary imperviousness percentages for South African urban catchments

DEA Land Use Number[@]	Land Use Type	Impervious Percentage (%)	Subarea Routing°	Percent Routed[#] (%)
2	Water permanent	100	Outlet	100
3	Wetlands	0	Outlet	100
5	Thicket/Dense bush	*	Pervious	100
6	Woodland/Open bush	*	Pervious	100
7	Grassland	*	Pervious	100
9	Low shrubland	*	Pervious	100
32	Plantations/Woodlots mature	0	Outlet	100
33	Plantation/Woodlots young	0	Outlet	100
35	Mines 1 bare	10	Pervious	100
36	Mines 2 semi-bare	10	Pervious	100
42	Urban commercial	95	Impervious	90
43	Urban industrial	95	Impervious	90
44	Urban informal (dense trees / bush)	85	Pervious	100
45	Urban informal (open trees / bush)	85	Pervious	100
46	Urban informal (low veg / grass)	85	Pervious	100
47	Urban informal (bare)	85	Pervious	100
48	Urban residential (dense trees/bush)	30	Pervious	85

DEA Land Use Number[@]	Land Use Type	Impervious Percentage (%)	Subarea Routing°	Percent Routed[#] (%)
49	Urban residential (open trees/bush)	38	Pervious	85
50	Urban residential (low veg / grass)	45	Pervious	85
51	Urban residential (bare)	50	Pervious	85
52	Urban school and sports ground	20	Pervious	85
53	Urban smallholding (dense trees / bush)	10	Pervious	100
54	Urban smallholding (open trees / bush)	10	Pervious	100
55	Urban smallholding (low veg / grass)	10	Pervious	100
56	Urban smallholding (bare)	10	Pervious	100
57	Urban sports and golf (dense trees/bush)	5	Pervious	100
58	Urban sports and golf (open trees/bush)	5	Pervious	100
59	Urban sports and golf (low veg / grass)	5	Pervious	100
60	Urban sports and golf (bare)	5	Pervious	100
61	Urban township (dense trees / bush)	85	Pervious	100
62	Urban township (open trees / bush)	85	Pervious	100
63	Urban township (low veg / grass)	85	Pervious	100
64	Urban township (bare)	85	Pervious	100
65	Urban village (dense trees / bush)	20	Pervious	100
66	Urban village (open trees / bush)	20	Pervious	100

DEA Land Use Number[@]	Land Use Type	Impervious Percentage (%)	Subarea Routing°	Percent Routed[#] (%)
67	Urban village (low veg / grass)	20	Pervious	100
68	Urban village (bare)	20	Pervious	100
69	Urban built-up (dense trees/bush)	85	Impervious	90
70	Urban built-up (open trees/bush)	85	Impervious	90
71	Urban built-up (low veg/grass)	85	Impervious	90
72	Urban built-up (bare)	85	Impervious	90

[@]Only land uses associated with urban areas are listed

*Values to be added based on the catchment characteristics

°Subarea routing legend:

Impervious	Runoff from pervious area flows to impervious area
Pervious	Runoff from impervious flows to pervious area
Outlet	Runoff from both areas flows directly to outlet

[#]The percentage of sub-area runoff to be directed to the other sub-area before reaching the outlet

9.1.3 Depression storage depths

Preliminary depression storage depths for the Green-Ampt method applied to urban land use types, as defined by the DEA, are shown in Table 9.4. Further verification of these preliminary results using catchments with different types of development is required.

