IMPROVED UNDERSTANDING AND MODELLING OF HYDROLOGICAL RESPONSES IN FORMAL AND INFORMAL URBAN AREAS: CASE STUDY IN TSHWANE, SOUTH AFRICA

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Submitted in fulfilment of the requirements for the degree of PhD

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PREFACE

The research contained in this thesis was completed by the candidate while based in the School of Engineering of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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Signed: Prof JC Smithers

Date: 17 June 2023

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Signed: Dr TR Kjeldsen

Date: 17 June 2023

DECLARATION 1: PLAGIARISM

I, Ione Loots, declare that

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

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

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

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   a. their words have been re-written but the general information attributed to them has been referenced;
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Signed: Ione Loots

Date: 17 June 2023

DECLARATION 2: PUBLICATIONS

My role in each paper and published document is indicated. The * indicates corresponding author.

Chapter 3

1. Loots, I*, Smithers, JC, Kjeldsen, TR. 2022. Quantifying the influence of urban development on runoff in South Africa. *Urban Water Journal*, pp. 1-14. https://doi.org/10.1080/1573062X.2022.2027472.

I contributed to the formulation of the research question (80%), design of the methodology (80%), processing and analysis of data (95%) and manuscript preparation (90%). JC Smithers contributed to the formulation of the research question (20%), design of the methodology (10%) and manuscript preparation (5%). TR Kjeldsen contributed to the design of the methodology (10%) and manuscript preparation (5%). A Joubert assisted with processing of data (5%). She was not listed as an author, but thanked as a contributor. Historical rainfall data was provided by the South African Weather Service (SAWS). The assistance from N Letsatsi and M Mkhwanazi is gratefully acknowledged.

Chapter 5

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Chapter 7

4. Loots, I* and Smithers, JC. 2020. *Design Flood Estimation in Urban Areas in South Africa: Preliminary Results from Tshwane Case Studies*. WRC Report No. 2747/1/20. Water Research Commission, Pretoria, South Africa.
5. Loots, I*, Smithers, JC, Kjeldsen, TR. 2023. Improved modelling of hydrological responses in South African urban areas. (Draft manuscript).

I contributed to the formulation of the research question (90%), design of the methodology (90%), data collection (50%), processing and analysis of data (100%) and report preparation (90%). JC Smithers contributed to the formulation of the research question (10%), design of the methodology (10%) and manuscript preparation (5%). A Scholtz, HS Oberholzer and JA Akura assisted with model configuration and data collection (50%). They were not listed as authors, but thanked as contributors. Historical rainfall data was provided by the South African Weather Service (SAWS). The assistance from E de Jager and M Mkhwanazi is gratefully acknowledged. Computation Hydraulics International (CHI) graciously awarded PCSWMM educational licences for use in this research project. This support is acknowledged with gratitude. The research presented in this report emanated from a study funded by the Water Research Commission (WRC), whose support is acknowledged with gratitude. The input from Project Reference Group members is also acknowledged: Mr W Nomquphu, Dr TR Kjeldsen, Prof RE Schulze, Prof SJ van Vuuren, Mr C Brooker, Mr S Dunsmore, Mr D van der Spuy, Dr S Lorentz, Dr OJ Gericke, Mr M Braune, Mr JP Calitz, Mr T Rowe, Mr P Rademeyer, Prof JA du Plessis, Prof JG Ndiritu, Mr M van Dijk, Mr JPJ Pietersen, Mr M Parak, Mr E Oakes.

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Date: 9 February 2023

ABSTRACT

It is widely accepted that urban development results in larger flood peak discharges with faster catchment response times, larger total runoff volumes and lower base flow volumes. However, these effects have not previously been studied in the South African context, where typical development characteristics in both formal and informal settlements differ from those reported in previous studies. In order to configure accurate hydrological models for South African conditions, it is important to understand the impacts of typical South African urban development types on runoff.

This study aims to gain new understanding of hydrological processes in the diverse range of South African urban environments and to use this knowledge to develop an improved approach for hydrological modelling in South African urban areas. This study investigates the effects of urban development on runoff, including: (a) total runoff volumes, (b) stormflow volumes, (c) base flow volumes, (d) flood peaks and (e) catchment response time from South African urban catchments, using case studies from Gauteng Province. It is shown that total runoff, stormflow volumes and base flow all increase in the study catchments regardless of whether the upstream development is formal or informal. However, contrary to current scientific consensus, changes in flood peaks and catchment response times with development are statistically insignificant in most catchments with formal urban development in this study. The seeming paradox of increased flood volumes without corresponding increase in flood peaks and decreased catchment response time is attributed to the temporary storage and subsequent attenuation of peaks in these catchments. The catchment with the largest proportion of informal development shows increasing trends in both volume and flood peaks, although catchment response times do not show significant change. It is postulated that the complexity of increased imperviousness without increased connectivity of impervious areas to drainage systems, as typically found in informal settlements, could contribute to this result.

In order to assess the impact of the improved understanding and quantification of urban responses on modelling, the Storm Water Management Model (SWMM) was configured for two catchments, first using conventional parameter sets, then incorporating measured and derived imperviousness and connectivity data from this study. The simulation results show that the parameter values proposed in this study improve the results in both catchments. Considerable additional improvement is achieved through the incorporation of pseudo storages to simulate unexpected attenuation in the catchments. Based on the results it is recommended that attenuation be incorporated in hydrological models of urban areas in ungauged catchments with similar characteristics. Recommendations are made for further investigation into reasons for the findings, as well as further studies in other South African urban areas, when additional data is available.

ACKNOWLEDGMENTS

I would not have been able to complete this thesis if it weren't for the support of my family, friends and colleagues. I am grateful to my family, and especially my parents, who graciously made meals, played babysitter and provided some space between the chaos to allow me to work on this project. I am equally grateful to my colleagues who shouldered some of my workload and who often gave advice and moral support. I am particularly grateful for the support from Marco van Dijk and Prof James Maina, who continue to play key mentorship roles. I am grateful for the prayers and support from my friends, and to those who knew not to ask that dreaded question, thank you.

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CHI Computation Hydraulics International (CHI) graciously awarded PCSWMM educational licences for use in this research project and some of the methodology applied in this project emanated from a Water Research Commission (WRC) funded project. This support is acknowledged with gratitude.

Most of all, I am grateful to my Lord and Saviour for being my source of strength and my provider. I am grateful that He has kept me from all harm and that He is watching over my life both now and forevermore.

Thando, my liefie-seun, mag hierdie eendag vir jou 'n voorbeeld wees van hoe ons opstaan, onsself regskud, en weer probeer na ons geval het. Vasbyt vorentoe, my seun, kop-af-en-dryf!

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Symbol/abbreviation	Description
α	Filter parameter used in baseflow separation
A	Sub-catchment surface area [m^2]
AMS	Annual Maximum Series
ARC	Agricultural Research Council
β	Filter parameter used in baseflow separation
Ba	Bare
BARE	Bare area
Bu	Buildings
CN	Curve Number
CN_C	Composite Curve Number
CN_P	Pervious Curve Number
COM	Commercial areas
CoT	City of Tshwane
DCIA	Directly Connected Impervious Areas
$DCIA_{\%}$	Directly connected impervious area, as a percentage
d	Ponding depth on sub-catchment surface [m]
d_s	Depression storage depth [m]
DWS	Department of Water and Sanitation
e	Surface evaporation rate [m/s]
EIA	Effective Impervious Area
$EIA_{\%}$	Effective impervious area, as a percentage
f	Infiltration rate [m/s]
G	Grass
i	Rate of rainfall plus snowmelt [m/s]
I_a	Initial abstraction [m]
IMP	Impervious area
IND	Industrial areas
INDCOM	All industrial and commercial land cover

Symbol/abbreviation	**Description**
K	Hydraulic conductivity [m/s]
n	Manning's surface roughness coefficient [s/m$^{1/3}$]
NGI	National Geo-spatial Information
P_{Exi}	Start of effective rainfall
PoT	Point over Threshold
PS	Parameter Set
q	Runoff rate [m/s]
Q	Volumetric flow rate [m^3/s]
Q_{Bxi}	Baseflow at time step i
Q_{Dxi}	Direct runoff at time step i
Q/P	Runoff as a proportion of precipitation
Q_{sum}/P_{sum}	Cumulative runoff as a proportion of cumulative precipitation
ρ	The Spearman ρ-value
R	Roads / Ratio of unconnected impervious areas to total impervious area
R^2	Coefficient of determination
RES_{Formal}	All formal residential land cover
$RES_{Informal}$	All informal residential land cover
RMSE	Root Mean Square Error
RURAL	All natural, agricultural and mining land uses
S	Sub-catchment slope [m/m]
SANLC	South African National Land Cover
SANSA	South African National Space Agency
SAWS	South African Weather Service
SCS	Soil Conservation Services
SCS-SA	Soil Conservation Services – South Africa
StatsSA	Statistics South Africa
SWMM	Storm Water Management Model
τ	The Kendall τ-value
T	Trees

Symbol/abbreviation	Description
T_C	Time of concentration [h]
T_{dry}	Drying time [days]
TIA	Total Impervious Areas
$TIA_{\%}$	Total impervious area, as a percentage of total catchment area
T_{Lx}	Lag time [h]
T_P	Time-to-peak [h]
T_{Px}	Conceptual time of concentration [h]
T_{Pxi}	The total time for all rising limbs of a flow hydrograph [h]
UIA	Unconnected Impervious Area
UNDP	United Nations Population Division
UNICEF	United Nations Children's Fund
URB_{Formal}	Formally developed urban areas
$URB_{Informal}$	Informally developed urban areas
URB_{Park}	Parks and fields surrounded by urban development
URB_{TOT}	The total extent of urban development, or urban footprint
$URB_{TOT\%}$	Developed urban area, as a percentage of total catchment area
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VEG	Vegetated area
W	Water / sub-catchment width [m]
WRC	Water Research Commission
WSUD	Water Sensitive Urban Design

1 INTRODUCTION

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). South Africa as a developing country is experiencing an especially high rate of increase in urban migration (UNDP, 2019; StatsSA, 2020) as people migrate to urban areas in search of employment and better service delivery (Geyer *et al.*, 2012). This has led to significant development of both formal and informal settlements on the outskirts of cities, with Thompson (2019) reporting a 30% increase in total urban footprint at a national scale between 1990 and 2018.

It is widely accepted that urban development results in a decrease in the permeability of a catchment (Jacobson, 2011; Ferreira *et al.*, 2016; Miller *et al.*, 2020; Macdonald *et al.*, 2022). This is generally associated with increased flood volumes with faster catchment response times and larger peak flow rates, combined with lower base flow volumes (Shuster *et al.*, 2005; Jacobson, 2011; Braud *et al.*, 2013; Sakijege, 2013; Gumindoga *et al.*, 2014; Gogate and Rawal, 2015; Ferreira *et al.*, 2016; Putro *et al.*, 2016; Gorani, 2019; Saurav *et al.*, 2021).

However, some studies (Brun and Band, 2000; Chin and Gregory, 2001; Burns *et al.*, 2005; Aichele and Andresen, 2013; Fletcher *et al.*, 2013; Gallo *et al.*, 2013; Miller and Hess, 2017) suggest that not all components of storm water runoff are necessarily impacted by urban development as expected. The materials, and types of infrastructure used in some developments, as well as local topography and slope changes, could impact on the rate and flow pathways of storm water runoff (McGrane, 2016; Fidal and Kjeldsen, 2020). In addition, the potential effects of poor maintenance of constructed water drainage and reticulation systems, and the possibility of retention and attenuation in urban systems due to property boundary walls that are typical in many South African urban areas, could substantially influence these parameters. The possible effects of informal settlements on runoff could prove to be vastly different to the effects of formal urban settlements, since development in these settlements is unplanned and generally unregulated, with little to no formal infrastructure. The impermeable areas in these settlements are generally not connected to drainage systems. The effects of informal development on runoff have not previously been quantified in a South African context. 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.

1.1 Problem Statement

South Africa is a developing country where people migrate to urban areas in search of employment and better service delivery. Studies have shown that the metropolitan and most intermediate sized cities in the country have experienced significant population increases in recent years, with approximately 65% of South Africans currently living in urban areas (StatsSA, 2020).

Urbanisation is often associated with more frequent and severe flooding (Jacobson, 2011; Braud *et al.*, 2013; Sakijege, 2013; Ferreira *et al.*, 2016; Saurav *et al.*, 2021). The effects of imperviousness associated with urban development on runoff have been extensively researched in developed countries (Chang, 2007; USEPA, 2008; Gallo *et al.*, 2013; Choi *et al.*, 2015; Redfern *et al.*, 2016; Walega *et al.*, 2019; Hamilton *et al.*, 2021; Macdonald *et al.*, 2022). However, very few urban catchments in developing countries are gauged, thus many studies in these areas rely on hydrological modelling in ungauged catchments, or catchments with limited datasets, rather than long-term observed data (Lei *et al.*, 2008; Gumindoga *et al.*, 2014; Remondi *et al.*, 2015; Schütte and Schulze, 2017; Hu *et al.*, 2020; Seidl *et al.*, 2020; Saurav *et al.*, 2021). Hydrological modelling of both formally and informally developed urban catchments presents numerous challenges, including: the connections between pervious and impervious areas (McGrane, 2016); variation in soil properties and condition (Rawls *et al.*, 1983; Chow *et al.*, 1988; Heymann, 2016; Dippenaar, 2019); and rainfall distribution, even in small catchments (Beven, 2012; Makgopa, 2015).

The extent of the impacts of urban development on runoff has not previously been quantified from observed data for South Africa. Therefore, the accuracy of hydrological model configurations in ungauged urban catchments in South African is unknown.

1.2 Research Aims

It is hypothesised that the runoff characteristics from South African urban areas, with mixed formal and informal levels of development, are different to the characteristics generally expected for developed catchments. These characteristics need to be understood, in order to improve the accuracy of urban runoff modelling in South Africa.

Therefore, the aims of this study were to gain new understanding of hydrological processes in the diverse range of South African urban environments and to use this knowledge to develop an improved approach for hydrological modelling in South African urban areas.

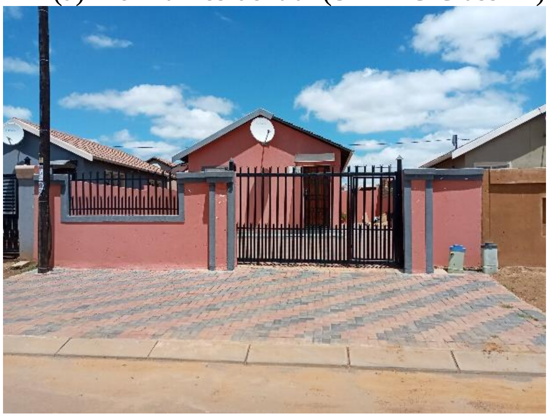
1.3 Research Scope

Although the study aimed to address urban hydrological modelling in all South African urban areas, access to reliable, long term, measured flow data was limited. Therefore, the focus of this study was on five urban and three rural catchments in the Gauteng Province, but with discussion on the wider applicability of certain results and recommendation for further studies in other South African urban areas when additional data is available. The urban areas in the selected study catchments represent a wide range of South African development types, with all eight urban residential South African National Land Cover (SANLC) classes, as well as Industrial and Commercial land cover classes, included. Figure 1.1 shows examples of typical developments found in the study area.

The annual average rainfall in Gauteng is approximately 715 mm, predominantly occurring in the summer (Dyson, 2009; Adeyemi *et al.*, 2015). The City of Tshwane, in the north of the Gauteng Province, has elevations ranging from 975 m above mean sea level in the north to 1620 m in the south (Conradie, 2017). According to Beck *et al.* (2018), the study catchments in Tshwane fall in the current Köppen-Geiger climatic zone 12: Cwb (temperate, dry winter, warm summer). The natural soil in the region is generally classified as non-differentiated fersiallitic soils, lithosols and litholic soils (ESDAC, 1965).


(a) Formal residential (SANLC Class 47)

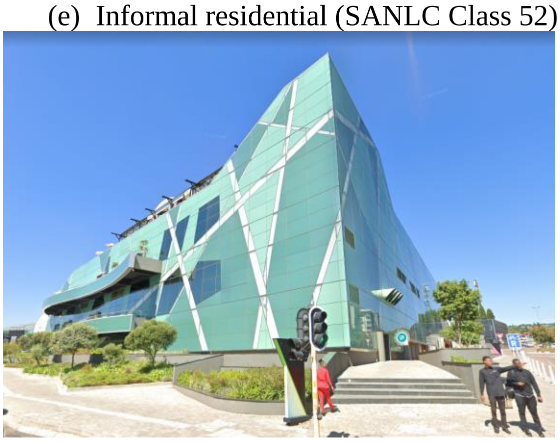

(b) Formal residential (SANLC Class 49)


(c) Formal residential (SANLC Class 50)


(d) Informal residential (SANLC Class 51)


(e) Informal residential (SANLC Class 52)


(f) Informal residential (SANLC Class 53)


(g) Commercial (SANLC Class 65)


(h) Industrial (SANLC Class 66)

Figure 1.1 Examples of typical development in the study area

1.4 Objectives of the Study

In order to achieve the research aims, the following objectives were set:

(a) To improve understanding of the complexities of urban areas and urban hydrological processes in South Africa as a diverse and developing country, with a combination of formal development and large areas where development is unplanned and unregulated (informal).

(b) To investigate the influence of formal and informal South African development types on runoff, based on analysis of currently available long-term data.

(c) To identify the causes of different hydrological trends in catchments with different development types.

(d) To recommend a new approach to model runoff from ungauged South African urban catchments, using data from the stations selected for this study, by incorporating the improved understanding obtained in the previous objectives.

The aims were achieved through various separate studies, each set out in in a different chapter. The layout of the document, with a description of each study, is provided in the next section.

1.5 Layout of the Document

This thesis consists of the following chapters:

- Chapter 1 serves as an introduction to the report. The problem statement, scope, research aims and objectives are discussed.
- Chapter 2 provides a summary of the literature review undertaken to understand trends in urbanisation, the impacts of urbanisation on hydrological responses, and hydrological modelling in developing countries. Relevant literature is discussed in further detail in applicable chapters.
- Chapter 3 contains the first research paper incorporated into this thesis. The influence of catchment development on runoff is quantified for five South African urban catchments and three neighbouring undeveloped catchments. Correlation is tested between the total extent of the urban footprint (URB_{TOT}) and the ratios between rainfall and runoff (Q/P), baseflow and peak flow rates as a first assessment of the effect of urbanisation on runoff.

- Chapter 4 describes the methodology followed to quantify historical and current imperviousness in the study catchments, as well as typical imperviousness for different South African National Land Cover (SANLC) classes.
- Chapter 5 contains the second research paper incorporated into this thesis. This chapter explores the impacts of changing catchment imperviousness on storm runoff volume, catchment response time and peak flow rates.
- The third research paper is included in Chapter 6. The purpose of this chapter is to describe the methodology followed to derive methods for predicting connectivity of impervious areas for different SANLC classes.
- Chapter 7 contains the fourth research paper. This paper presents two case studies where gauged catchments are modelled using the Storm Water Management Model (SWMM) with continuous observed rainfall data. An improved approach is proposed to modelling runoff from formal urban development in South Africa.
- Discussion and conclusions made from previous chapters are presented with recommendations for future studies in Chapter 8.

In addition to the overall thesis objectives, each chapter also has specific objectives. The relevant study objectives dealt with in each chapter, as well as specific chapter objectives, are summarised in Table 1.1.

Table 1.1 Study objectives and specific chapter objectives summarised per chapter

Chapter No.	**Study Objectives**	**Chapter Objectives**
2	(a)	The objective of this chapter is to present a summary of the important aspects from the literature review to provide a basis for the objectives of subsequent chapters.
3	(b)	The objectives of this chapter are to investigate the effects of development on runoff responses, specifically: (i) runoff volumes, (ii) base flow volumes and (iii) flood peaks, in South African urban areas

Chapter No.	Study Objectives	Chapter Objectives
4	(a), (c)	The objectives of this chapter are to: (i) quantify historical and current total imperviousness percentages and impervious area density in selected study catchments; and (ii) determine if remote sensing could be used to generate typical estimates of imperviousness percentages for different South African National Land Cover (SANLC) classes
5	(b), (c)	The objectives of this chapter are to investigate whether a correlation exists between imperviousness associated with different types of formal and informal urban development and: (i) flood volumes, (ii) catchment response time and (iii) flood peaks. Correlation between flood peaks and (iv) flood volumes, as well as (v) catchment response times, were also evaluated.
6	(a), (c)	The objectives of this chapter are to: (i) measure impervious area connectivity to drainage systems for different urban South African Land Cover (SANLC) classes, and (ii) derive and test prediction equations from the measured data to estimate typical representative connectivity percentages of impervious area for use in hydrological modelling of urban areas in South Africa.
7	(d)	The specific objectives of this chapter are to: (i) determine the performance of a rainfall-runoff model that is applicable for use in South African urban areas with parameter values derived from literature; and (ii) propose an improved approach to model runoff from formally developed urban catchments in South Africa using the catchment attributes derived in Chapters 4 and 6 and knowledge gained in Chapters 3 and 5.