Table 9.4 Preliminary depression storage depths

DEA Land Use Number@	Land Use Type	Depression Storage	
		Impervious Areas (mm)	Pervious Areas (mm)
2	Water permanent	0.0	-
3	Wetlands	5.0	5.0
5	Thicket/Dense bush	8.0	8.0
6	Woodland/Open bush	2.5	2.5
7	Grassland	5.0	5.0
9	Low shrubland	8.0	8.0
32	Plantations/Woodlots mature	8.0	8.0
33	Plantation/Woodlots young	8.0	8.0
35	Mines 1 bare	2.0	2.5
36	Mines 2 semi-bare	2.0	2.5
42	Urban commercial	2.0	2.5
43	Urban industrial	2.0	2.5
44	Urban informal (dense trees / bush)	2.0	8.0
45	Urban informal (open trees / bush)	2.0	2.5
46	Urban informal (low veg / grass)	2.0	5.0
47	Urban informal (bare)	2.0	2.5
48	Urban residential (dense trees/bush)	2.0	8.0
49	Urban residential (open trees/bush)	2.0	2.5
50	Urban residential (low veg / grass)	2.0	5.0
51	Urban residential (bare)	2.0	2.5
52	Urban school and sports ground	2.0	5.0
53	Urban smallholding (dense trees / bush)	2.0	8.0
54	Urban smallholding (open trees / bush)	2.0	2.5
55	Urban smallholding (low veg / grass)	2.0	5.0
56	Urban smallholding (bare)	2.0	2.5
57	Urban sports and golf (dense trees/bush)	8.0	8.0
58	Urban sports and golf (open trees/bush)	2.5	2.5

DEA Land Use Number@	Land Use Type	Depression Storage	
		Impervious Areas (mm)	Pervious Areas (mm)
59	Urban sports and golf (low veg / grass)	2.5	5.0
60	Urban sports and golf (bare)	2.5	2.5
61	Urban township (dense trees / bush)	2.0	8.0
62	Urban township (open trees / bush)	2.0	2.5
63	Urban township (low veg / grass)	2.0	5.0
64	Urban township (bare)	2.0	2.5
65	Urban village (dense trees / bush)	2.0	8.0
66	Urban village (open trees / bush)	2.0	2.5
67	Urban village (low veg / grass)	2.0	5.0
68	Urban village (bare)	2.0	2.5
69	Urban built-up (dense trees/bush)	2.0	8.0
70	Urban built-up (open trees/bush)	2.0	2.5
71	Urban built-up (low veg/grass)	2.0	5.0
72	Urban built-up (bare)	2.0	2.5

@Only land uses associated with urban areas are listed

9.1.4 Roughness parameters

The Manning roughness values proposed for use in SWMM and other literature for overland flow are significantly higher than the Manning roughness values traditionally used for defined watercourses. The overland flow Manning roughness values as first proposed by the United States Department of Agriculture (USDA, 1986) and later extended by McCuen *et al.* (2002) (Table 6.10) are proposed for preliminary use, as shown in Table 9.5. The land use types were categorised according to the DEA classification to achieve consistency.

Table 9.5 Proposed Manning roughness values for overland flow

DEA Land Use Number@	Land Use Type	Manning n-value	
		Impervious Areas	Pervious Areas
2	Water permanent	0.010	-
3	Wetlands	0.240	0.24

DEA Land Use Number@	Land Use Type	Manning n-value	
		Impervious Areas	Pervious Areas
5	Thicket/Dense bush	0.800	0.80
6	Woodland/Open bush	0.400	0.40
7	Grassland	0.240	0.24
9	Low shrubland	0.400	0.40
32	Plantations/Woodlots mature	0.800	0.80
33	Plantation/Woodlots young	0.400	0.40
35	Mines 1 bare	0.024	0.02
36	Mines 2 semi-bare	0.024	0.02
42	Urban commercial	0.013	0.15
43	Urban industrial	0.013	0.15
44	Urban informal (dense trees / bush)	0.024	0.80
45	Urban informal (open trees / bush)	0.024	0.40
46	Urban informal (low veg / grass)	0.024	0.15
47	Urban informal (bare)	0.024	0.02
48	Urban residential (dense trees/bush)	0.024	0.80
49	Urban residential (open trees/bush)	0.024	0.40
50	Urban residential (low veg / grass)	0.024	0.15
51	Urban residential (bare)	0.024	0.02
52	Urban school and sports ground	0.024	0.15
53	Urban smallholding (dense trees / bush)	0.024	0.80
54	Urban smallholding (open trees / bush)	0.024	0.40
55	Urban smallholding (low veg / grass)	0.024	0.15
56	Urban smallholding (bare)	0.024	0.02
57	Urban sports and golf (dense trees/bush)	0.024	0.80
58	Urban sports and golf (open trees/bush)	0.024	0.40
59	Urban sports and golf (low veg / grass)	0.024	0.15
60	Urban sports and golf (bare)	0.024	0.02
61	Urban township (dense trees / bush)	0.024	0.80
62	Urban township (open trees / bush)	0.024	0.40
63	Urban township (low veg / grass)	0.024	0.15