2 LITERATURE REVIEW

A literature review was undertaken to partly address objective (a) of this thesis, namely to improve understanding of the complexities of urban areas and hydrological processes in South Africa, a developing country with a diverse range of formal and informal urban developments. This chapter presents a summary of the important aspects from the literature review. Relevant literature is discussed in further detail in subsequent chapters and is not repeated here to prevent unnecessary repetition in this document. This chapter is divided into four sections. First, trends in global and South African urbanisation are discussed. The impacts of urbanisation on hydrological responses are reviewed, followed by a review of the modelling of heterogeneous urban catchments. The last section in this chapter provides a summary of important aspects in the literature that may be applicable in a South African context.

2.1 Trends in Urbanisation

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

It is reported that 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 (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 unplanned and disorganised manner (Gogate and Rawal, 2015).

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). 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 differing 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 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 (Shuster *et al.*, 2005; Jacobson, 2011; Braud *et al.*, 2013; Gumindoga *et al.*, 2014; Gogate and Rawal, 2015; Putro *et al.*, 2016; Todeschini, 2016; Gorani, 2019; Seidl *et al.*, 2020). These impacts include, amongst others: increased flood frequency, increased peak flow particularly for low-order floods (Aichele and Andresen, 2013), decreased base flow (Smakhtin, 2001; Shuster *et al.*, 2005; Jacobson, 2011; Braud *et al.*, 2013; Gogate and Rawal, 2015) 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 flood attenuation in the system. 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 (Chang, 2007; Semadeni-Davies *et al.*, 2008; Praskievicz and Chang, 2009). Some studies have attempted to quantify the effect of urban development on runoff, with results varying significantly. Salavati *et al.* (2016) found differences in mean annual flow of rural and neighbouring urban catchments ranging between -13% and 50%. Blum *et al.* (2020) estimate an increase of 3.3% in flood peak for each percentage point increase in catchment imperviousness. 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 2.1.

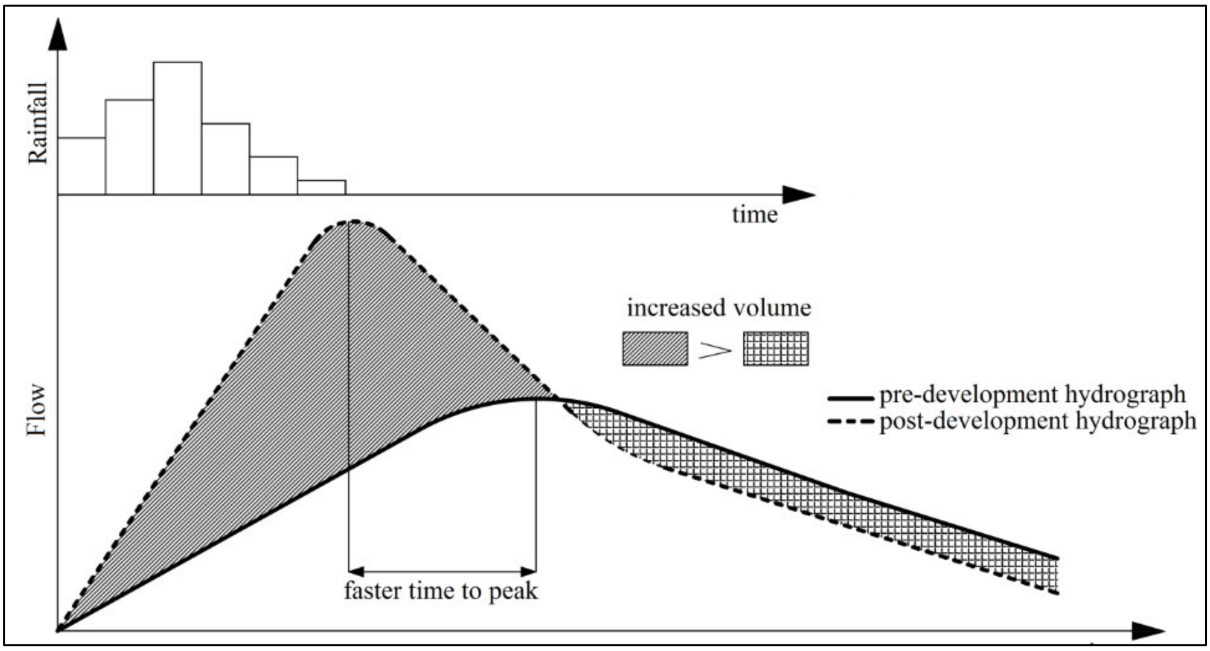


Figure 2.1 The perceived effect of urbanisation on runoff (Houghton-Carr, 1999)

However, some studies (Brun and Band, 2000; Chin and Gregory, 2001; Burns *et al.*, 2005; Aichele and Andresen, 2013; Fletcher *et al.*, 2013; Gallo *et al.*, 2013; Miller and Hess, 2017) suggest that not all aspects of storm water runoff are necessarily impacted by urban development as expected. The materials, and types of infrastructure used in some developments, as well as local topography and slope changes, could impact on the rate and flow pathways of storm water runoff (McGrane, 2016; Fidal and Kjeldsen, 2020). Van Vuuren (2012) noted that in many South African formal urban developments, solid security boundary walls are often constructed around properties, causing temporal storage in the system. In addition, inter-catchment transfers and wastewater flows, may also change the net impact on hydrological responses (Brandes *et al.*, 2005; Whitney *et al.*, 2015). 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).

Only a few studies on hydrological responses from urban areas have been conducted in developing countries, with very little information available on the impact of informal settlements on runoff (Parkinson *et al.*, 2007; Gogate and Rawal, 2015). Due to a lack of gauged catchments, studies in developing countries have generally relied on hydrological modelling with little to no data available for calibration (Parkinson *et al.*, 2007; Van Vuuren, 2012; Gumindoga *et al.*, 2014; Igulu and Mshiu, 2020; Dumedah *et al.*, 2021; Musonye *et al.*, 2022).

2.3 Modelling Urban Hydrological Responses

Hydrological modelling of heterogeneous urban catchments presents numerous challenges. Although the influence of impervious surfaces on runoff is relatively straightforward, the role of pervious areas within the urban environment is still not well understood (McGrane, 2016). In addition, there are significant variations in soil properties in South Africa, even on areas smaller than one hectare (Dippenaar *et al.*, 2014; Heymann, 2016; Dippenaar, 2019). This is compounded by the significant variation in the hydraulic conductivity of the soils, even for soils with similar classifications (Rawls *et al.*, 1983; Chow *et al.*, 1988; Heymann, 2016).

Landcover and soil properties are 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 catchment 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. Antecedent soil moisture conditions can also 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).

The Storm Water Management Model (SWMM) is one of the most widely used urban storm water models both internationally (Elliot and Trowsdale, 2007; Fletcher *et al.*, 2013; Arjenaki *et al.*, 2021; Dell *et al.*, 2021; Zeng *et al.*, 2021) and in South Africa (City of Cape Town Development Service, 2002; Barnard *et al.*, 2019). This semi-distributed model can be run as an event-based or a continuous runoff quantity and quality model (Fletcher *et al.*, 2013). Time steps of between 1 minute and a number of days can be used, depending on the application and desired detail of the model (Rossman and Huber, 2016). The Green-Ampt model, Horton model or Curve Numbers can be used to account for losses due to infiltration. Routing can be simulated using steady wave routing, kinematic wave routing or dynamic wave routing (Bisht *et al.*, 2016). In addition to its wide range of uses, the SWMM engine is open source software and therefore widely accessible (Elliot and Trowsdale, 2007), with a number of companies having built modelling software that offer sophisticated user interfaces around the SWMM engine.

As with many other models currently used for urban hydrological modelling, the SWMM requires 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 (Sahoo and Sreeja, 2016).

2.4 Chapter Summary

It is clear from the literature that the urban population is growing both globally and in South Africa. Many studies have been conducted to assess the impact of urban development on hydrological responses. Most have found increasing runoff volumes, increasing flood peaks, decreasing catchment response time and decreasing base flows with increasing urban development.

However, some studies suggest that not all aspects of storm water runoff are necessarily impacted by urban development as expected. To date, only a few studies have been conducted in developing countries, with little information available on the impact of informal settlements on runoff. Therefore, the need to improve the understanding of hydrological processes in the full range of South African urban environments is evident.

Due to a lack of gauged catchments in developing countries, most of the studies in these countries have relied on hydrological modelling with little to no calibration data. Hydrological modelling of heterogeneous urban catchments presents numerous challenges. The SWMM is a semi-distributed rainfall-runoff model with the capability of modelling spatially varied land cover and precipitation, with hydraulic routing incorporated into the model. As with many other models currently used for urban hydrological modelling, the SWMM requires a significant amount of input data. This data is not always available, especially for informal settlements in developing countries. There is thus a need to quantify the important hydrological parameters for the catchments used in this study and to develop an improved approach to hydrological modelling in South African urban areas.

3 QUANTIFYING THE INFLUENCE OF URBAN DEVELOPMENT ON RUNOFF IN SOUTH AFRICA

The first aim of this thesis is to gain new understanding of hydrological processes in the diverse range of South African urban environments. Objective (b) to achieve this aim is to quantify the influence of formal and informal South African development types on runoff. This chapter presents the quantification of the effects of the extent of urban development (URB_{TOT}) on: (a) runoff volumes, (b) base flow volumes and (c) flood peaks in catchments with typical urban development types found in South Africa. As a first analysis on the impacts of urbanisation on hydrological responses, the study presented in this chapter considers the extent of urban development, rather than imperviousness per se.

3.1 Authorship Statement

Status	Published in the Urban Water Journal
Details	Loots, I., Smithers, J.C., Kjeldsen, T.R. 2022. Quantifying the influence of urban development on runoff in South Africa. *Urban Water Journal*, pp. 1-14. https://doi.org/10.1080/1573062X.2022.2027472.
Authors' contribution	The author of this thesis was is the primary author of this original research paper. I Loots contributed to the formulation of the research question (80%), design of the methodology (80%), processing and analysis of data (95%) and manuscript preparation (90%). J.C. Smithers contributed to the formulation of the research question (20%), design of the methodology (10%) and manuscript preparation (5%). T.R. Kjeldsen contributed to the design of the methodology (10%) and manuscript preparation (5%). A. Joubert assisted with processing of data (5%). She was not listed as an author, but thanked as a contributor.
Purpose	This paper presents original research contributing to achievement of the first aim of this thesis.

3.2 Abstract

It is widely accepted that urban development results in larger flood peak discharges with faster catchment response times, larger total runoff volumes and lower base flow volumes compared to non-urbanised catchments. However, these effects have not previously been studied in the context of the specific characteristics of fast-growing urban areas in developing countries, which are generally unregulated. This study quantifies the effects of urban development on runoff, including: (a) runoff volumes, (b) base flow volumes and (c) flood peaks from eight South African catchments using the Mann-Kendall test and Kendall's τ. Both total runoff and base flow volumes are found to increase with increased development levels and possible reasons for this are discussed. Analysis of flood peaks shows statistically insignificant trends in most catchments. However, there is an increasing trend in the catchment with the highest proportion of informal development. Recommendations are made for further investigation into reasons for the findings.

3.3 Introduction

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). South Africa as a developing country is experiencing an especially high rate of increase in urban migration (UNDP, 2019; StatsSA, 2020) as people migrate to urban areas in search of employment and better service delivery (Geyer *et al.*, 2012). This has led to significant development of both formal and informal settlements on the outskirts of cities. Thompson (2019) reported a 30% increase in total urban footprint at a national scale between 1990 and 2018.

The development associated with urbanisation could lead to significant impacts on hydrological responses of catchments. These responses need to be understood in order to implement sustainable water solutions. Although traditional urban drainage systems were designed with focus on design flood peaks, flood volumes, base flow volumes and catchment response times are required for the planning and design of all urban drainage systems (Marvin, 2018; Valizadeh *et al.*, 2019; Ghodsi *et al.*, 2020). This is especially applicable in a water-scarce country like South Africa, where proper planning and Water Sensitive Urban Design (WSUD) could provide opportunities to augment water supply to rapidly increasing urban populations (Fletcher *et al.*, 2013; Fisher-Jeffes *et al.*, 2017).

Since Leopold (1968) first found up to a 10-fold increase in mean annual peak floods with urban development, it has become widely accepted that urban development can result in significant changes to the hydrological response from a catchment (Shuster *et al.*, 2005; Jacobson, 2011; Braud *et al.*, 2013; Gumindoga *et al.*, 2014; Gogate and Rawal, 2015; Putro *et al.*, 2016; Todeschini, 2016; Gorani, 2019; Seidl *et al.*, 2020). Beighley and Moglen (2003) found changes ranging from 0 – 47% for the 100-year peak flow rate. Hejazi and Markus (2009) found flood peak increases ranging from 17 – 196%. Salavati *et al.* (2016) found differences in mean annual flow of rural and neighbouring urban catchments ranging between -13% and 50%. Blum *et al.* (2020) estimate an increase of 3.3% in flood peak for each percentage point increase in catchment imperviousness. 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. In addition, the flow paths and velocities are altered, as runoff is generally collected by pipe networks and conveyed rapidly to streams. This combination is expected to result not only in larger and faster flood peak responses, but also smaller base flows and less groundwater recharge (Chang, 2007; Semadeni-Davies *et al.*, 2008; Praskievicz and Chang, 2009). The accepted impacts of urban development on runoff include, amongst others: increased flood frequency, increased peak flow and total flow volume, particularly for low-order floods (Aichele and Andresen, 2013), decreased base flow (Smakhtin, 2001; Shuster *et al.*, 2005; Jacobson, 2011; Braud *et al.*, 2013; Gogate and Rawal, 2015) and decreased catchment response time (Chang, 2007; USEPA, 2008; Gallo *et al.*, 2013; Choi *et al.*, 2015).

However, some studies (Brun and Band, 2000; Chin and Gregory, 2001; Burns *et al.*, 2005; Aichele and Andresen, 2013; Fletcher *et al.*, 2013; Gallo *et al.*, 2013; Miller and Hess, 2017) suggest that not all aspects of storm water runoff are necessarily impacted by urban development as expected. The materials, and types of infrastructure used in some developments, as well as local topography and slope changes, could impact on the rate and flow pathways of storm water runoff (McGrane, 2016; Fidal and Kjeldsen, 2020).

A number of typical urban development characteristics found in developing countries could potentially cause different runoff responses to those expected in developed countries. The possibility of retention and attenuation in urban systems due to property boundary walls and/or the levelling of naturally sloping areas, combined with the potential effects of long-term blockages and poor maintenance of constructed water drainage and reticulation systems, which are typical in formal settlements in many developing countries, could substantially influence these parameters. In addition, the possible effects of informal settlements on runoff are not yet properly understood (Parkinson *et al.*, 2007; Capps *et al.*, 2016; Fell, 2017) and could prove to differ from the effects of more formal urban settlements, since the impermeable areas in these settlements are generally not connected to drainage systems (Parkinson *et al.*, 2007; Sakijege, 2013; Gogate and Rawal, 2015). The influence of development on drainage paths is closely linked to the influence of directly connected impervious areas (Lee and Heaney, 2003; Roy and Shuster, 2009; Yao *et al.*, 2015; Redfern *et al.*, 2016; Miller *et al.*, 2020). However, drainage paths will not always be made more efficient by development, with various factors potentially causing flood attenuation 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.

There is therefore a need to quantify the effects of urban development on flow, including: (a) runoff volumes, (b) base flow volumes and (c) flood peaks in catchments with typical urban development types found in South African to facilitate applicable sustainable urban water design. This study investigates the effects using five gauged urban catchment areas in the City of Tshwane, South Africa, as a pilot study, with three neighbouring gauged rural catchments included to confirm whether changes in runoff characteristics can be attributed to urban growth. The Mann-Kendall test and Kendall's τ are used to assess the statistical significance of temporal trends in selected runoff characteristics, in particular correlation between increasing urban development and: (a) runoff volumes, (b) base flow volumes and 9c) flood peak magnitude.

3.4 Site Selection and Data Collation

As the objectives of this study are to investigate the effects of development on runoff responses, specifically: (a) runoff volumes, (b) base flow volumes and (c) flood peaks, in South African urban areas, gauged urban catchments with good quality long term data were identified and compared with neighbouring gauged catchments in undeveloped areas.

3.4.1 Study areas

Five gauged catchments monitored by the Department of Water and Sanitation (DWS) (Catchments A2H027, A2H029, A2H054, A2H055, A2H063) with reliable flow records and at least 15% developed urban area, as a percentage of total catchment area ($URB_{TOT\%}$) as of 2018 were selected for use in this study. All five catchments are located within the City of Tshwane Metropolitan Municipality (CoT), South Africa (Figure 3.1). Hydrological data from an additional three neighbouring gauged catchments (Catchments A2H030, B2H004, B2H007) which had less than 5% developed urban area as of 2018 were included in the study. The contrasting results from the urban and less developed catchments were used to determine whether trends in hydrological responses found in the urban catchment areas could be related to increasing developed urban area. Table 3.1 provides a summary of the eight study area catchments.

Table 3.1 Study area information

DWS Gauging Station	River	Area (km^2)	Slope (m/m)	Longest River (km)	Start of Record (mm/yyyy)	End of Record (mm/yyyy)	Record Length (years)
A2H027	Pienaars River	357	0.011	39	05/1962	05/2021	59
A2H029	Edendale Spruit	129	0.012	24	05/1962	06/2019	57
A2H030[a]	Roodeplaat Spruit	116	0.013	23	05/1962	06/2018	56
A2H054	Hartbees Spruit	35	0.011	14	09/1982	05/2021	39
A2H055	Moretele River	106	0.011	20	10/1982	06/2018	36
A2H063	Wonderboom Spruit	30	0.009	6	05/1984	07/2018	34
B2H004[a]	Osspruit	123	0.012	15	10/1984	05/2021	37
B2H007[a]	Koffiespruit	317	0.006	25	05/1985	05/2021	36

[a]Rural catchments

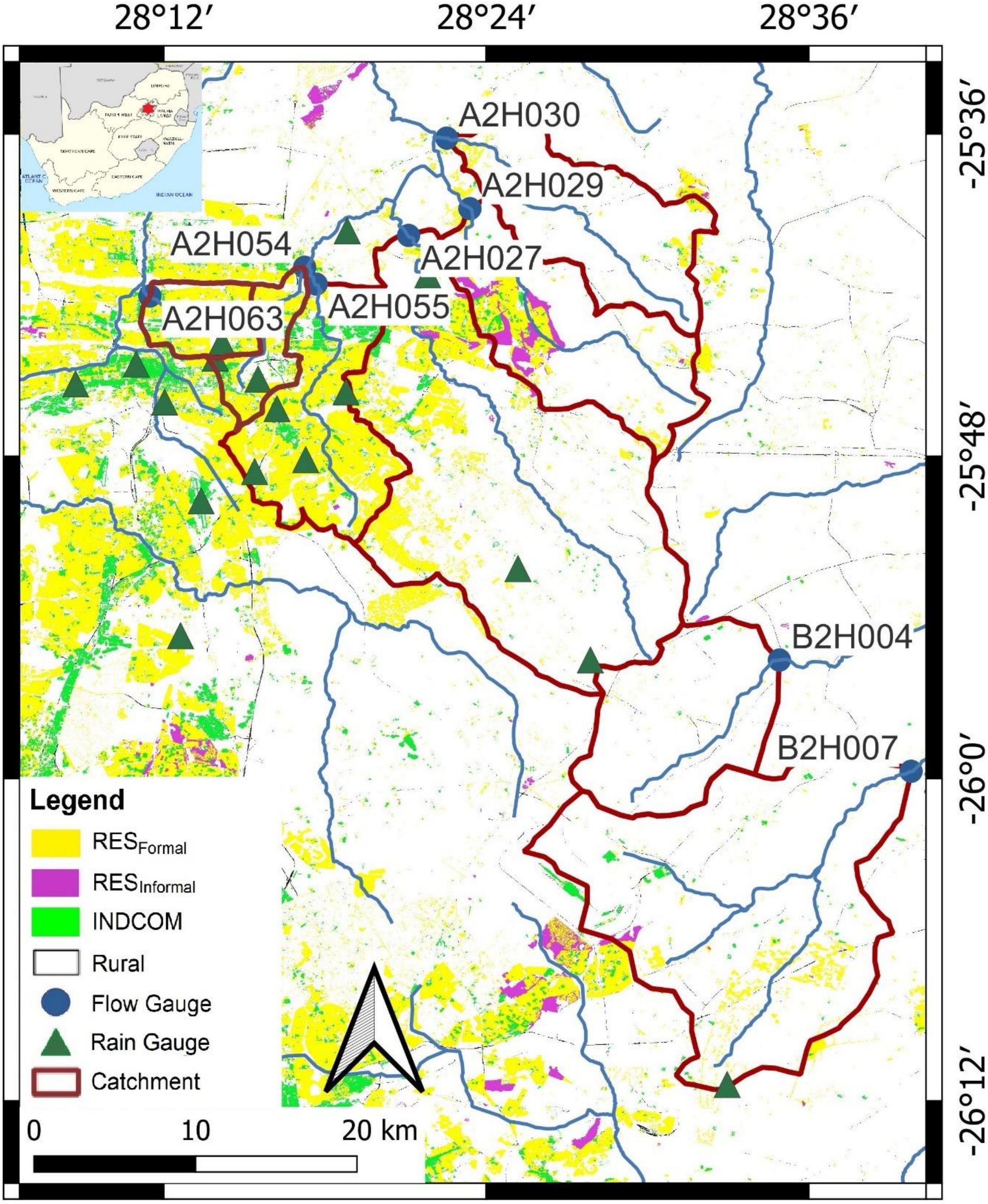


Figure 3.1 Locations of the study areas, including catchment boundaries and urban land-use classifications

3.4.2 Land use data

A series of historical land use data was extracted from applicable sources for all the catchments. Topographical maps with a scale of 1:50 000 were used to delineate the extent of development for the years 1965 or 1969, as well as 1975, 1995 and 2001 (Surveyor General, 1965, 1969, 1975, 1979, 1995, 2001). The South African National Land Cover (SANLC) data sets were used for the identification of urban areas in 1990 (Geoterraimage, 2015b), 2013 (Geoterraimage, 2015a) and 2018 (Geoterraimage, 2019). The 1990 and 2013 SANLC data sets contain 72 land use classes and the 2018 set contains 73 classes. All formal residential, industrial and commercial land classes, as well as roads, were classified as formal urban areas (URB_{Formal}). All informal residential and village classes were classified as informal urban areas ($URB_{Informal}$). All natural, agricultural and mining land uses were considered as rural area (RURAL). Since smallholdings are expected to have similar runoff characteristics to rural areas these areas were considered RURAL for the purposes of this study. URB_{Formal} and $URB_{Informal}$ were combined to calculate the total extent of urban development (URB_{TOT}). The topographical maps do not differentiate between different land uses, but do indicate areas with urban development, industrial buildings, and buildings in rural areas. URB_{Formal} and $URB_{Informal}$ were differentiated with reference to aerial photographs obtained from National Geo-spatial Information (NGI). All urban and industrial areas were measured to estimate the URB_{TOT} of each catchment for each available map. Linear interpolation was applied to estimate URB_{TOT} for periods between map dates. Where discrepancies were found between the topographical maps, SANLC data and photographs, the photographs took precedence. The URB_{Formal}, $URB_{Informal}$ and RURAL area, as percentages of each catchment for each available historical data set, are summarised in Table 3.2.

3.4.3 Observed records of rainfall and runoff

Observed and infilled daily rainfall depths from 1903 and up to August 2000 for 17 stations in or around the study catchment areas were extracted from the database collated by Lynch (Lynch, 2003). Rainfall data for the remainder of the study period was obtained from the South African Weather Service (SAWS). The locations of the rainfall stations in and around Tshwane are shown in Figure 3.1. Annual rainfall statistics were calculated for each station showing that all the stations have median annual precipitation values ranging between 650 mm and 750 mm, with similar upper and lower quartile values, but with inter-annual variability in annual rainfall totals observed across all stations. Apparent inconsistencies in the data were checked. Since no data flags were indicated at any of the outliers, the data was accepted as correct. The median, lower and upper quartiles, as well as 5^{th} and 95^{th} percentile values are indicated in Figure 3.2.

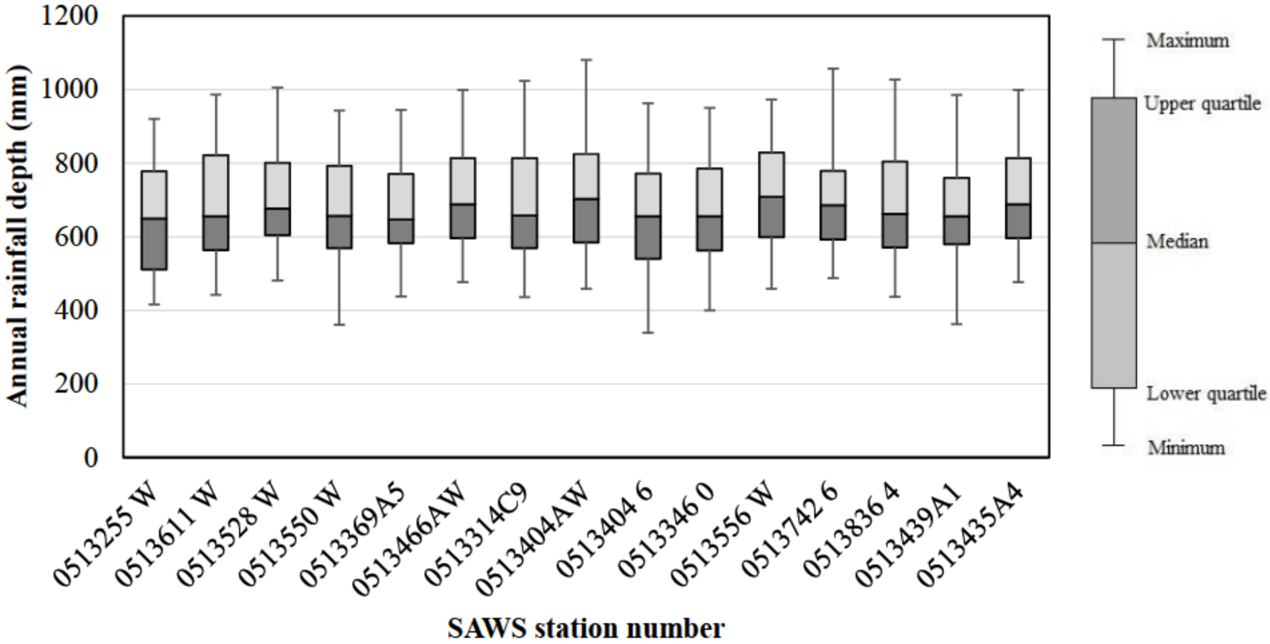


Figure 3.2 Annual total rainfall depths from 1960 to 2020

Table 3.2 Temporal evolution of $URB_{TOT\%}$ for each of the eight test catchments

DWS Station Number	1960			1979			1990			1995		
	URB_{Formal} (%)	$URB_{Informal}$ (%)	RURAL (%)	URB_{Formal} (%)	$URB_{Informal}$ (%)	RURAL (%)	URB_{Formal} (%)	$URB_{Informal}$ (%)	RURAL (%)	URB_{Formal} (%)	$URB_{Informal}$ (%)	RURAL (%)
A2H027	0.0	1.6	98.4	1.5	1.5	97.0	3.4	0.1	96.5	3.5	0.1	96.4
A2H029	0.0	0.0	100.0	0.0	0.0	100.0	1.5	0.7	97.8	0.0	2.8	97.2
A2H030[a]	1.7	0.0	98.3	1.7	0.0	98.3	1.7	0.0	98.3	1.7	0.0	98.3
A2H054	27.1	0.0	72.9	39.6	0.0	60.4	41.0	0.0	59.0	41.6	0.0	58.4
A2H055	20.3	0.0	79.7	28.0	0.0	72.0	39.8	0.0	60.2	45.1	0.0	54.9
A2H063	66.5	0.0	33.5	68.7	0.0	31.3	69.6	0.0	30.4	70.0	0.0	30.0
B2H004[a]	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0
B2H007[a]	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.1	0.0	99.9

DWS Station Number	2001			2013			2018		
	URB_{Formal} (%)	$URB_{Informal}$ (%)	RURAL (%)	URB_{Formal} (%)	$URB_{Informal}$ (%)	RURAL (%)	URB_{Formal} (%)	$URB_{Informal}$ (%)	RURAL (%)
A2H027	5.0	0.1	94.9	10.0	0.7	88.5	12.9	3.3	83.8
A2H029	0.0	7.7	92.3	3.9	9.3	86.7	11.3	8.6	80.1
A2H030[a]	1.7	0.0	98.3	3.5	0.0	96.5	3.5	0.0	96.5
A2H054	44.3	0.0	55.7	62.3	0.0	37.7	62.5	0.0	37.5
A2H055	54.2	0.0	45.8	66.9	0.0	33.1	70.6	0.0	29.4
A2H063	71.0	0.0	29.0	71.1	0.0	28.9	71.2	0.0	78.8
B2H004[a]	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0
B2H007[a]	0.1	0.0	99.9	0.2	0.3	99.5	0.2	0.3	99.5

[a]Rural catchments

Daily and monthly catchment rainfall for each catchment were estimated from the gauged data using Thiessen polygons. Since the rainfall stations used in this study have similar median annual precipitation, and since there are no major topographical or meteorological differences between different sections of any catchments in the study area, this widely-used method to estimate catchment rainfall from gauged values for urban hydrological studies (Blume *et al.*, 2007; Miller and Hess, 2017) was deemed acceptable.

The available instantaneous flow data for each catchment was obtained from DWS for each station. Prior to December 2003 the stations recorded water levels at intervals determined by relative water levels between measurements. The loggers recorded every 15 minutes during periods when changes in river stage were detected, and did not record when the stage levels were not changing. Post December 2003 the stations recorded water levels at intervals determined by relative water levels between measurements, but at an average of 20-minute time intervals. Periods of missing flow data were manually inspected and infilled using representative base flow for the relevant period if no rain was measured. Any gaps in the flow data during periods with rainfall were removed, both from the flow and rainfall datasets and not included in the analyses. The annual runoff per area, divided by representative rainfall depth for one urban catchment (Catchment A2H054) and one rural catchment (Catchment B2H004) are shown in Figure 3.3 as illustration. Visual inspection of the representative curves over the study period shows generally higher relative flow rates in the urban catchment than rural catchment. Visual inspection of the other six catchments shows similar trends. Since the trends could not be quantified through visual inspection alone, changes in: a) runoff volumes, b) base flow volumes and c) flood peaks needed to be analysed statistically. Statistical trend analysis and results are described in the following section.

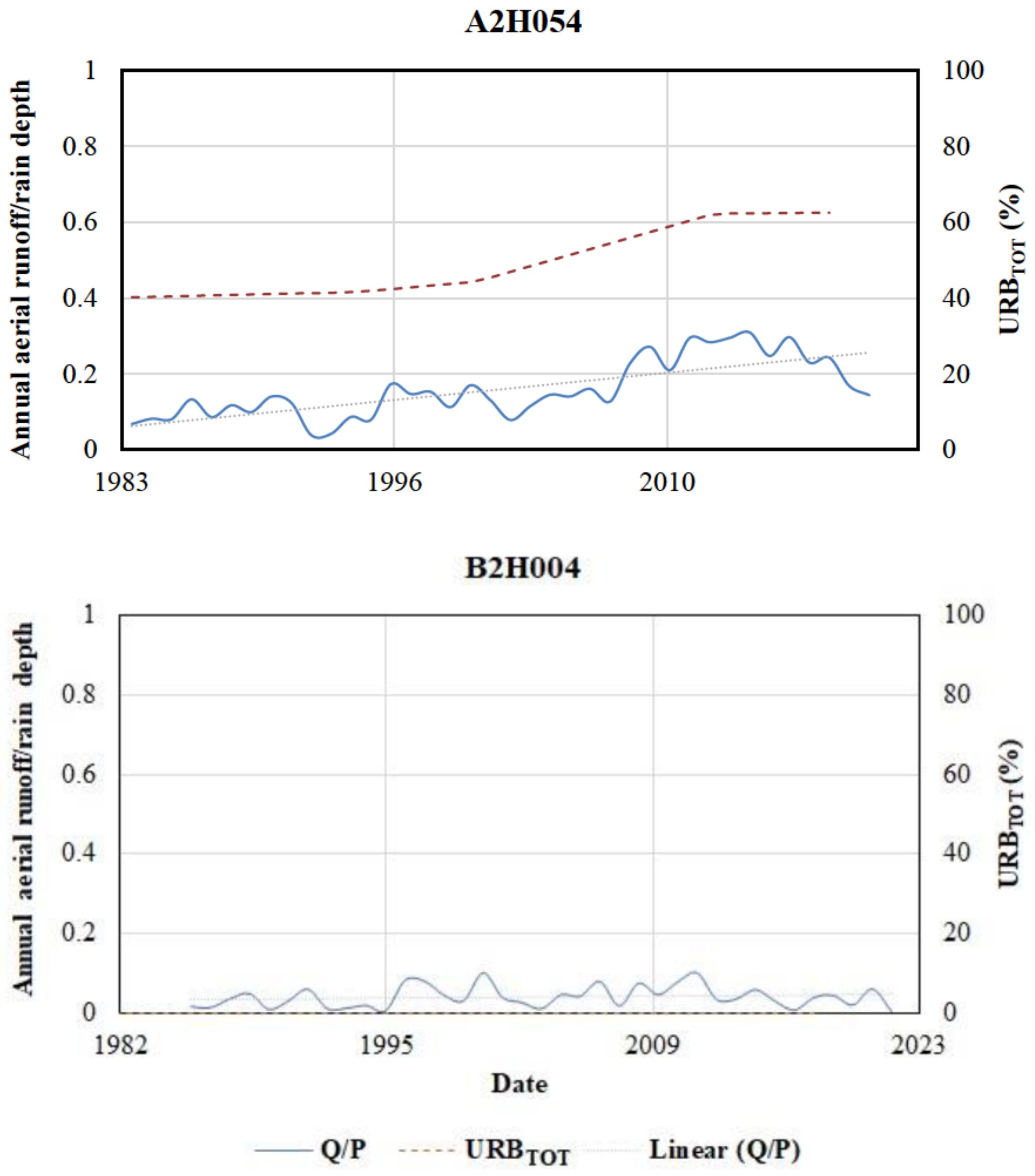


Figure 3.3 Examples of annual runoff volume per area, divided by representative rainfall depth for (a) Catchment A2H054 and (b) Catchment B2H004

3.5 Trend Analysis and Results

Firstly, the statistical significance of temporal trends in rainfall data needed to be assessed in order to establish if climatological non-stationarity could influence trends in the runoff responses. Next, the statistical significance of temporal trends in: a) runoff volumes, b) base flow volumes, and c) flood peak magnitude were investigated. The widely used non-parametric Mann-Kendall test (Brandes *et al.*, 2005; Gocic and Trajkovic, 2013; Ahmad *et al.*, 2015; Coch and Mediero, 2015; Requena *et al.*, 2017; Atif *et al.*, 2018; Coen *et al.*, 2020) was used to test a null-hypothesis of no association between two variables. In this study the co-evolution of time and the selected runoff characteristics were studied. Correlation between $URB_{TOT\%}$ and a) runoff volumes, b) base flow volumes and c) flood peaks was also assessed using Kendall's τ, with the magnitude of the Kendall τ-value between 0 and 1 giving an indication of the monotonic association between the two variables, with higher values indicating stronger association (Gocic and Trajkovic, 2013; Helsel *et al.*, 2020; Pohlert, 2020). Although most publications do not provide specific ranges for the strength of association of the Kendall τ-value, (Van den Berg, 2020)The magnitude of the Kendall τ-value is usually in the order of 0.7 to 0.8 times the Spearman ρ-value (Helsel *et al.*, 2020; Van den Berg, 2020). Van den Berg (2020) proposed a τ-value of 0.07 to indicate a weak association, 0.21 a medium association and 0.35 a strong association. The sign of the τ-value is in indication of positive or negative correlation (Helsel *et al.*, 2020). The statistical significance was assessed at the 95% confidence level, therefore, any p-value smaller than 0.05 would indicate statistical significance. Where results were significant at the 1% confidence level, this was also reported.

3.5.1 Stationarity of rainfall data

Since non-stationarity of rainfall data could influence runoff responses, the possible existence of temporal trends in daily, monthly and annual rainfall were analysed using the Man-Kendall test. The daily rainfall depth analysis was performed using the Annual Maximum Series (AMS). Time series of both the annual maximum daily rainfall depth and annual rainfall depth analysis were run considering the South African hydrological year that runs from October to September. The monthly rainfall depth analysis was performed using a seasonal Mann-Kendall test with a 12-month period in order to account for seasonality (Hirsch and Slack, 1984; Helsel *et al.*, 2020). In this test, monthly seasons were applied in order to compare January data only with January, etc. (Helsel *et al.*, 2020).

The results in Table 3.3 show that a significant trend was detected in one of the 17 stations at the 5% ($p<0.05$) significance level at a daily scale and for two stations at the 1% ($p<0.01$) significance level. Of the three stations with statistically significant trends, Stations 0477071 3 and 0477494 W showed the strongest association. Both these stations are in the southern region of the study area and were only used in the analysis for Catchment B2H007. Therefore, all subsequent analysis of Catchment B2H007 had to consider the increasing trend of extreme daily rainfall in this catchment. Considering the monthly analysis, four stations showed trends at the 5% significance level and one station at the 1% significance level. All five stations with statistically significant trends at a monthly scale showed decreasing trends. The low Kendall τ-values at a monthly scale indicates weak association due to significant variability of the rainfall data. Only two stations showed statistically significant increasing trends at the 5% significance level at an annual aggregation. The relatively low Kendall τ-values for these stations are indicative of relatively weak trends, despite being statistically significant (Helsel *et al.*, 2020; Van den Berg, 2020). Therefore, the notion of non-stationarity of rainfall data was disregarded in further trend analysis, for all catchments with the exception for Catchment B2H007, where non-stationarity of extreme daily rainfall could not be excluded.

Table 3.3 Rainfall depth statistical test results

Station	**τ for Monthly Rainfall Depth**	**τ for Annual Rainfall Depth**
0513255 W	0.003	0.174*
0513611 W	-0.073**	0.028
0513528 W	-0.014	0.117
0513550 W	-0.057*	-0.002
0513369 A 5	-0.051*	0.043
0513466 A W	-0.030	0.095
0513314 C 9	-0.048	0.023
0513404 A W	-0.008	0.114
0513404 6	-0.036	-0.012
0513346 0	-0.031	0.035
0513556 W	-0.010	0.129
0513742 6	-0.056*	-0.078
0513836 4	0.011	0.046
0513439 A 1	-0.060*	-0.013
0513435 A 4	-0.030	0.095
0477071 3	0.037	0.209*
0477494 W	-0.025	0.090

*Statistically significant trend at the 5% significance level

**Statistically significant trend at the 1% significance level

3.5.2 Flow volumes

Two approaches were followed to meet Objective (a) of this paper. Firstly, ratios between runoff and rainfall (Q/P) were estimated by comparing the cumulative total annual runoff volumes with the estimated cumulative annual representative catchment rainfall volumes to obtain annual Q_{sum}/P_{sum} ratio values, as percentages. The annual Q_{sum}/P_{sum} percentages were compared with $URB_{TOT\%}$ in the same year, for each year in the study period, and it was confirmed that catchments with lower $URB_{TOT\%}$ tend to have lower Q_{sum}/P_{sum} percentages, as shown in Figure 3.4.