DEA Land Use Number[@]	Land Use Type	Manning n-value	
		Impervious Areas	Pervious Areas
64	Urban township (bare)	0.024	0.02
65	Urban village (dense trees / bush)	0.024	0.80
66	Urban village (open trees / bush)	0.024	0.40
67	Urban village (low veg / grass)	0.024	0.15
68	Urban village (bare)	0.024	0.02
69	Urban built-up (dense trees/bush)	0.013	0.80
70	Urban built-up (open trees/bush)	0.013	0.40
71	Urban built-up (low veg/grass)	0.013	0.15
72	Urban built-up (bare)	0.013	0.02

[@]Only land uses associated with urban areas are listed

Proposed Manning roughness values used for pipes, canals and rivers are based on the materials typically used or found in these conduits and associated Manning roughness values as proposed by the American Society of Civil Engineers (ASCE, 2007). The proposed Manning roughness values are shown in Table 9.6.

Table 9.6 Proposed Manning roughness values for conduits (based on (ASCE, 2007)

Material	Manning N-value for Pervious Areas
Concrete pipe	0.015
Concrete canal	0.018
Grass-lined channel	0.030
Natural river	0.040-0.100

9.2 SCS-SA Curve Numbers

The only parameters that were calibrated, verified and extrapolated for the CN model were the Curve Numbers, with associated depression storage values. The suggested preliminary CN values are shown in Table 9.7. It should, however, be noted that the derived CN values may overestimate peak flow rates for large flood events, but underestimate small events. Emphasis is placed on the fact that the proposed parameters in this section can only be seen as preliminary parameters, and verification using catchments with different types of development is required.

Table 9.7 Preliminary Curve Numbers used in SWMM

DEA Land Use Number[@]	Land Use Type	Curve Number						
		A	A/B	B	B/C	C	C/D	D
5	Thicket/Dense bush	25	47	55	64	70	74	77
6	Woodland/Open bush	45	56	66	75	77	80	83
7	Grassland	49	61	69	75	79	82	84
9	Low shrubland	28	36	44	53	60	64	66
32	Plantations/Woodlots mature	34	47	59	64	69	72	75
33	Plantation/Woodlots young	37	49	60	66	71	74	77
35	Mines 1 bare	89	91	92	93	94	95	95
36	Mines 2 semi-bare	89	91	92	93	94	95	95
42	Urban commercial	89	91	92	93	94	95	95
43	Urban industrial	89	91	92	93	94	95	95
44	Urban informal (dense trees / bush)	60	68	74	78	82	85	86
45	Urban informal (open trees / bush)	64	69	77	81	84	86	87
46	Urban informal (low veg / grass)	66	71	79	83	86	88	89
47	Urban informal (bare)	78	82	86	88	90	91	92
48	Urban residential (dense trees/bush)	51	59	65	69	73	76	77
49	Urban residential (open trees/bush)	55	60	68	72	75	77	78
50	Urban residential (low veg / grass)	57	62	70	74	77	79	80
51	Urban residential (bare)	69	73	77	79	81	82	83
52	Urban school and sports ground	49	61	69	75	79	82	84
53	Urban smallholding (dense trees / bush)	27	49	57	66	72	76	79
54	Urban smallholding (open trees / bush)	47	58	68	77	79	82	85
55	Urban smallholding (low veg / grass)	50	62	70	76	80	83	85
56	Urban smallholding (bare)	55	67	75	81	85	88	90
57	Urban sports and golf (dense trees/bush)	39	51	61	68	74	78	80
58	Urban sports and golf (open trees/bush)	45	56	66	75	77	80	83