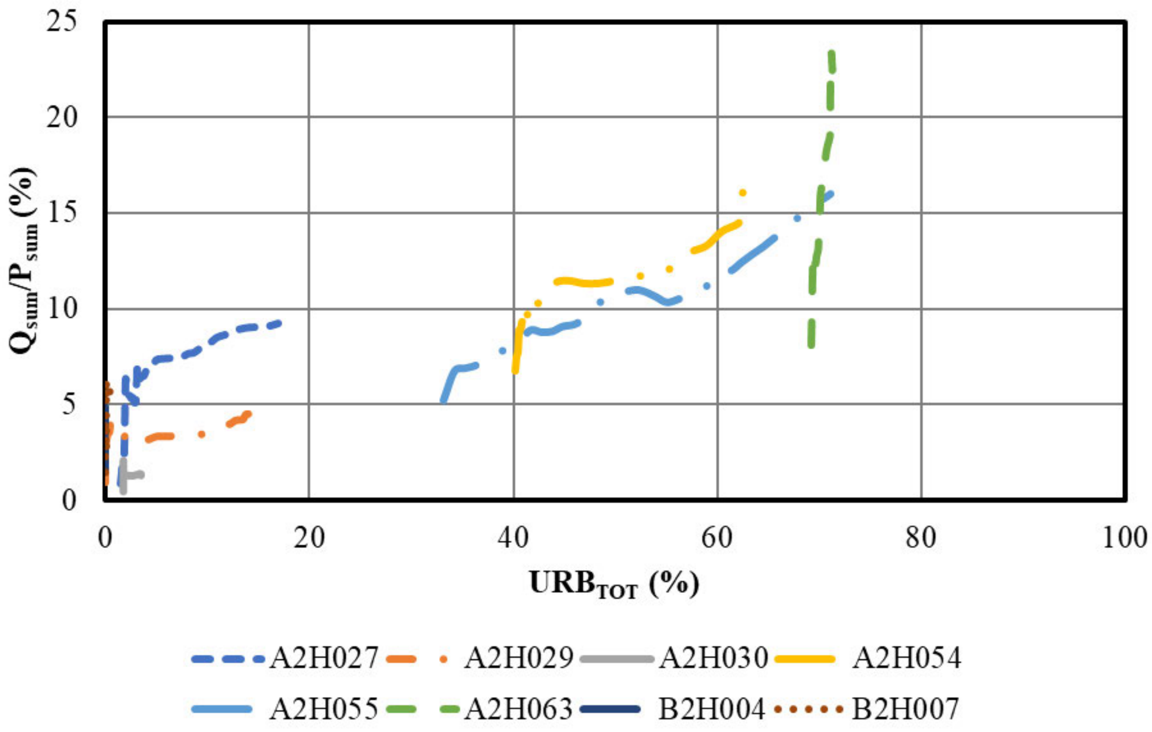


Figure 3.4 The relationship between cumulative annual Q/P and $URB_{TOT\%}$ for each of the eight test catchments

For the second part of the Q/P analysis, the significance of trends in annual Q/P with time and with $URB_{TOT\%}$ were assessed (Table 3.4). This was achieved through comparison of total annual runoff volumes with the estimated annual representative catchment rainfall volumes. The annual Q/P ratios shown in Figure 3.5 depict the influence of catchment development on flow volume. With p-values significantly lower than 0.01 for most of the urban catchments, the results in Table 3.4 show that strong trends exist in the temporal Q/P ratios as well as the $URB_{TOT\%}$ Q/P ratios for the urban catchments. The high Kendall's τ-values for Catchments

A2H027, A2H054 and A2H055 are indicative of particularly strong association. None of the undeveloped catchments showed statistically significant results, with Catchment A2H030 indicating a negative trend (Figure 3.5). This analysis indicates an increase in total flow volumes follows from an increase in urbanisation.

Table 3.4 τ values for trends in annual Q/P ratios over time and with $URB_{TOT\%}$

DWS Gauging Station	**Annual Q/P τ**	
	Temporal	**$URB_{TOT\%}$**
A2H027	0.592**	0.586**
A2H029	0.307**	0.342**
A2H030[a]	-0.001	0.098
A2H054	0.556**	0.603**
A2H055	0.670**	0.717**
A2H063	0.276*	0.383**
B2H004[a]	0.084	-
B2H007[a]	0.042	0.059

[a]Rural catchment

*Statistically significant trend at the 5% significance level

**Statistically significant trend at the 1% significance level

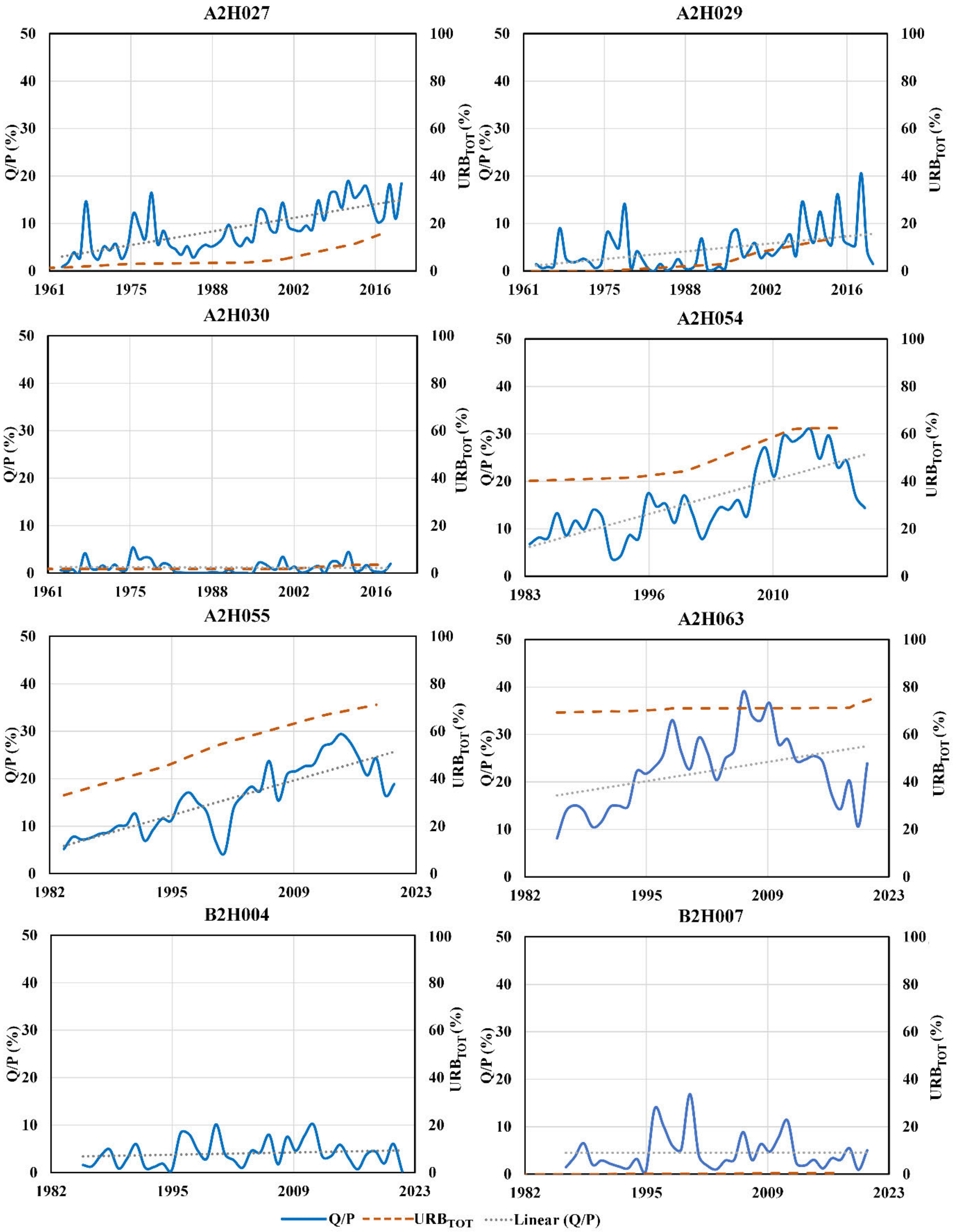


Figure 3.5 Co-evolution of annual Q/P and $URB_{TOT\%}$ over time for each of the eight test catchments

3.5.3 Base flow volumes

For Objective (b) of this paper, trends in base flow were studied for the eight catchment areas. Various methods could be used to separate the surface runoff and base flow in the primary flow data (Lyne and Hollick, 1979; Arnold *et al.*, 1995; Chapman, 1999; Smakhtin, 2001; Gericke and Smithers, 2017). For the purposes of this study, the base flow was separated from the instantaneous flow data and extracted at 30-minute intervals using the HYBASE application in the HYDSTRA/TS data management system developed by KISTERS (Pty) Ltd (formerly Hydsys (Pty) Ltd, Hydstra (Pty) Ltd). This tool applies recursive digital filtering as first proposed by Lyne and Hollick (1979). This methodology was also adopted for other studies in South Africa (Smakhtin and Watkins, 1997; Hughes *et al.*, 2003; Gericke and Smithers, 2017). Smakhtin and Watkins (1997) established that α-parameters of between 0.995 and 0.997 were applicable for most catchments in South Africa and Hughes *et al.* (2003) found a β-parameter of 0.5 to be acceptable. Gericke and Smithers (2017) found that catchments with sub-daily flow measurements produced better results when an α-parameter 0.997 was applied. Since all the data sets for this study had sub-daily measurements from 2003, a fixed α-parameter of 0.997 and β-parameter of 0.5 was used to separate the base flow from the primary flow time series. It is important to note that the base flow separation did not consider catchment response to precipitation directly, but considered all base flow at the catchment outlet.

In order to compare results, the base flow rates are shown in Figure 3.6 as a percentage of the 1-year recurrence interval event estimated as the median of the annual maximum series (AMS). From this figure it is clear that the three catchments with the highest $URB_{TOT\%}$ (Catchments A2H054, A2H055 and A2H063) have the lowest base flows relative to the AMS. Increasing trends are visible in Catchments A2H027 and A2H029 at this scale.

The Mann-Kendall tests for base flow were done by comparing annual base flow volumes, calculated by summing the 30-minute interval extracted base flow data over a hydrological year, with time and with increased $URB_{TOT\%}$. The results showed statistically significant trends at the 1% significance level for four of the urban catchments (Catchments A2H027, A2H029, A2H054 and A2H055), and at the 5% significance level for the catchment with the highest $URB_{TOT\%}$ (Catchment A2H063). The Kendall τ-values indicated the strongest association for Catchments A2H027 and A2H055 (Table 3.5).

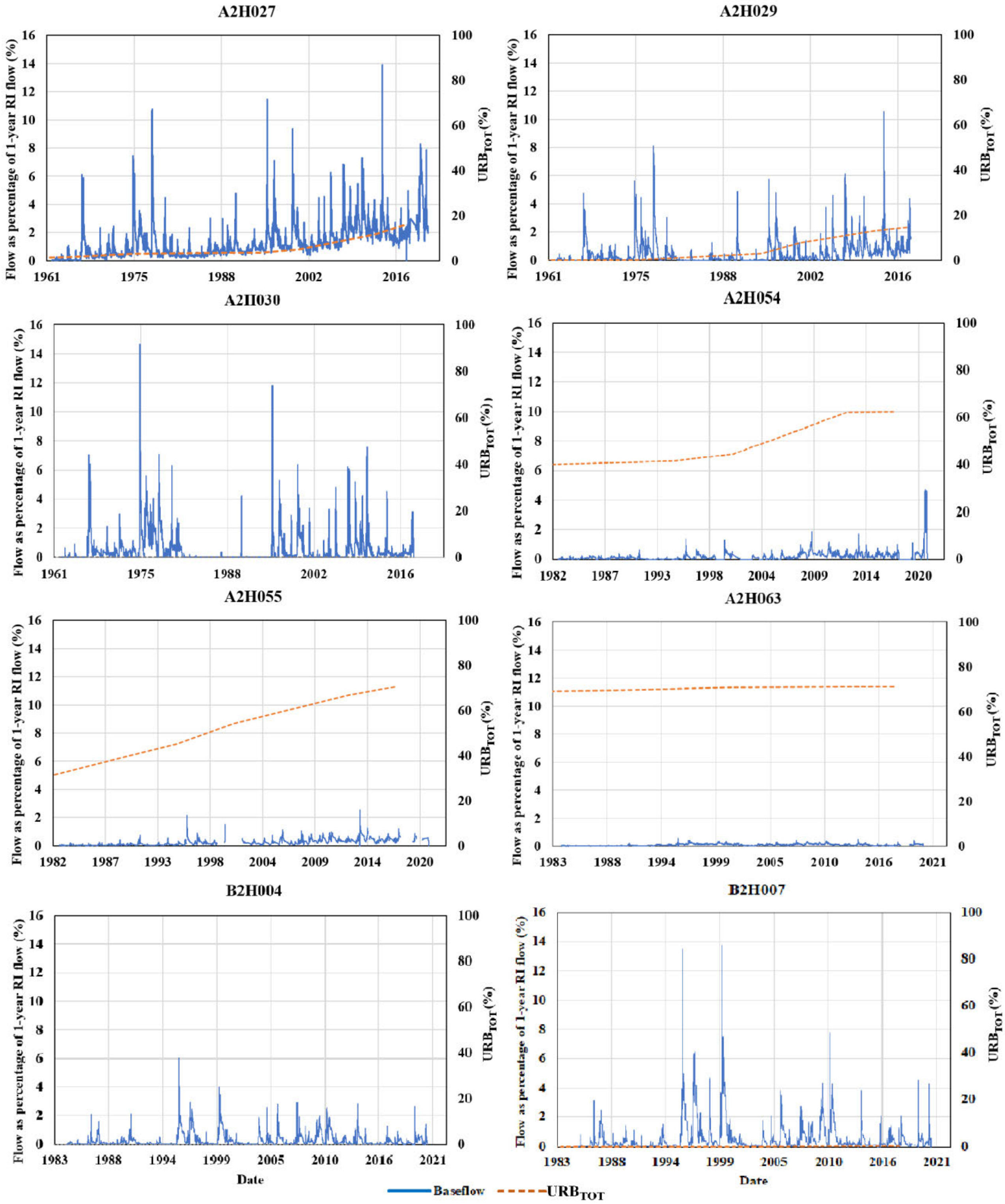


Figure 3.6 Trends in observed base flow rates expressed as percentage of the 1-year RI flood peak

Table 3.5 Statistical test results for base flow

DWS Gauging Station	Temporal τ	$URB_{TOT\%}$ τ
A2H027	0.601**	0.575**
A2H029	0.274**	0.273**
A2H030[a]	0.035	0.141
A2H054	0.380**	0.454**
A2H055	0.562**	0.715**
A2H063	0.257*	0.319*
B2H004[a]	0.137	-
B2H007[a]	0.076	0.098

[a]Rural catchment

*Statistically significant trend at the 5% significance level

**Statistically significant trend at the 1% significance level

3.5.4 Flood peaks

For Objective (c) of this paper, the flood peaks were assessed in two ways: i) for the AMS and ii) for all flood peak points in the instantaneous flow data above the 1-year recurrence interval threshold, estimated as the median of the AMS, or Point over Threshold (PoT). The trend over time in the data for each catchment was compared using the Mann-Kendall test. In addition, the trends in peak discharge with increasing $URB_{TOT\%}$ was assessed. The three catchments with longer data sets (Catchments A2H027, A2H029 and A2H030) experienced a number of high peaks before 1982. This influenced the results of both sets of analysis, but especially the PoT analysis. Therefore, both sets of analysis were run twice: first with flood peaks for the entire record period included, and then with only flood peaks after 1982. The second analysis was run in order to compare the results from these three stations with similar record periods at the other five stations. The AMS is shown as a percentage of the 1-year recurrence interval flood peak for each catchment in Figure 3.7, with linear regression curves shown to identify trends. Of significance are the slopes of the AMS linear regression curves for Catchment A2H029, at 0.010 when considering the entire data period and 0.023 when considering the data set from 1982; and Catchment A2H063 with dataset starting in 1985, at 0.004. The slope of the PoT linear regression curves for Catchment A2H027, at -0.013 considering the entire data period and -0.009 for the data set from 1982, are also noteworthy.

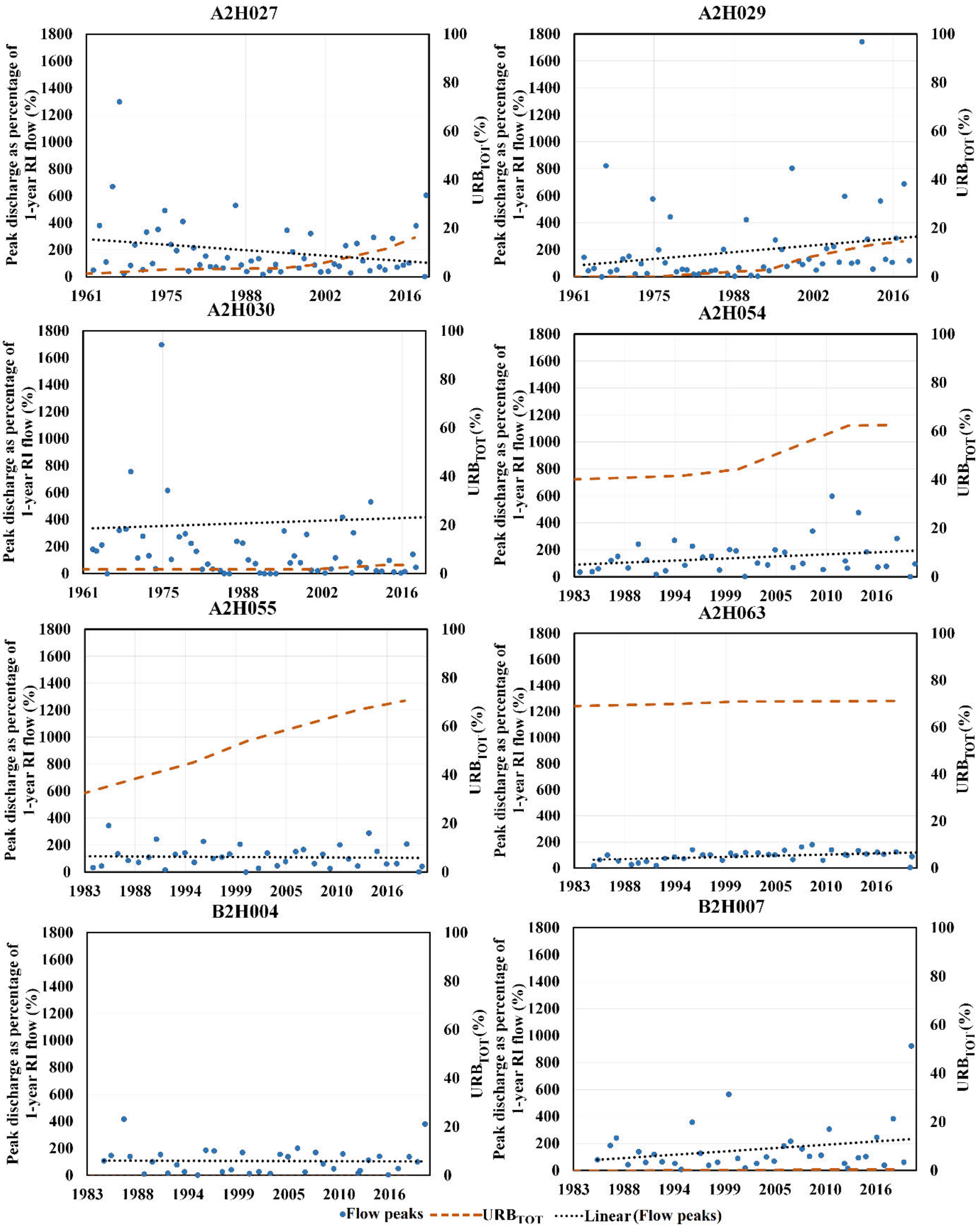


Figure 3.7 Trends in observed peak flow rates, expressed as a percentage of the 1-year RI flood peak, and $URB_{TOT\%}$ over time

The Mann-Kendall statistical test results for trends between peak discharges over time and with $URB_{TOT\%}$ are shown in Table 3.6. These results show that for the peak discharge analysis, Catchments A2H029 and A2H063 have the highest Kendall's τ-values, with trends significant at the 1% ($p<0.01$) level. For Catchment A2H029 these trends are evident when considering either the full data period, or the shorter period from 1982. For the PoT analysis, only Catchment A2H027 shows a trend at the 1% ($p<0.01$) significance level, and Catchment A2H029 at the 5% significance level, and in both cases only for the analysis considering the full data period. Both are negative trends.

Table 3.6 Statistical test results for flood peaks

DWS Gauging Station	AMS Analysis τ		PoT analysis τ	
	Temporal	**$URB_{TOT\%}$**	**Temporal**	**$URB_{TOT\%}$**
A2H027	-0.145 0.043[b]	-0.145 0.043[b]	-0.377** -0.179[b]	-0.377** -0.179[b]
A2H029	0.232** 0.366[b]**	0.240** 0.366[b]**	-0.128* -0.028[b]	-0.128 -0.029[b]
A2H030[a]	-0.175 0.159[b]	-0.066 0.136[b]	-0.089 0.099[b]	-0.076 -0.087[b]
A2H054	0.155	0.155	0.178	0.175
A2H055	0.006	0.006	0.154	0.091
A2H063	0.330**	0.348**	0.191	0.188
B2H004[a]	-0.002	-	0.117	-
B2H007[a]	0.092	0.110	0.000	0.003

[a]Rural catchment

[b]Results for analysis only considering data after October 1982

*Statistically significant trend at the 5% significance level

**Statistically significant trend at the 1% significance level

3.6 Discussion

3.6.1 Flow volumes

The results of the flow volume analysis indicate that an increase in total flow volumes follows from an increase in urbanisation. Q_{sum}/P_{sum} ratios range between just above 0 and 5% in undeveloped catchments, between 3.5% and 8% at $URB_{TOT\%}$ of 10%, approximately 11% at $URB_{TOT\%}$ of 50%, between 12% and 14% at $URB_{TOT\%}$ of 60% and between 8% and 23% at $URB_{TOT\%}$ of 70%. The significant Q_{sum}/P_{sum} increase in Catchment A2H063 despite minimal increase in $URB_{TOT\%}$ could possibly be attributed to densification of urban areas in the catchment. Different Q_{sum}/P_{sum} ratios in catchments with similar $URB_{TOT\%}$ could be caused by different development densities in formal and informal residential areas in South Africa, as well as per capita water consumption. Both the density of development, as well as higher per capita water consumption, could lead to increased demand and, subsequently, increased leaked volumes flowing into the river system, should leaks occur. With South Africa's aging water infrastructure, leaks have become common in both water supply and sanitation systems (Ruiters and Amadi-Echendu, 2022). The imperviousness of different South African urban land use types needs to be quantified in order to analyse this further. Kendall τ-values are the highest in the catchments with the highest degrees of temporal change in URB_{TOT}. The increase in total runoff with increased urbanisation is consistent with findings of most other studies (Konrad, 2003; Putro *et al.*, 2016).

3.6.2 Base flow volumes

The results of the base flow analysis indicate that the largely urbanised catchments tend to have lower relative base flow volumes than rural catchments, however, statistical analysis found that base flow tends to increase with an increase in URB_{TOT}. The increasing base flow trends are contrary to findings in most other catchments (Smakhtin, 2001; Shuster *et al.*, 2005; Jacobson, 2011; Braud *et al.*, 2013; Gogate and Rawal, 2015). Some activities associated with urbanisation, including inter-catchment transfers and wastewater flow, may well change the net impact on hydrological responses (Brandes *et al.*, 2005; Meyer, 2005; Whitney *et al.*, 2015; Schütte and Schulze, 2017). Although the specific causes of the base flow trends cannot be determined from the data collated for this study, it should be noted that South Africa is a water-scarce country with developmental hubs far away from natural water sources. The country therefore has a number of potable water transfer schemes that supply water to urban regions through long piped distribution networks. It is postulated that the water transferred into the catchments may contribute to baseflow through pipe bursts, pipe leaks, garden irrigation, swimming pool backwashing and other activities. As shown in Figure 3.6 the sudden increase in base flows in Catchments A2H027, A2H029, A2H054 and A2H055 do not correlate exactly with change in $URB_{TOT\%}$, nor do the start of the changes occur at the same time in all catchments. The effect of water transfer into the catchments is potentially combined with aging, poorly maintained, or poorly installed infrastructure leading to leakage of potable water and waste water into the river systems. A wastewater treatment plant in Catchment A2H027 could also contribute to increased base flow in this catchment.

The reasons for this phenomenon need to be further investigated and quantified, since it is expected that this phenomenon will occur in other South African urban areas, as well as urban areas in other water-scarce countries. Base flow, whether naturally occurring or due to urban activities and infrastructure failure, needs to be incorporated into hydrological models and drainage system design, especially when lower-order flood events are of significance. It is therefore recommended that the changes in surface runoff be investigated further by considering Q/P to base flow trends.

It should be noted that this study only considered URB_{TOT} using land use data. In order to incorporate possible effects into design of sustainable urban water systems in developing countries, distinction between effects in formal and informal settlements, as well as impervious percentage and directly connected impervious areas within urban land use classes needs to be investigated and quantified.

3.6.3 Flood peaks

The flood peak analysis delivered different results depending on whether the AMS or the PoT data set was considered. The AMS analysis delivered statistically significant increasing trends with the strongest association for the catchment with the highest proportion of informal development (Catchment A2H029), followed by the catchment with the highest percentage of formal development and URB_{TOT} (Catchment A2H063). Of the two, the linear regression line for Catchment A2H029 shows a steeper slope than for Catchment A2H063, with Catchment A2H063 also showing little variation from the linear regression line. The characteristics of the informal development might influence rainfall-runoff responses in this catchment differently to characteristics in the catchments with more formal development. This observation needs to be investigated further.

Despite the AMS analysis for Catchment A2H027 not showing a statistically significant trend, the PoT analysis for the entire data period showed a negative trend of statistical significance. Of interest is the different results for Catchment A2H029 when considering AMS or PoT, with the AMS showing positive trends and the PoT showing the opposite trend. This could be attributed to the 1967 hydrological year that experienced above-average rainfall, both in annual totals and in events above the AMS.

Both the AMS and PoT results also showed the potential significance of data set length, where the exclusion of the period between 1962 and 1982 from the data set for Catchment A2H029 resulted in an increase of the Kendall τ-values between the AMS and both time and $URB_{TOT\%}$. Although the AMS results in Catchments A2H027 and A2H030 did not show statistical significance, and only showed weak association with low Kendall's τ-values, it is still interesting to note the changes from negative to positive trends. For the PoT analysis the Kendall τ-values and p-values decreased for Catchment A2H027 with a shorter data set. The question could therefore be raised what influence a longer data set would have had on trends in the other catchments.

The AMS results for Catchments A2H029 and A2H063 are similar to results of most studies in other urbanising catchments (Konrad, 2003; Lee and Heaney, 2003; Putro *et al.*, 2016; Todeschini, 2016), however, the fact that the trend in Catchment A2H063 is relatively flat, and the fact that three of the urbanised catchments did not show trends in the AMS, brings into question whether formal South African urban development causes increased flood peaks. This observation has previously been made in other international studies (Burns *et al.*, 2005; Aichele and Andresen, 2013; Miller and Hess, 2017). The causes of the negative trends in Catchment A2H027 also need to be investigated further. Possible causes could be drainage path inefficiency and ponding between dwellings. The causes need to be investigated and verified in other catchments.

It is widely accepted that connectivity of impervious areas to formal drainage systems play a major role in runoff response (Lee and Heaney, 2003; Roy and Shuster, 2009; Yao *et al.*, 2015;

Redfern *et al.*, 2016; Miller *et al.*, 2020). However, since Catchment A2H029 is the catchment with the largest proportion of informal development, this assertion might not be applicable in certain South African informal developments. Therefore, it is imperative that the types of urban development, total impervious areas and impervious area connectivity of this catchment need to be quantified and compared with the results from the other catchments in this study in order to further investigate this unexpected result.

It should be noted that the flood peaks in Catchment B2H007 did not show a statistically significant increasing trend, despite the increase in extreme rainfall events in this catchment. This could be due to the hydrological processes in this rural catchment that dampen the effect of extreme rainfall events.

3.7 Conclusions and Recommendations

The aims of this study were achieved using the Mann-Kendall method and Kendall's τ-value to test for trends over time and with urban development in: (a) flood volumes, (b) base flow and (c) flood peaks. Five urban catchment areas and three undeveloped catchment areas were used as case studies and trends in urban and rural catchments were compared.

It was established that strong increasing trends exist in the urban catchments in the temporal Q/P ratios and base flows, as well as between Q/P ratios and $URB_{TOT\%}$ and base flow and $URB_{TOT\%}$. Despite the strong correlation for Q/P ratios and base flows, the magnitudes of flood peaks do not seem to be affected to the same extent by the degree of urban development, with statistically insignificant changes in most catchments, negative trends evident in some catchments, and an unexpected positive trend in the catchment where development commenced most recently and is unregulated.

Increases in Q_{sum}/P_{sum} despite minimal URB_{TOT}, as well as different Q_{sum}/P_{sum} ratios in catchments with similar $URB_{TOT\%}$ could possibly be attributed to densification of urban areas and different development densities in formal and informal residential areas in South Africa. The imperviousness of different South African urban land use types needs to be quantified in order to further analyse this.

Base flow, whether naturally occurring or due to urban activities and infrastructure failure, needs to be incorporated into hydrological models and drainage system design, especially when lower-order flood events are of significance. It is therefore recommended that the changes in surface runoff be investigated further by considering trends between Q/P ratios and base flow. The possible effects of water transfer into the catchments as development and population increases, combined with aging, poorly maintained, or poorly installed infrastructure leading to leakage of potable water and waste water into the river systems also need to be considered in order to understand the results from this study. It should be noted that this study only considered URB_{TOT} using land use data. In order to incorporate possible effects into design of sustainable urban water systems in developing countries, distinction between effects in formal and informal settlements, as well as total imperviousness and impervious area connectivity within urban land use classes need to be investigated and quantified.

The fact that few statistically significant trends were found in the flood peak analysis, but significant trends were evident in the flow volume and base flow analyses supports the argument for flood peak attenuation in urban areas in South Africa (Van Vuuren, 2012). The analysis of flood peaks in urban catchments showed the potential significance of record length on the results, especially for PoT analysis, where years with more high flow events could significantly alter analysis results. Both Catchments A2H027 and A2H029 had higher Kendall τ-values and levels of significance for the PoT analysis considering the entire record length.

The catchment with the strongest association in the flood peak AMS analysis is Catchment A2H029, which is the catchment with the highest proportion of informal development. The causes for the trends in this catchment need to be investigated and verified in other catchments to confirm whether the trends are linked to the URB_{TOT}, or possibly the types of development in the catchment, as well as the influence of total impervious area and impervious area connectivity.

Quantification of the effects of URB_{TOT} on catchment response times was not considered in this paper, but this will also influence design decisions for sustainable urban drainage systems and therefore it is recommended that this be investigated in future studies.

4 QUANTIFYING IMPERVIOUSNESS IN THE STUDY AREA

The journal paper presented in Chapter 3 recommended further investigation into possible causes for contradictory trends in storm runoff from urban catchments with different levels of development. The study considered change in the total urban footprint and different runoff characteristics between urban and rural catchments as a first analysis on the effects of urbanisation on runoff, but did not consider impervious areas directly. The results considering runoff ratios as a proportion of flow and changing flood peaks were inconsistent in some catchments with similar urban footprints. This chapter contributes to achieving objective (a) of the study to improve understanding of the complexity of urban areas in South Africa as a diverse and developing country. Changing imperviousness is quantified in the study catchments in order to assess if imperviousness influences the different trends in hydrological responses in catchments with different development types, as stated in objective (c) of this thesis. The impervious proportions of formal and informal urban land cover classes are quantified using remote sensing and verified using ground-based observations. Historical and current levels of imperviousness in each study catchment are quantified and temporal change in the density of impervious areas within the urban footprint assessed. Typical estimates of imperviousness percentages for different South African National Land Cover (SANLC) classes are also derived, for use in hydrological modelling of formal and informal urban areas in South Africa.

4.1 Introduction

In South Africa, as in many other developing regions, people migrate to urban areas from the surrounding rural areas (Cohen, 2006; Capps *et al.*, 2016; UNDP, 2019). Most cities in South Africa have experienced significant population increases in recent years (Mlambo, 2018; StatsSA, 2020; Mubangizi, 2021). Geyer *et al.* (2012) noted a trend in the post-Apartheid era where people migrate from urban centres towards urban fringes and smaller towns, while the informal townships on the outskirts of cities have experienced continued growth as a result of migration of people from rural areas in search of improved livelihood opportunities in urban areas. This combination has led to significant development of both formal and informal settlements on the outskirts of cities. For example, Thompson (2019) reported a 30% increase in total urban footprint nationally in South Africa between 1990 and 2018. In 2019 an estimated

12.7% of the population lived in informal dwellings and 5.1% in traditional dwellings. In Gauteng, which is the most urbanised of the nine provinces in South Africa, 18.7% of the households resided in informal dwellings in 2019 (StatsSA, 2020).

Hydrological models are often used to simulate and better understand the specific impacts of urban development on rainfall-runoff processes in ungauged catchments. Results are used for various applications, including the estimation of design floods, as well as the planning, design and establishment of safe and sustainable urban drainage systems (El Hattab *et al.*, 2020; Ambrosio *et al.*, 2022; Ferrans *et al.*, 2022). In order to configure realistic models for ungauged urban catchments, it is important to have a reasonable estimate of impervious land cover in a catchment and to understand the effects of impervious land cover on stormflow parameters.

However, determining imperviousness at a catchment scale is challenging, particularly in developing countries where appropriate data are not available to undertake detailed studies. This, combined with the fact that very few urban catchments in developing countries are gauged, leaves a knowledge gap on the impacts of catchment imperviousness on runoff characteristics from urban areas in developing countries. This study aims to address the first portion of this knowledge gap by investigating impervious land cover of formal and informal developments in South Africa. Objective (a) of this study is to quantify historical and current total imperviousness percentages and impervious area density in selected study catchments. Objective (b) is to determine if remote sensing could be used to generate typical estimates of imperviousness percentages for different South African National Land Cover (SANLC) classes, for use in hydrological modelling of formal and informal urban areas in South Africa.

4.2 Methods

This section describes the catchments used for this study, as well as the methodology followed to measure historical changes in imperviousness in these catchments. The methodology followed to derive general imperviousness values for different South African National Land Cover (SANLC) classes is also detailed.

4.2.1 Study areas

It was previously established that urban development influences hydrological processes in South African catchments (Loots *et al.*, 2022). Therefore, five gauged catchments with at least

14% developed urban area as of year 2020 were selected for this study. All five catchments are located within the City of Tshwane Metropolitan Municipality, South Africa (Figure 4.1), with two catchments containing informal settlements. Formal residential areas in the study area typically contain houses or intensive residential developments with high boundary walls and a combination of paved and vegetated area around dwellings, with formalised drainage networks. Informal settlements are typically constructed in a haphazard manner, with little impervious area apart from the roofs of dwellings and with no formal drainage systems. The relevant urban land cover classes, as classified in the 2018 and 2020 South African National Land Cover (SANLC) assessments (Geoterraimage, 2019; Geoterraimage, 2021), were grouped as summarised in Table 4.1 and the distribution mapped across the study area for each group as shown in Figure 4.1. Land cover classes were organised into formal residential (RES_{Formal}), informal residential ($RES_{Informal}$) and commercial and industrial (INDCOM) groupings. The SANLC classifications are applicable to all similarly developed areas across South Africa (Geoterraimage, 2019; Geoterraimage, 2021), and both classes and categories described in Table 4.1 could be used for similar types of land uses in other developing countries.

Table 4.1 SANLC classes used in this study

SANLC Class No.	**Description**	**Assigned $URB_{TOT\%}$ Group**
47	Residential Formal (Tree)	RES_{Formal}
48	Residential Formal (Bush)	
49	Residential Formal (Grass)	
50	Residential Formal (Bare)	
51	Residential Informal (Tree)	$RES_{Informal}$
52	Residential Informal (Bush)	
53	Residential Informal (Grass)	
54	Residential Informal (Bare)	
65	Commercial	INDCOM
66	Industrial	

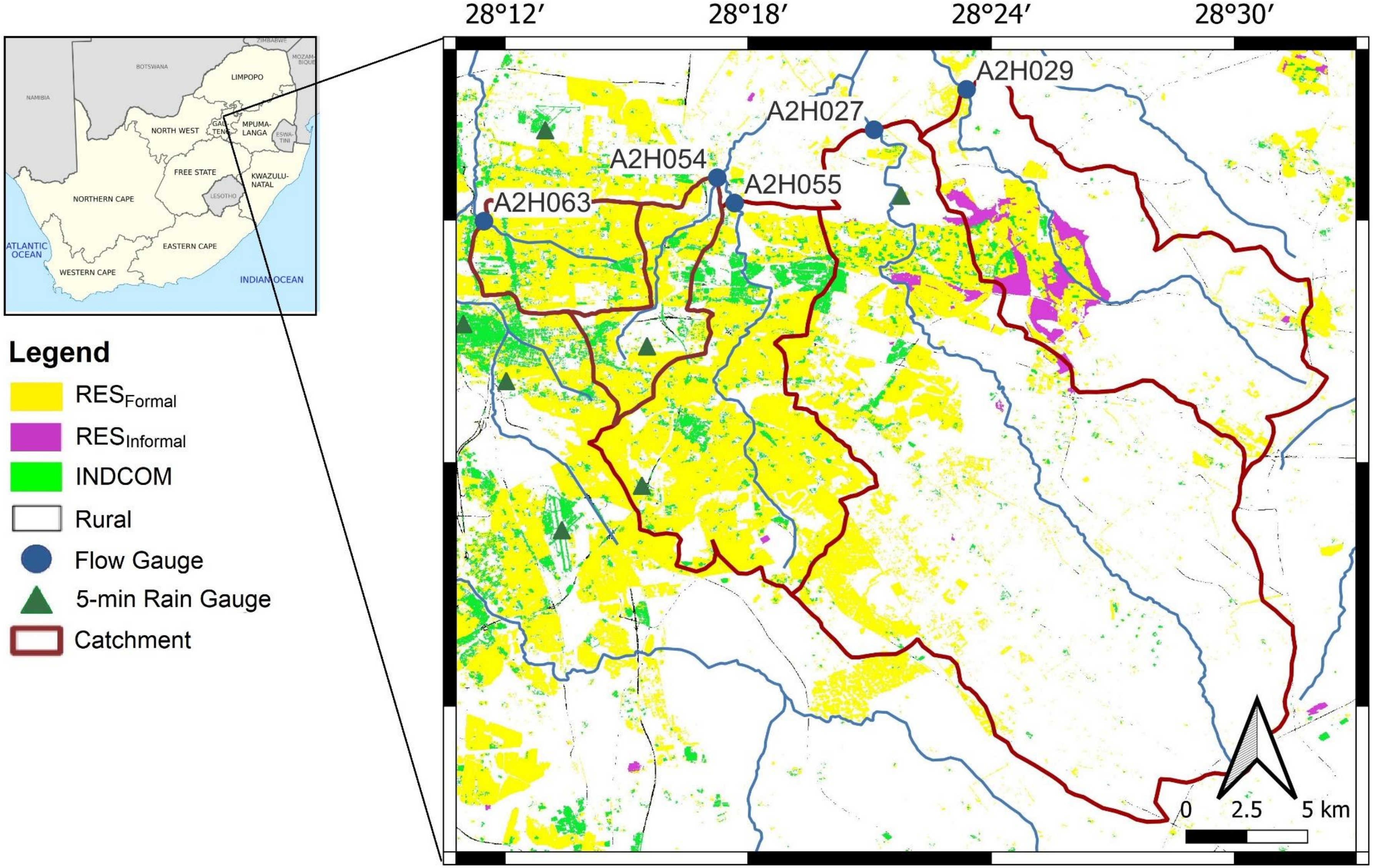


Figure 4.1 Location of study catchments and distribution of groupings of urban areas

4.2.2 Measurement of historical changes in imperviousness

In order to quantify changes in imperviousness within the urban footprint, historic and current estimates of the Total Impervious Area (TIA) in each of the study catchments were extracted using images taken on cloud-free days for different time periods within the study period. Where possible, images from winter months, when there is less vegetation covering impervious areas, were used to get as good a representation of impervious area as possible.

Prior to 2002, the only available images in the study areas are grayscale aerial photos taken by the South African National Geo-spatial Information (NGI) in 1958, 1962, 1965, 1976 1985, 1991 and 2001, digitised to a resolution of 2.5 m by 2.5 m pixels from the analogue data. Impervious built-up areas were identified from the images taken between 1958 and 2001 through a combination of remote sensing and manual correction of mis-classified areas. Post-2002, satellite images taken from Google Earth were used to detect impervious areas. High-resolution images were extracted from Google Earth from 2002 to 2021 at approximately 5-year intervals. In some cases, images from different years were used for different catchments, as image selection was based on image quality. Cross comparison was undertaken between the 2001 NGI images and the 2002 Google Earth dataset. A 2.1% difference was found between the imperviousness measured using the two datasets. The discrepancy was deemed sufficiently small to combine the results from the different datasets for this study.