DEA Land Use Number[@]	Land Use Type	Curve Number						
		A	A/B	B	B/C	C	C/D	D
59	Urban sports and golf (low veg / grass)	25	47	55	64	70	74	77
60	Urban sports and golf (bare)	68	74	79	83	86	88	89
61	Urban township (dense trees / bush)	73	77	81	84	76	87	88
62	Urban township (open trees / bush)	75	79	83	86	78	89	90
63	Urban township (low veg / grass)	76	80	84	87	79	90	91
64	Urban township (bare)	77	81	85	88	80	91	92
65	Urban village (dense trees / bush)	37	59	67	76	82	86	89
66	Urban village (open trees / bush)	57	68	78	87	89	92	95
67	Urban village (low veg / grass)	60	72	80	86	90	93	95
68	Urban village (bare)	65	77	85	91	95	98	95
69	Urban built-up (dense trees/bush)	89	91	92	93	94	95	95
70	Urban built-up (open trees/bush)	89	91	92	93	94	95	95
71	Urban built-up (low veg/grass)	89	91	92	93	94	95	95
72	Urban built-up (bare)	89	91	92	93	94	95	95

[@]Only land uses associated with urban areas are listed

10 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The major aims of this project, as stated in the contract, consisted of major objectives related to design flood estimation for urban areas in South Africa, including the following:

i. To improve the understanding of hydrological processes in the South African urban and sub-urban environments.
ii. To develop a calibrated design flood estimation method for urban and sub-urban areas, either by updating existing methods, or developing a new method, by focussing on two case studies in urbanised areas of South Africa.
iii. To disseminate any new-found knowledge through scientific papers and at conferences.

The first aim was achieved by conducting a detailed literature review focussing on urbanisation trends in Chapter 2; the impacts of urbanisation on hydrological responses in Chapter 3; challenges with hydrological modelling in developing countries in Chapter 4; and models used in urban runoff modelling in Chapter 5 of this report.

The second objective of this research project was achieved by obtaining preliminary calibrated catchment parameters that are associated with each of the urban land use types on the DEA land use maps (Geoterraimage, 2015) and that could be used for deterministic design flood estimation. The literature review was used to inform the methodology used to develop a calibrated design flood estimation method for South African urban and sub-urban areas using the Storm Water Management Model (SWMM) software developed by the Environmental Protection Agency (EPA).

A small catchment was selected to use as a pilot study area in order to establish an applicable methodology for the catchment configuration and calibration applied in this project. This process is outlined in Chapter 6. After the SWMM parameters for the configuration using the Modified Green-Ampt method were calibrated by adjusting the infiltration and imperviousness parameters, the adjusted parameters were verified on an adjacent catchment area, as discussed in Chapter 7.

The calibration and verification process showed that the parameters currently used for runoff modelling in South African urban areas do not provide accurate results in gauged catchments. The need for updated parameters was therefore confirmed.

The SCS-SA method was identified as a method that could be used more widely in urban design flood estimation if the curve numbers were verified. SWMM also has the option to use an SCS infiltration method for urban models. After the SWMM parameters for the catchment configurations using the Modified Green-Ampt method were calibrated and verified, the calibrated configurations were used to derive applicable SCS Curve Numbers for urban land use types in the calibration and verification catchments, as detailed in Chapter 8.

The verified parameters for the study area catchments were used as basis for the preliminary extrapolation of applicable parameter values for urban design flood estimation and storm water infrastructure design in South Africa, described in Chapter 9. Emphasis is placed on the fact that the proposed parameters in this section can only be seen as preliminary parameters, and further verification using catchments with different types of development is required. It is recommended that the extrapolated results be verified using catchment areas with applicable urban land use types. It is also recommended that further work be undertaken to verify the preliminary CN values at more catchments and for a wider range or urban development types found in South Africa.

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