The total extent of urban development, or urban footprint ($URB_{TOT\%}$), was previously delineated (Loots *et al.*, 2022) using topographical maps at a scale of 1:50 000 for years up to 2001 and the SANLC data sets were used for the identification of urban areas in 1990 (Geoterraimage, 2015b), 2013 (Geoterraimage, 2015a) and 2018 (Geoterraimage, 2019). In this study the same method was applied to delineate $URB_{TOT\%}$ for 2020 using the 2020 SANLC data set (Geoterraimage, 2021).

The density of developed impervious areas within the catchments was calculated as the ratio of $TIA_{\%}$ to $URB_{TOT\%}$ in each catchment over time. Increasing values of density thus indicate densification of impervious areas within a catchment.

4.2.3 Measurement of imperviousness of SANLC classes

A combination of remote sensing and ground-truthing was applied in order to measure the typical imperviousness of different urban SANLC classes and to verify the results:

(i) Remote sensing was used to identify sample points of impervious and other land covers in the study area. The imperviousness for urban SANLC classes was then measured using sample areas, or zones, within the landcover of each class (Table 4.2) from satellite images. They were used as training and validation points in order to identify impervious areas on the images. Sample zones were then identified from each of the 10 SANLC classes included in this investigation. The imperviousness of each sample zone was determined through remote sensing and trends investigated. The minimum, maximum, median, as well as lower and upper quartile values were determined.

(ii) The same methodology was applied using additional images outside the study area to verify the results.

(iii) Further verification was undertaken through physical measurement of imperviousness of independent sample sites in the study area and the results compared with the remote sensing results.

The methodology is described in the following paragraphs.

The Environmental Mapping and Analysis Program Box (EnMAP-Box) plugin available in QGIS (ENMAP-Box_Developers, 2019) has been extensively used in other studies for extracting Total Impervious Area (TIA) data (Marcinkowska-Ochtyra *et al.*, 2017; Castaldi *et al.*, 2019; Cipta Ramadhan Kete *et al.*, 2019; Pan *et al.*, 2020). Therefore, this methodology was applied to classify the land cover images in this study. The impervious areas of the high-resolution Spot 6-7 SANSA satellite images dated 2017 were used for this analysis and compared with the 2018 SANLC database. Land cover sample points were manually selected to achieve a distribution among the six initially-classified general land cover types, being: (1) Buildings (Bu), (2) Trees (T), (3) Grass (G), (4) Bare (Ba), (5) Roads (R), and (6) Water (W). These six land cover types were chosen to distinguish impervious areas from pervious areas. Training and independent validation points were selected to cover different chromatic shades representing these classes in the study area. Between 50 and 200 points for each general land cover type were selected from each image used in the study, dependent on the availability of land cover types in the available images. To simplify output, land cover types were grouped into three categories as shown in Table 4.2.

Table 4.2 Land cover type grouped for imperviousness estimation

Land Cover Type No.	Type Name	Grouped Sample Zone Classification
1	Buildings (Bu)	Impervious area (IMP)
2	Trees (T)	Vegetated area (VEG)
3	Grass (G)	Vegetated area (VEG)
4	Bare (Ba)	Bare area (BARE)
5	Roads (R)	Impervious area (IMP)
6	Water (W)	Bare area (BARE)

After the images were classified, the imperviousness of different SANLC classes needed to be estimated. Sample zone areas were selected from each of the eight SANLC urban residential land use classes as well as the urban commercial and industrial land use classes using the 2018 SANLC data. Sample zones were selected from all five study catchments and made as large as possible, with some SANLC land use classes having larger uninterrupted areas than others. Sample zones were selected based on SANLC classes only, without considering other data sources, in order to avoid bias in the selection. The total area sampled for each SANLC land use class, as well as the average area per sample zone, are summarised in Table 4.3. The grouped classification was overlaid with the sample zones to calculate the impervious area (IMP), bare area (BARE) and vegetated area (VEG) of each sample zone. The median, 25^{th} and 75^{th} percentile, as well as maximum and minimum percentages of each of the three grouped classifications were calculated for each SANLC class.

Table 4.3 SANLC areas sampled for imperviousness calculation

SANLC Class No.	SANLC Class Description	Sample Zones		
		Number of Zones Sampled	**Total Sampled Area (m^2)**	**Average Area per Zone (m^2)**
47	Residential Formal (Tree)	416	1151204	2774
48	Residential Formal (Bush)	126	560219	4482
49	Residential Formal (Grass)	117	790991	6819
50	Residential Formal (Bare)	36	1818962	51970
51	Residential Informal (Tree)	132	314109	2398
52	Residential Informal (Bush)	179	486299	2732
53	Residential Informal (Grass)	41	534094	13352
54	Residential Informal (Bare)	38	831868	30810
65	Commercial	348	1922515	5540
66	Industrial	81	1954666	24433

Verification zones were selected from each of the eight SANLC urban residential land use classes as well as the urban commercial and industrial land use classes. Verification zones were selected randomly from areas in Tshwane, but outside the five study catchments. The total verification areas are summarised in Table 4.4. The mean values for the verification zones of each SANLC class were compared with the mean values in the sample zones and the differences were noted.

It should be noted that seasonal variation between VEG and BARE areas are possible. However, the focus of this research was on quantifying IMP areas. Where possible, images from winter months, when there is less vegetation covering impervious areas, were used to get as good a representation of impervious area as possible.

Table 4.4 SANLC imperviousness verification areas

SANLC Class No.	SANLC Class Description	Sample Zones		
		Number of Zones	**Total Area (m^2)**	**Average Area per Zone (m^2)**
47	Residential Formal (Tree)	39	171045	4501
48	Residential Formal (Bush)	21	124673	6234
49	Residential Formal (Grass)	42	309280	7543
50	Residential Formal (Bare)	13	1036182	86349
51	Residential Informal (Tree)	7	9786	1631
52	Residential Informal (Bush)	45	44715	1016
53	Residential Informal (Grass)	20	853911	44943
54	Residential Informal (Bare)	30	379729	13094
65	Commercial	12	677901	61627
66	Industrial	18	514723	30278

Further verification was achieved through field work. Independent sample sites for all SANLC classes under investigation were identified and TIA measured at the sites. Sample sites from different neighbourhoods with similar SANLC classes were included in the sampling. For each sample site, the total area with impervious land cover was measured on site on properties where access was granted. On properties where access was denied, notes regarding the location of vegetation covering impervious areas were taken from the street and the TIA was calculated using high resolution 2020 Google Earth images. The total sample area was 0.45 km^2 from 292 individual sample sites. A number of the sampled sites cover multiple SANLC classes and were therefore divided into parcels based on SANLC class coverage. In total, 477 sample parcels were included, with distribution per SANLC class as shown in Table 4.5. A descriptive figure showing the differentiation between parcels, sample sites, SANLC classes and assigned $URB_{TOT\%}$ group (as described in Table 4.1) is provided in Figure 4.2. The different colours depict different SANLC classes, sample sites indicate stands used in the sampling process, parcels are individual classes within sample sites, and assigned $URB_{TOT\%}$ groups show similar types of developments grouped together.

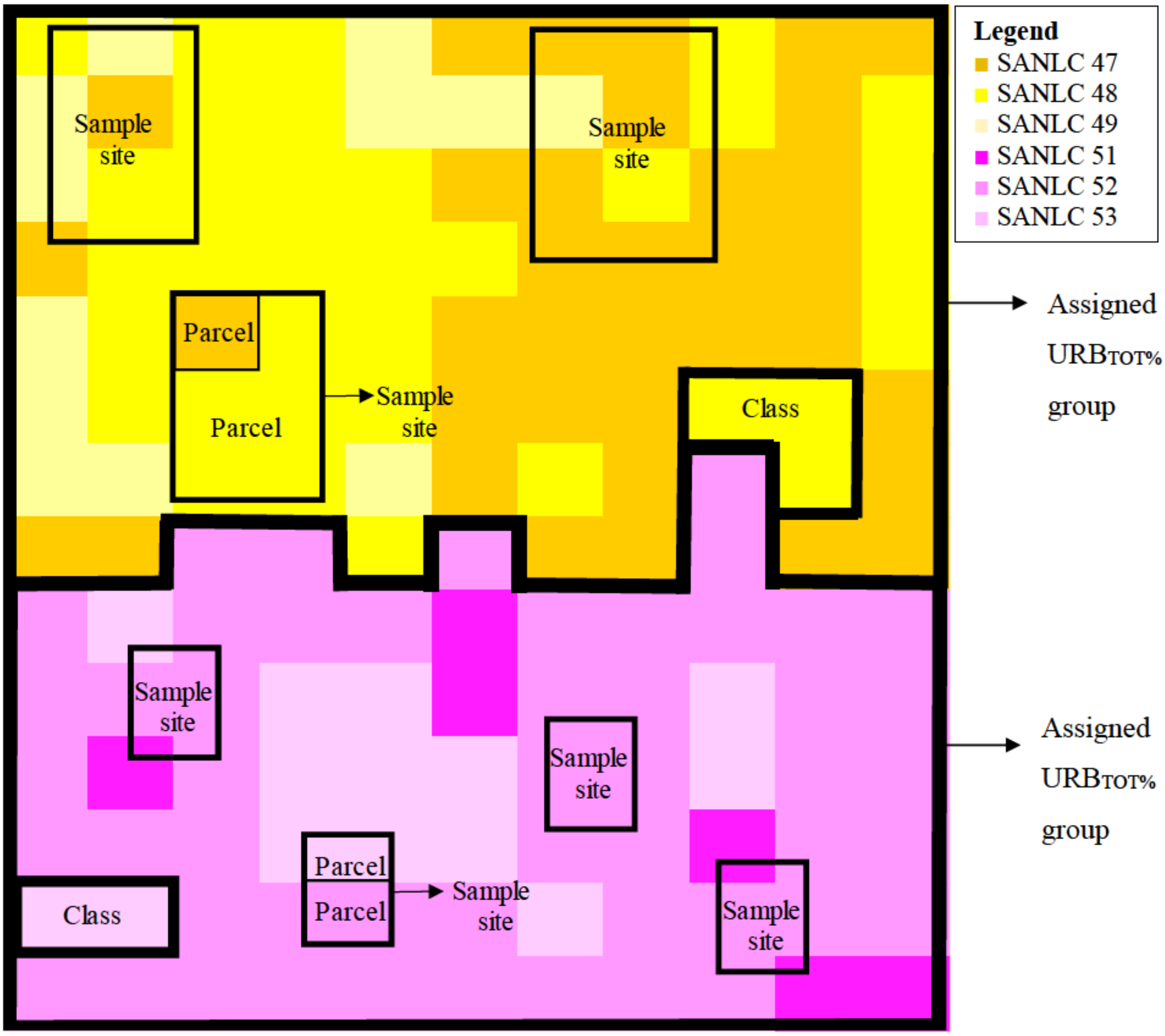


Figure 4.2 Differentiation between sample parcels, sample sites, SANLC classes and assigned $URB_{TOT\%}$ groups

Table 4.5 Ground-truthing verification representation per SANLC class

SANLC Class No.	Description	Number of Sample SANLC Parcels per Class
47	Residential Formal (Tree)	87
48	Residential Formal (Bush)	84
49	Residential Formal (Grass)	67
50	Residential Formal (Bare)	59
51	Residential Informal (Tree)	54
52	Residential Informal (Bush)	30
53	Residential Informal (Grass)	9
54	Residential Informal (Bare)	38
65	Commercial	32
66	Industrial	17

4.3 Results

This section provides summaries of results obtained in the analysis of historical changes in imperviousness in the study catchments, as well as generalised imperviousness percentages for different urban SANLC classes. Results are discussed in Section 4.4.

4.3.1 Changes in imperviousness

Historical changes in the urban footprint ($URB_{TOT\%}$), total imperviousness as a percentage of the catchment area ($TIA_{\%}$) and the density of the TIA were quantified for each catchment over the study period. The results from this analysis are used in Chapter 5 to test correlation between urbanisation and runoff. Table 4.6 provides a summary of the most recent $URB_{TOT\%}$ information obtained from the 2020 images, with formal residential (RES_{Formal}), informal residential ($RES_{Informal}$), urban parks and recreational areas (URB_{Park}) and commercial/industrial (INDCOM) land uses reported separately. Parks and recreational areas were included for $URB_{TOT\%}$ calculations, but not for imperviousness calculations, since these areas form part of the urban footprint, but do not typically contain impervious areas. The results in Table 4.6 show similar current levels of formal residential development in Catchments A2H027 and A2H029, as well as Catchments A2H055 and A2H063. Catchment A2H029 has the highest proportion of informal settlements. Catchments A2H027 and A2H029, as well as Catchments A2H054, A2H055 and A2H063, have similar proportions of industrial and commercial developments.

Table 4.6 $URB_{TOT\%}$ information based on 2020 SANLC classification

DWS Gauging Station	RES_{Formal} (%)	$RES_{Informal}$ (%)	URB_{Park} (%)	INDCOM (%)	$URB_{TOT\%}$ (%)
A2H027	11.8	0.6	0.2	1.9	14.5
A2H029	10.7	7.2	0.2	1.9	20.0
A2H054	49.2	0.0	4.0	10.9	64.1
A2H055	60.0	0.1	2.4	9.8	72.3
A2H063	62.7	0.0	0.7	10.1	73.5

Figure 4.3 shows the $URB_{TOT\%}$, reported as a percentage of total catchment area for each of the five catchments over the study period. Catchment A2H063 has the highest $URB_{TOT\%}$ over the study period, with the smallest change, from 69.2% to 73.6%. Catchment A2H055 (33.9% to 72.4%) and Catchment A2H054 (40.3% to 64.1%) show the highest total change in $URB_{TOT\%}$. Catchments A2H027 and A2H029 also show changes in $URB_{TOT\%}$ over time, specifically after 1994, with values of $URB_{TOT\%}$ in Catchment A2H027 changing from 4.2% to 14.6% and in Catchment A2H029 changing from 3.8% to 19.2% from 1994 - 2022.

Figure 4.4 shows the TIA as a percentage of the total catchment area. Catchment A2H063 shows the highest TIA percentages over the study period, increasing from 36.0% to 55.2%. Catchment A2H054 (29.5% to 50.0%) and Catchment A2H055 (26.2% to 43.1%) show similar TIA trends to Catchment A2H063. Catchments A2H027 and A2H029 have the lowest total TIA, but with significant change after 1994 (2.3% to 10.1% and 1.9% to 12.5%, respectively).

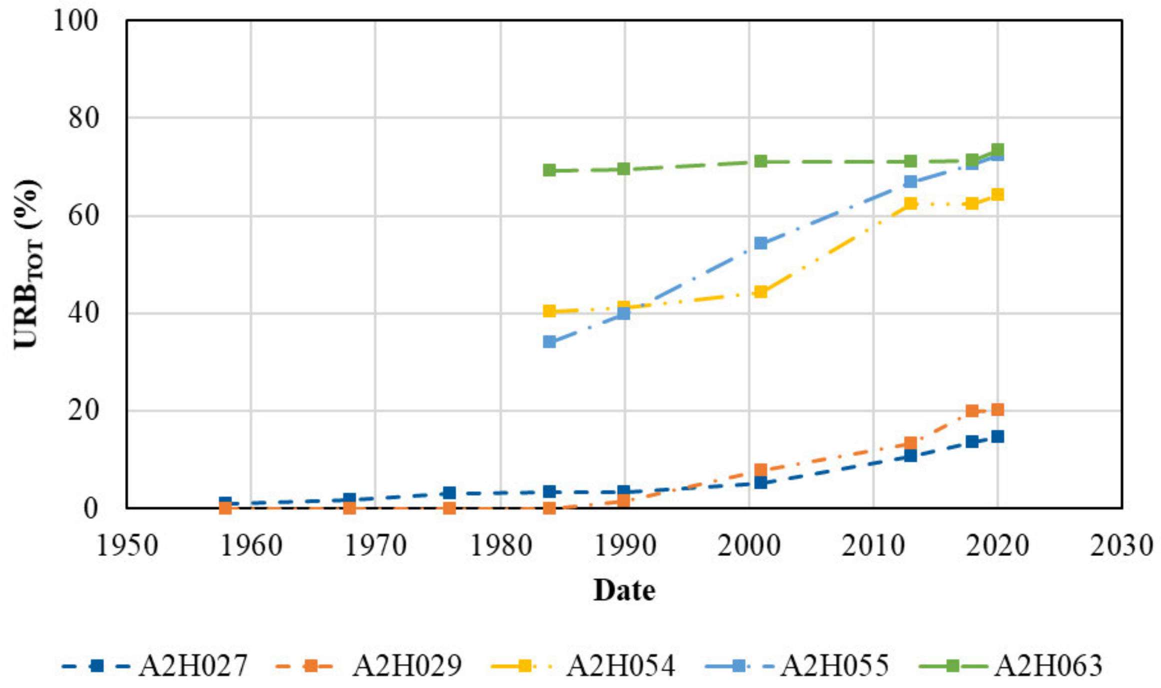


Figure 4.3 Extent of the urban footprint as percentage of catchment area over the study period

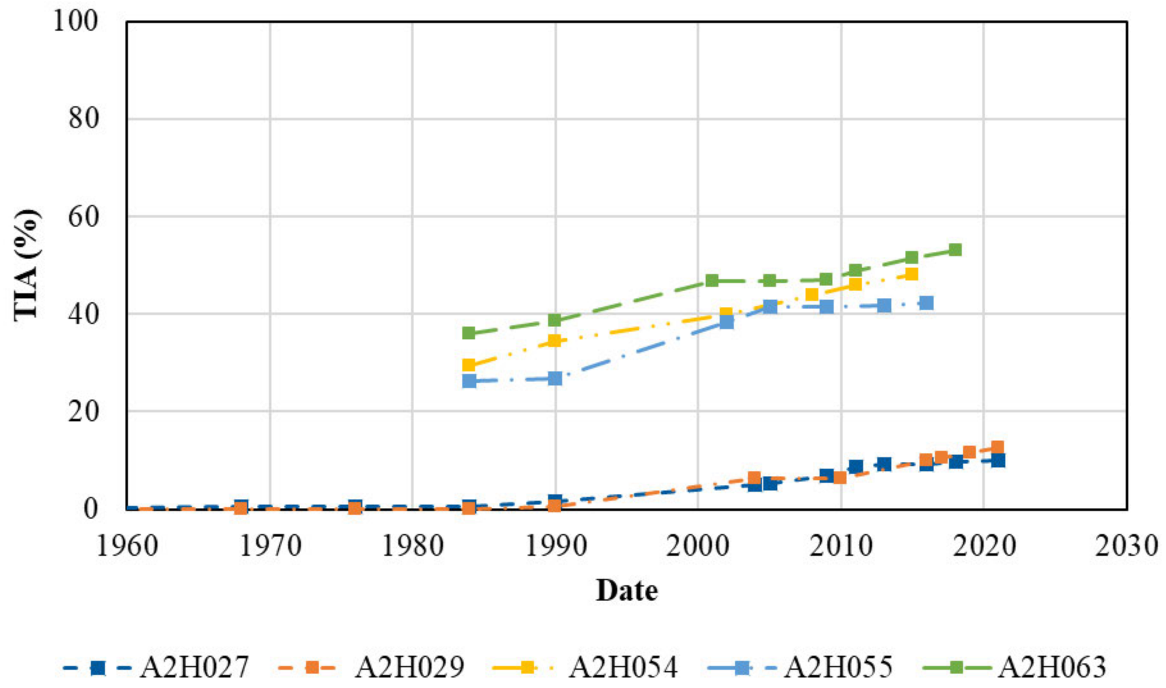


Figure 4.4 Total impervious areas as percentage of catchment area over the study period

Figure 4.5 shows the density of the TIA, reported as a ratio of $URB_{TOT\%}$ in each catchment over the study period. Catchment A2H054 has the highest density for most of the study period, with Catchment A2H063 being the only catchment with a consistent density pattern. Significant differences in density are evident for different catchments.

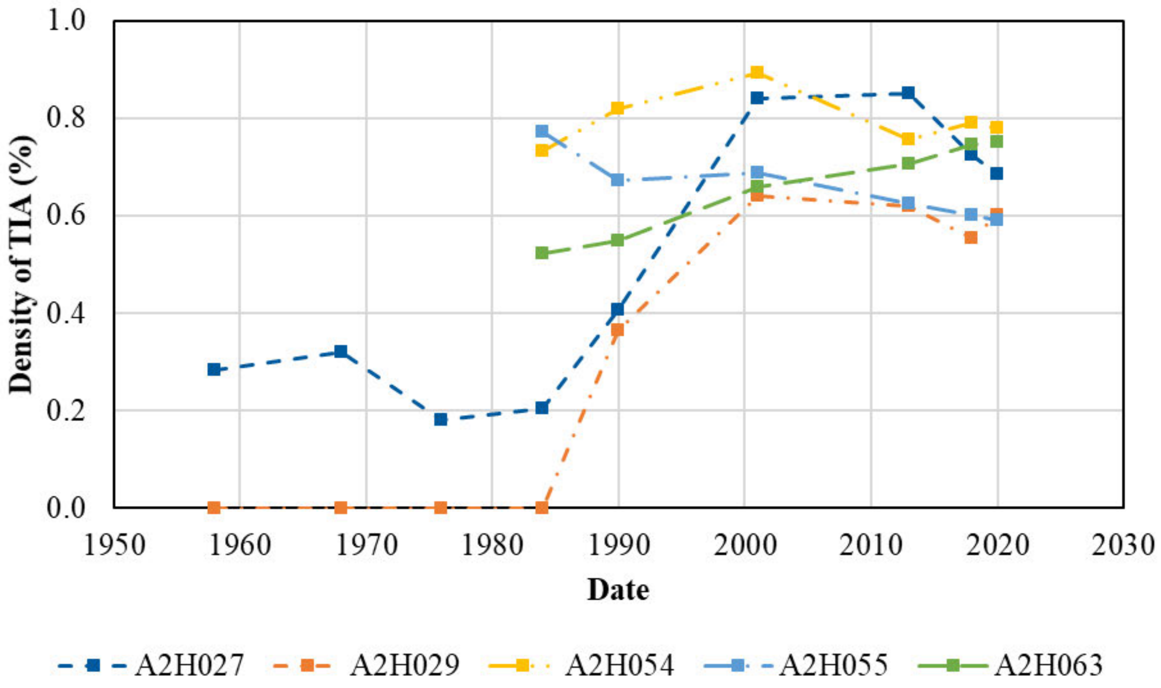


Figure 4.5 Density of urban development over the study period

4.3.2 Imperviousness of SANLC classes

The TIA were extracted for different 2018 SANLC classes from the 2017 SANSA images as described above. Median values, mean values and standard deviations of IMP, VEG and BARE areas (as defined in Table 4.2) are shown in Figure 4.6 for RES_{Formal} areas, Figure 4.7 for $RES_{Informal}$ areas and Figure 4.8 INDCOM for SANLC urban land cover classes, with class descriptions provided in Table 4.1. The impervious area median for $RES_{Informal}$ (Bare) was lower than expected when compared with other informal residential classes. Closer inspection of the satellite images showed that informal areas classified as $RES_{Informal}$ (Bare) had high proportions of bare surfaces between dwellings, with small, impervious dwellings located in the areas. As expected, commercial and industrial areas have high percentages of imperviousness (Figure 4.8).

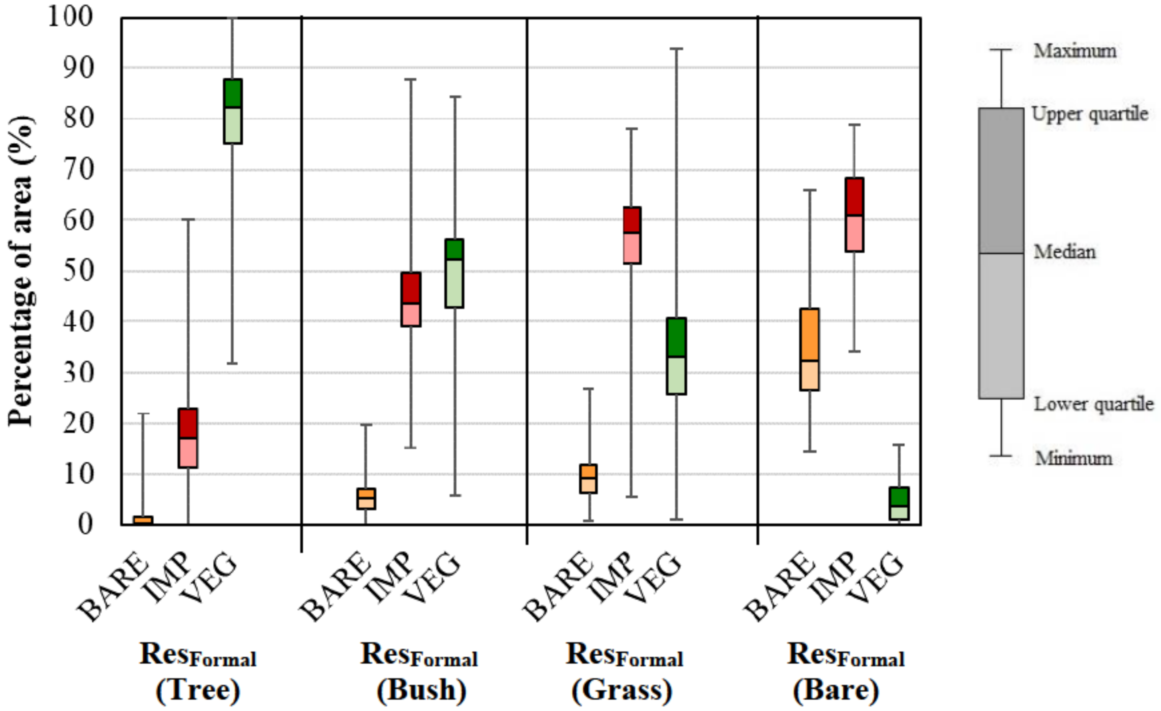


Figure 4.6 Remotely sensed TIA of formal residential SANLC classes within the RES_{Formal} group

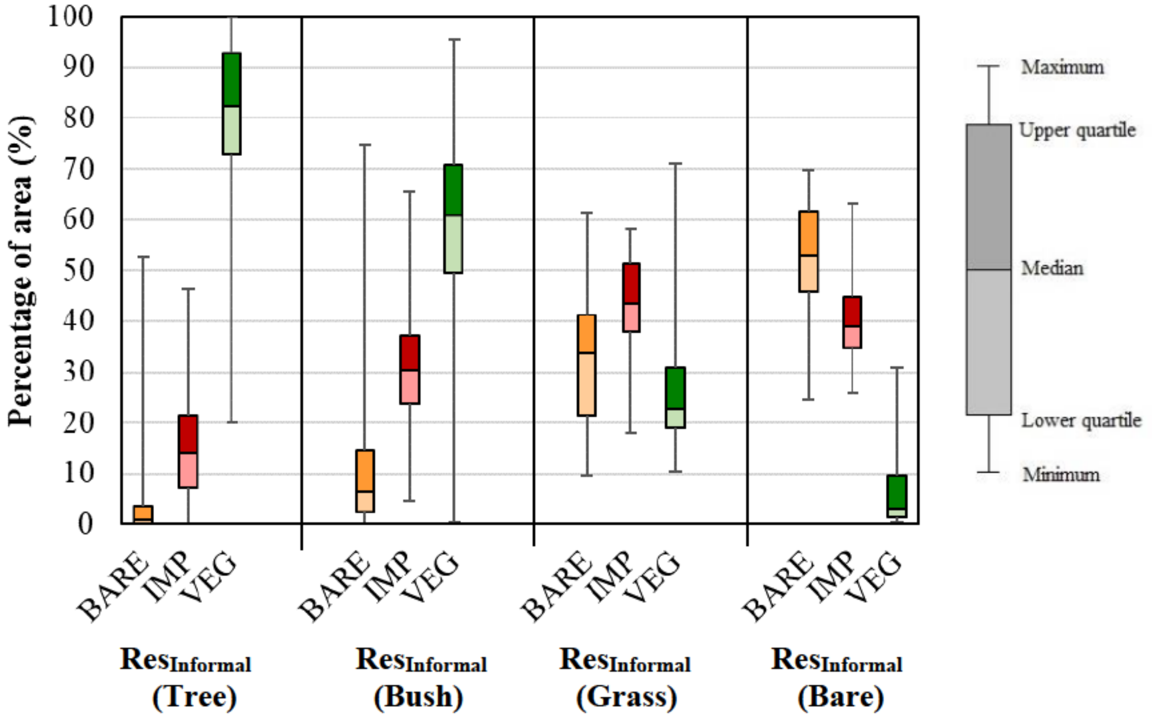


Figure 4.7 Remotely sensed TIA of informal residential SANLC classes within the $RES_{Informal}$ group

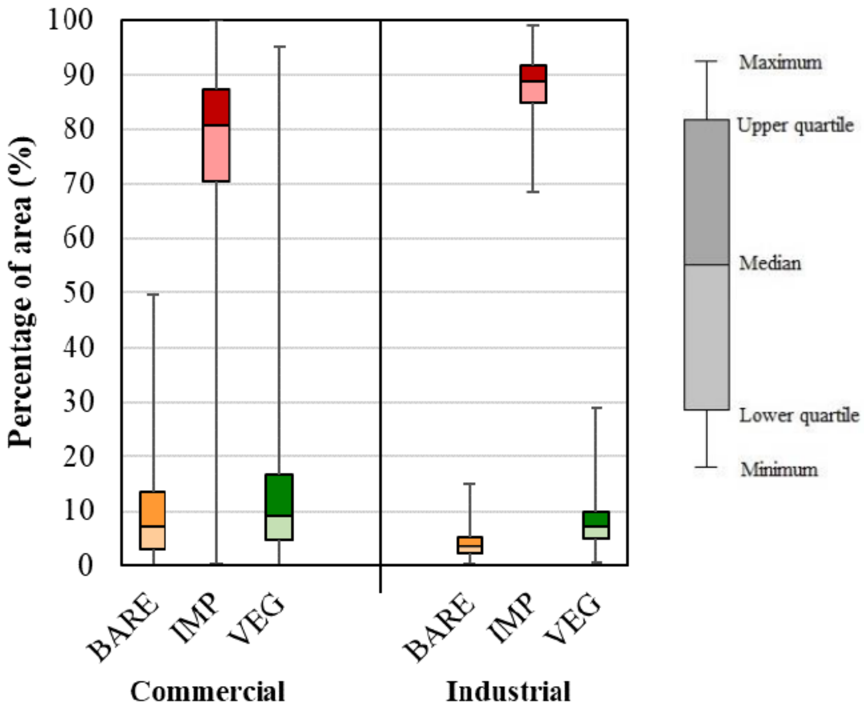


Figure 4.8 Remotely sensed TIA of industrial and commercial SANLC classes within the INDCOM group

The results from the verification zones (Figure 4.9, Figure 4.10 and Figure 4.11) compared well with the TIA as calculated in the sample zones, with differences between the mean values of the sample zones and verification zones of 1.5% for RES_{Formal} areas, 0.6% for Commercial areas and 1.8% for Industrial areas. The sampled area for $RES_{Informal}$ (Tree) was the smallest of all 10 areas due to limited landcover with this classification in the five study catchments. The area that was available for verification of TIA in $RES_{Informal}$ (Tree), was significantly smaller than the sampled area. Less than 1 ha of this land cover class is located in the rest of Tshwane. Therefore, verification was not done on this class. The differences between the mean values of the sample zones and verification zones of the verification of impervious areas in the other three $RES_{Informal}$ SANLC classes was 1.9%.

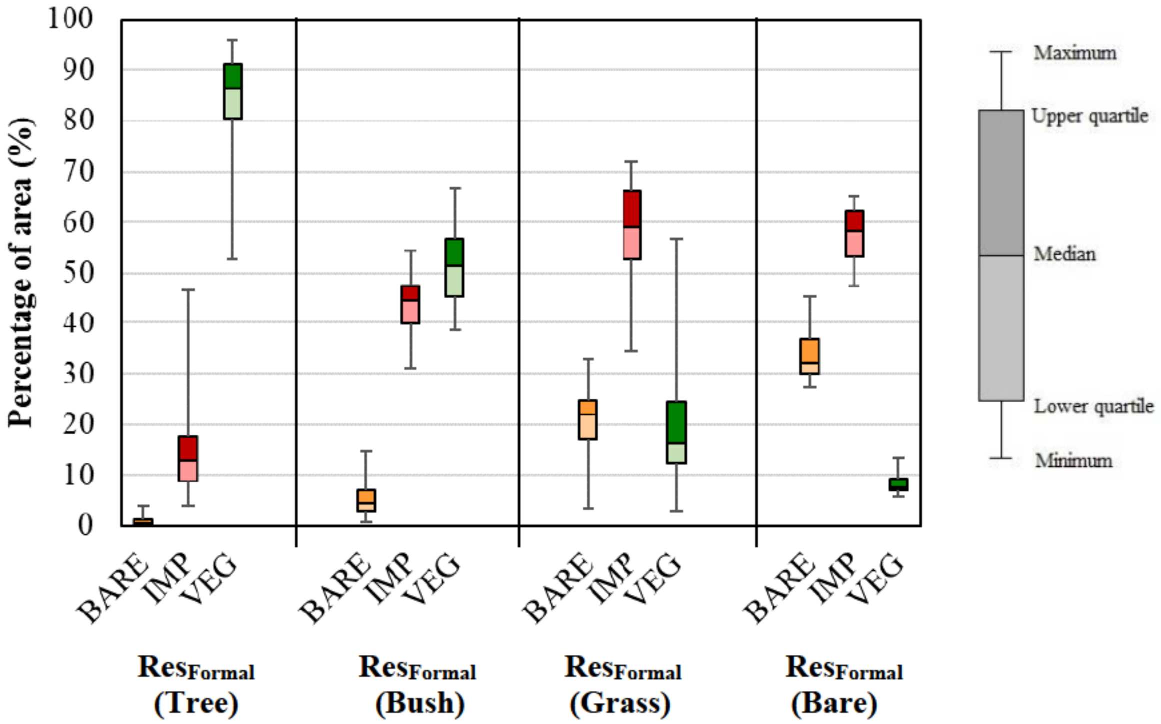


Figure 4.9 Results from verification zones for remotely sensed TIA of formal residential SANLC classes within the RES_{Formal} group (comparable to results in Figure 4.6)

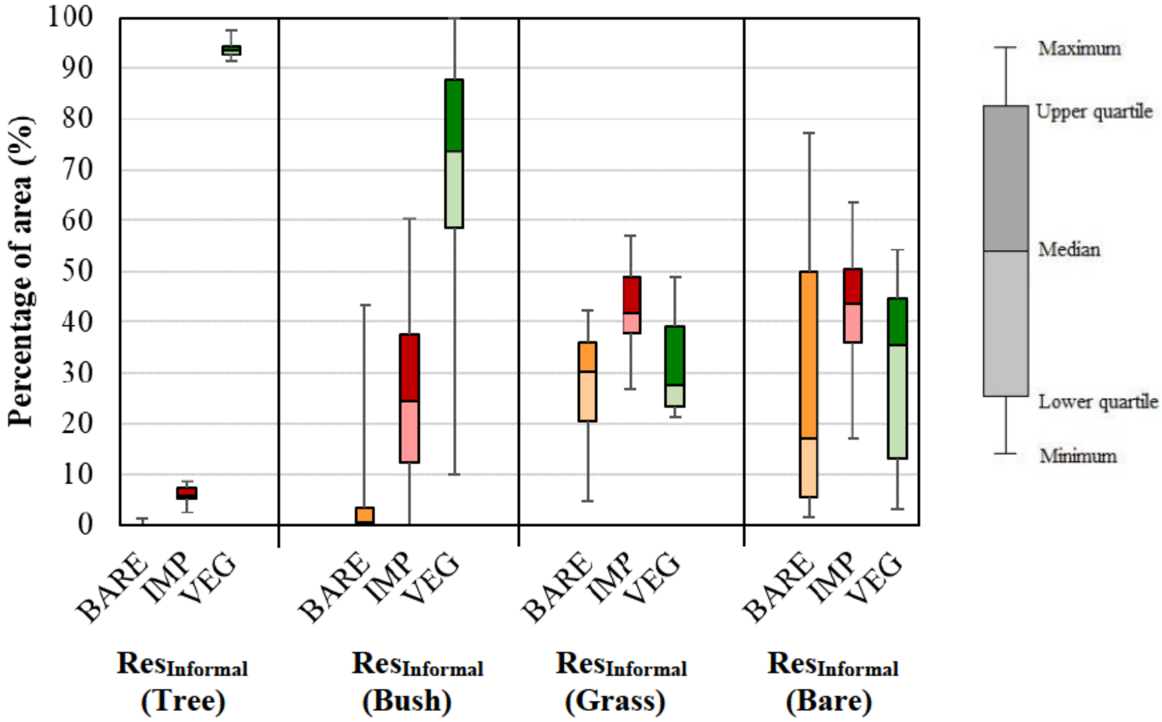


Figure 4.10 Results from verification zones for remotely sensed TIA of informal residential SANLC classes within the $RES_{Informal}$ group (comparable to results in Figure 4.7)

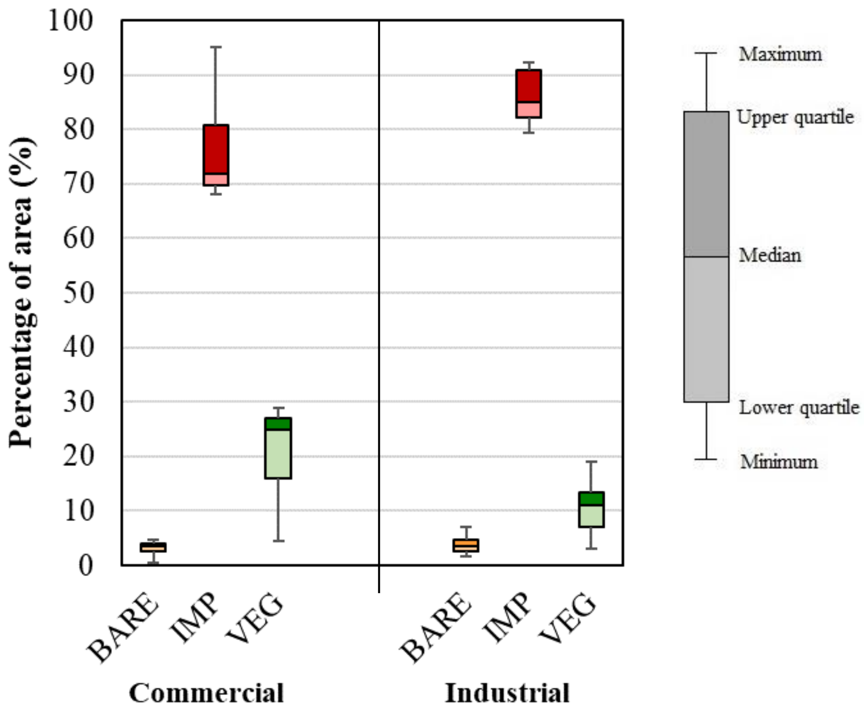


Figure 4.11 Results from verification zones for remotely sensed TIA of industrial and commercial SANLC classes within the INDCOM group (comparable to results in Figure 4.8)

Representative properties for all SANLC classes under investigation were identified and TIA measured in the field for further verification of the remote sensing results. Box-and -whisker plots of TIA as measured on the independent sample stands are shown in Figure 4.12. As shown in Figure 4.12, the median values of all verification results are within 10% of the median of measured results. The median results from the field verification therefore compared reasonably well with the TIA measured using remote sensing, with field verification values showing wider ranges ranges of values between the 25th and 75th percentiles of TIA.

The results were therefore reasonable and median values were chosen as recommended estimates of imperviousness percentages, with the 25th and 75th percentile values of the median suggested as lower and upper confidence intervals. The median values for TIA of each of the 10 investigated urban SANLC classes were used as proposed parameter values of TIA, with 75th percentile and 25th percentile values provided as upper and lower confidence interval ranges, as summarised in Table 4.7.

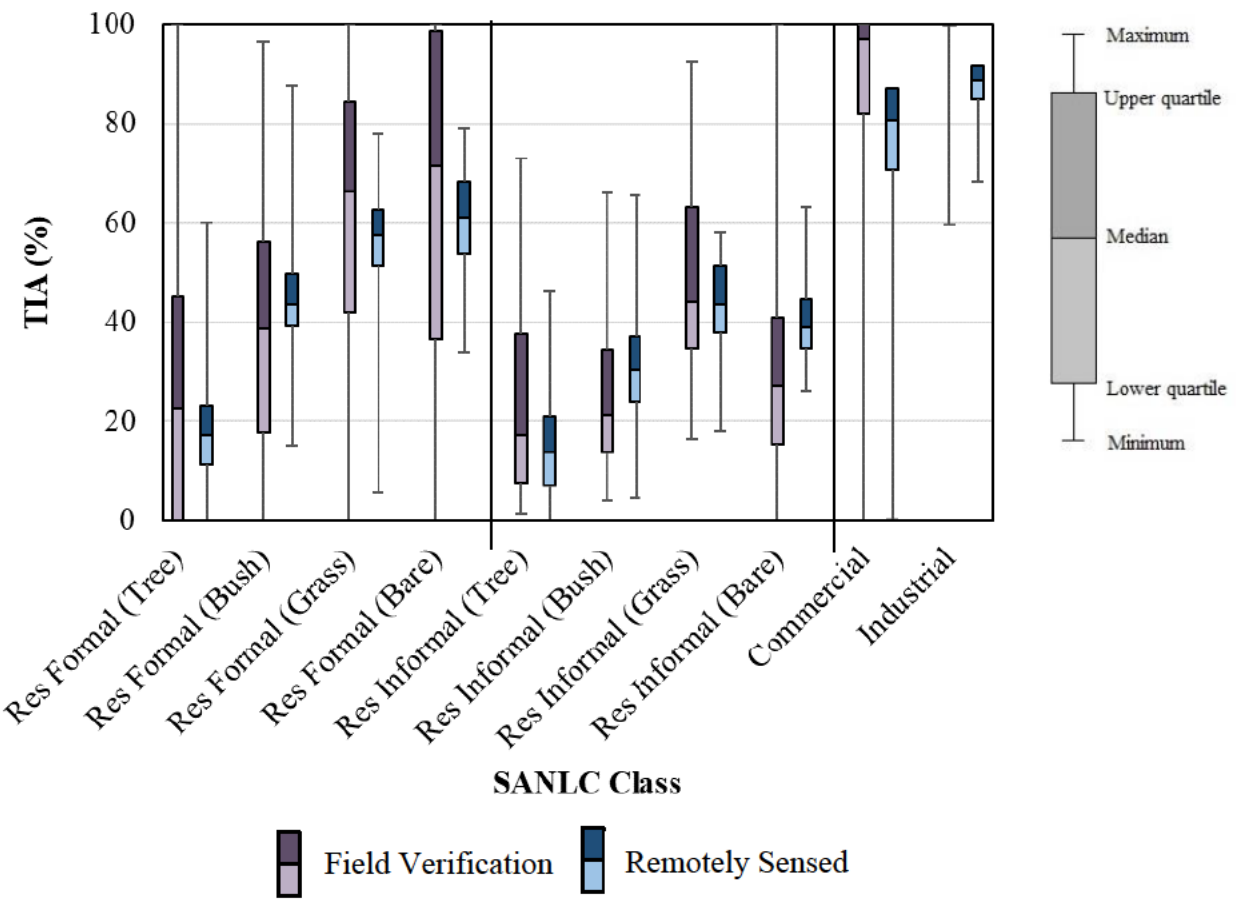


Figure 4.12 Field measurement results for TIA in urban built-up SANLC classes

Table 4.7 Proposed TIA percentages for urban SANLC classes

SANLC Class No.	SANLC Description	TIA (%)		
		L	M	H
47	Residential Formal (Tree)	11	17	23
48	Residential Formal (Bush)	39	44	50
49	Residential Formal (Grass)	51	58	63
50	Residential Formal (Bare)	54	61	68
51	Residential Informal (Tree)	7	14	21
52	Residential Informal (Bush)	24	30	37
53	Residential Informal (Grass)	38	43	51
54	Residential Informal (Bare)	35	40	45
65	Commercial	71	81	87
66	Industrial	85	89	92

4.4 Discussion

The results obtained in this study are discussed in the following paragraphs. First, the historical change in impervious land cover is compared with the urban footprint and then the generalised imperviousness values for different urban SANLC classes are described.

4.4.1 Changes in imperviousness

Objective (a) was to quantify historical and current total imperviousness percentages and impervious area density in the study catchments. Catchment A2H063 had the highest relative developed area of the five study catchments over the study period. It also had the highest $TIA_{\%}$ over the study period. However, Figure 4.5 shows that the development density in this catchment was lower than most of the other study catchments for at least a portion of the study period. Catchment A2H063 was the only catchment showing consistent densification of developed areas over the study period.

Catchments A2H027 and A2H029 had similar trends of $URB_{TOT\%}$ (Figure 4.3) and $TIA_{\%}$ (Figure 4.4) changes over the study period. The density ratios follow almost similar patterns, with Catchment A2H027 having higher development density than Catchment A2H029 (Figure 4.5). Both catchments experienced significant densification in the 1990s, i.e. post-Apartheid. This is attributed to increased urbanisation during this period (Geyer *et al.*, 2012).

Catchments A2H054 and A2H055 also had similar trends of $URB_{TOT\%}$ (Figure 4.3) and $TIA_{\%}$ (Figure 4.4) changes over the study period, but with density ratios that did not show consistent patterns, with Catchment A2H054 initially experiencing increasing development density before experiencing a drop from the year 2000 and density in Catchment A2H055 dropping over most of the study period.

It is evident that all catchments experienced temporal changes in density. Significant variation is also present between catchments This is an indication that different types of development have different levels of imperviousness and that $URB_{TOT\%}$ and $TIA_{\%}$ should not be used interchangeably in a developing country, such as South Africa.

4.4.2 Imperviousness of SANLC classes

Objective (b) was to determine typical permeability percentages for different SANLC classes. It is evident from Figure 4.6 that areas classified as Residential Formal (Trees) have higher percentages of vegetation than other classes, with vegetation percentages decreasing progressively from Residential Formal (Tree) to Residential Formal (Bush) to Residential Formal (Grass) to Residential Formal (Bare). The same trend is evident for informal residential classes, as shown in Figure 4.7. This result was expected and served as confirmation that the methodology was sound.

The results from both remote sensing verification and field verification compared well with the remotely sensed results, with the exception being remotely-sensed imperviousness in RES_{Formal} areas. This is ascribed to trees covering sections of roof and paved areas in RES_{Formal} areas. This error is seen as small enough to justify the remote sensing methodology applied in this study as an acceptable measurement technique for TIA. The analysis of imperviousness therefore showed that, despite variation, it is possible to estimate TIA values for the 10 urban SANLC classes under investigation. It is emphasised that the results from this study are limited to one geographic area as a consequence of the limited availability of observed data in urban areas in South Africa. However, it is postulated that the results are applicable to other regions given the relationships developed with national land cover classes in this study. Also, the specific climate of a study area will be represented by a local climate station during modelling. Thus, until additional data are available and further research is undertaken to improve the results, it is proposed that the imperviousness values in Table 4.7 be considered for hydrological modelling of South African urban areas. Site-specific values are recommended for hydrological modelling where possible.

It was shown that imperviousness is different in RES_{Formal} and $RES_{Informal}$ areas, and also for SANLC classes within land cover groups. Therefore, it is recommended that TIA, rather than $URB_{TOT\%}$, be used to estimate catchment area imperviousness in South African urban hydrological studies. It is proposed that the imperviousness values in Table 4.7 be considered for hydrological modelling of South African urban areas or other areas and regions with similar development characteristics, where site-specific conditions are not easy to quantify.

4.5 Conclusions

This study quantified historical changes in impervious land cover in the five urban study catchments. This data can now be used to test whether links exist between catchment imperviousness and storm runoff responses. This is explored in Chapter 5.

Imperviousness of formal and informal urban land cover types were generalised based on a South African case study. Typical permeability percentages were assigned to different South African National Land Cover (SANLC) classes. The use of these values is recommended as default values for hydrological modelling of South African formal and informal urban areas, or for use in similar land cover classes in other developing countries, where site-specific information is not readily available.

5 ON THE EFFECTS OF IMPERVIOUSNESS ON STORMFLOW IN SOUTH AFRICAN URBAN LANDSCAPES

The journal paper presented in Chapter 3 recommended further investigation into the effect of urban development on catchment response times as well as possible causes for different trends in runoff volumes and flood peaks in the different study catchments. In Chapter 4 the historical and current impervious areas are quantified in the urban study catchments. This chapter focusses on the effects of impervious land cover on catchment response time to rainfall events, as well as storm runoff volume and peak flow rates. This contributes to study objective (b) to quantify the influence of formal and informal South African development types on runoff, as well as study objective (c) to identify the causes of different hydrological trends in catchments with different development types. The study is presented as a draft version of a journal paper.

5.1 Authorship Statement

Status	Draft manuscript
Details	Loots, I., Smithers, J.C., Kjeldsen, T.R. 2023. On the effects of imperviousness on stormflow in South African urban catchments.
Authors' contribution	The author of this thesis is the primary author of this original research manuscript. I Loots contributed to the formulation of the research question (90%), design of the methodology (80%), collection and processing of data (75%), analysis of data (100%) and manuscript preparation (90%). J.C. Smithers contributed to the formulation of the research question (10%), design of the methodology (10%) and manuscript preparation (5%). T.R. Kjeldsen contributed to the design of the methodology (10%) and manuscript preparation (5%). G Mogale, L Moleka and T Mposhomali assisted with data collection in the field and processing of remotely sensed imperviousness data (25%). They were not listed as authors, but thanked as contributors.
Purpose	This paper presents original research that flows from the recommendations made in Chapter 3 and contributes to achieving the first aim of this thesis.

5.2 Abstract

The impacts of imperviousness associated with urban development on flood peaks, flood hydrograph volumes and catchment response times have been extensively researched in developed countries. However, the extent of these impacts has not previously been quantified for urban areas in developing countries where the characteristics of the urban landscapes can differ significantly from typical settlements in developed countries. The aim of the study reported in this chapter was to quantify the impact of increased imperviousness associated with formal and informal urbanisation on storm runoff responses in South Africa. Five representative urban catchments in the city of Tshwane, South Africa were used as case study areas. The link between catchment imperviousness and direct storm runoff volume, runoff peak flow and catchment response time, as well as the relationships between flood peaks and catchment response time and flood peaks and volumes, were investigated using Spearman's correlation coefficient (ρ). Statistically significant correlation was evident between imperviousness and storm runoff volume, which was expected. However, contrary to expectation, catchment response times and peak flow rates did not show statistically significant correlation with the proportion of imperviousness for most catchments with formal urban development. However, the catchment dominated by informal development showed increasing trends in both volume and flood peaks. It is postulated that unexpected attenuation in the formally developed catchments does contribute to these results and it is therefore recommended that it be incorporated in hydrological models of urban catchments with similar characteristics. It is also recommended that increased storm runoff volume be considered in the planning and design of urban drainage systems for expanding formal and informal settlements.

5.3 Introduction

Urbanisation is often associated with more frequent and severe flooding (Jacobson, 2011; Braud *et al.*, 2013; Sakijege, 2013; Ferreira *et al.*, 2016; Saurav *et al.*, 2021). The effects of imperviousness associated with urban development on flood peaks, flood hydrograph volumes and catchment response times have been extensively researched in developed countries (Chang, 2007; USEPA, 2008; Gallo *et al.*, 2013; Choi *et al.*, 2015; Redfern *et al.*, 2016; Walega *et al.*, 2019; Hamilton *et al.*, 2021; Macdonald *et al.*, 2022). However, since very few urban catchments in developing countries are gauged, many studies in these areas rely on hydrological modelling in ungauged urban catchments, or use information from urban catchments with limited datasets, rather than long-term observed data (Lei *et al.*, 2008; Gumindoga *et al.*, 2014; Remondi *et al.*, 2015; Schütte and Schulze, 2017; Hu *et al.*, 2020; Seidl *et al.*, 2020; Saurav *et al.*, 2021). Thus, the extent of the impacts on hydrological responses has not previously been quantified for urban areas in developing countries where the characteristics of the urban landscapes can differ significantly from typical urban developments in developed countries. Although most studies cite imperviousness of entire catchments, rather than specific land uses with in a catchment (Ansari *et al.*, 2016; Sahoo and Sreeja, 2016; Hwang *et al.*, 2017; Schoener, 2017; Sultana *et al.*, 2020), some studies quantified imperviousness of catchments at up to 95% (Hwang *et al.*, 2017). Sohn *et al.* (2017) reported certain residential areas in Houston, Texas, having average impervious proportions of up to 72.8%(Sohn *et al.*, 2017). Koga *et al.* (2016) reported imperviousness of low-rise residential land of 72% in Tokyo, Japan. All of these values differ significantly from the mean imperviousness values calculated for South African National Land Cover (SANLC) (Chapter 4). This contributes to the lack of understanding and knowledge on the impacts of catchment imperviousness on runoff characteristics from formal and informal urban areas in developing countries.

The aim of this study was to quantify the impact of increased imperviousness associated with formal and informal urbanisation on storm runoff responses in South Africa. The specific objectives were to investigate whether a correlation exists between imperviousness associated with different types of formal and informal urban development and: (a) flood volumes, (b) catchment response time and (c) flood peaks. Correlation between flood peaks and (d) flood volumes, as well as between (e) catchment response times, were also evaluated.

5.4 Methods

As this study aims to quantify imperviousness in a range of South African urban land uses, catchment areas with different urban characteristics were identified for inclusion in this study. The following sections describe the study areas and data collation.

5.4.1 Study areas

Five gauged catchments with at least 14% developed urban area as of the year 2020, and with reliable flow records, were selected for use in this study. In each catchment the flow was monitored and made available by the Department of Water and Sanitation (DWS). All five catchments are located within the City of Tshwane Metropolitan Municipality, South Africa (Figure 5.1), with two catchments (Catchments A2H027 and A2H029) containing informal settlements. Formal residential areas in the study area typically contain houses or intensive residential developments with high boundary walls and a combination of paved and vegetated area around the dwellings, with formalised drainage networks. Informal settlements are typically constructed in a haphazard manner, with little impervious area apart from dwelling roofs and generally with no formal drainage systems.

The relevant urban land cover classes, as classified in the 2020 South African National Land Cover (SANLC) assessment (Geoterraimage, 2021), were grouped as summarised in Table 5.1 and the distribution mapped across the study area for each group as shown in Figure 5.1. Land cover classes were organised into formal residential (RES_{Formal}), informal residential ($RES_{Informal}$) and commercial and industrial (INDCOM) groupings. The SANLC classifications are applicable to all similarly developed areas across South Africa (Geoterraimage, 2019; Geoterraimage, 2021), and both classes and assigned groups described in Table 5.1 could be used for similar types of land uses in other developing countries. provides a summary of the five study area catchments. It should be noted that URB_{Park} percentages were not reported here, as they are not relevant to the chapter. Also, URB_{TOT} refers to the urban footprint and TIA refers to the total impervious area. Therefore, the columns in are not meant to add up to 100%.

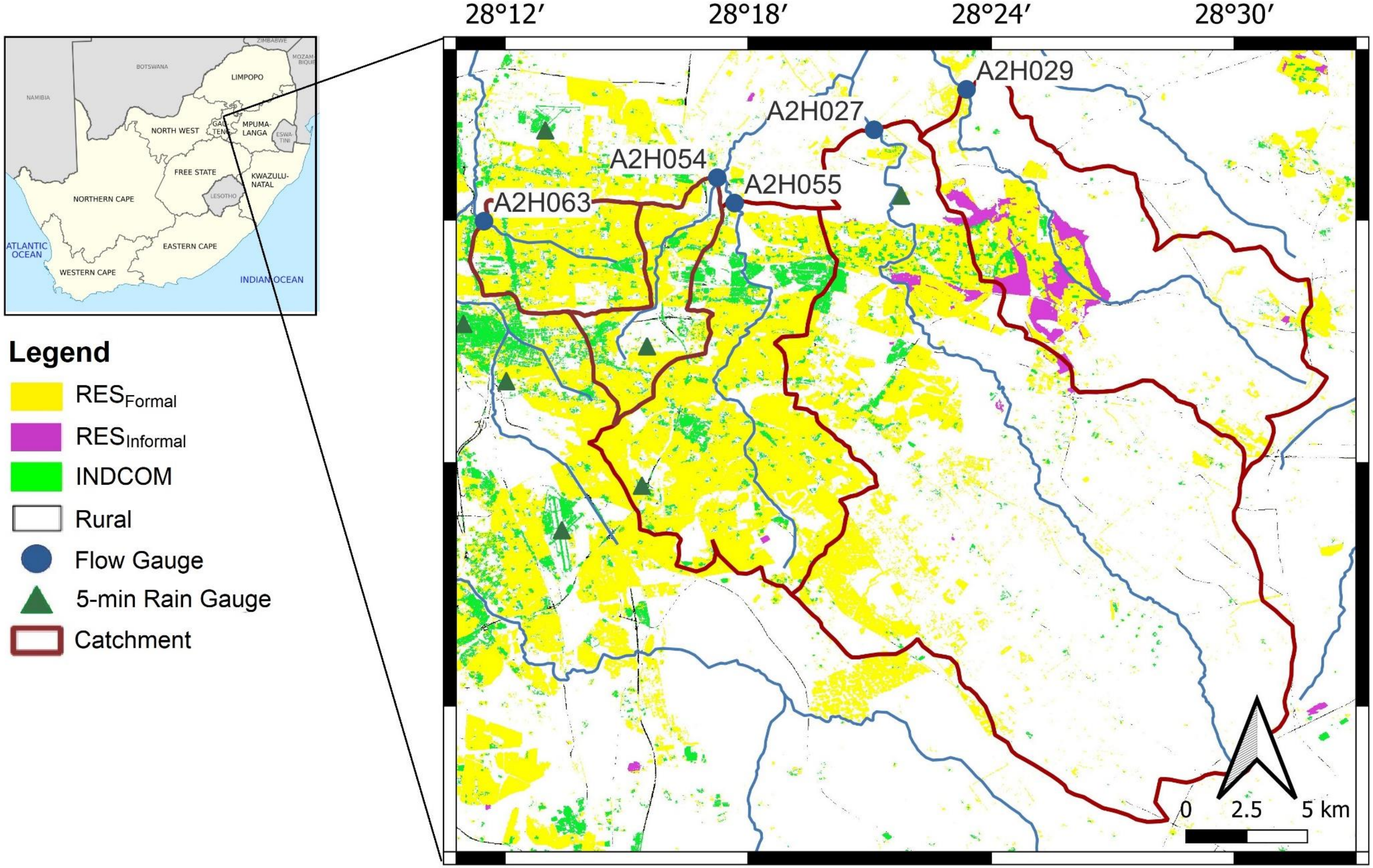


Figure 5.1 Location of study catchments and distribution of groupings of urban areas

Table 5.1 SANLC classes used in this study

SANLC Class No.	**Description**	**Assigned $URB_{TOT\%}$ Group**
47	Residential Formal (Tree)	RES_{Formal}
48	Residential Formal (Bush)	
49	Residential Formal (Grass)	
50	Residential Formal (Bare)	
51	Residential Informal (Tree)	$RES_{Informal}$
52	Residential Informal (Bush)	
53	Residential Informal (Grass)	
54	Residential Informal (Bare)	
65	Commercial	INDCOM
66	Industrial	

Table 5.2 Study area information

DWS Gauging Station	River	Gauge Location (Lat, Long)	Catchment Size (km^2)	Start of Record (month/ year)	End of Record (month/ year)	Catchment Slope (m/m)	URB_{TOT} in 2020 (%)	RES_{Formal} in 2020 (%)	$RES_{Informal}$ in 2020 (%)	INDCOM in 2020 (%)	TIA in 2020 (%) (Ch 4)
A2H027	Pienaars River	-25.66^{O}S 28.35^{O}E	357	05/1962	05/2021	0.011	14.56	11.77	0.57	1.92	9.99
A2H029	Edendale Spruit	-25.65^{O}S 28.39^{O}E	129	05/1962	06/2019	0.012	19.17	10.72	6.55	1.61	12.02
A2H054	Hartbees Spruit	-25.68^{O}S 28.29^{O}E	35	09/1982	05/2021	0.011	64.10	49.22	0.00	10.71	49.90
A2H055	Moretele River	-25.69^{O}S 28.29^{O}E	106	10/1982	06/2018	0.011	72.34	60.00	0.10	9.81	42.67
A2H063	Wonderboom Spruit	-25.70^{O}S 28.19^{O}E	30	05/1984	07/2018	0.009	73.52	62.73	0.00	10.11	55.20

5.4.2 Quantifying the effect of imperviousness on storm runoff

The availability of short duration rainfall in the study area is limited, with only one Automatic Weather Station (AWS) from the South African Weather Service (SAWS) located in three of the catchments. One of the stations has been operational since 2006 and two of the stations have been in operation since 2012, but one station has more than 20% missing data in wet months and another has 10% missing data (Mouton *et al.*, 2022). AWS data from neighbouring catchments are available from 1994 for one station and from 2003 from another station. Due to inadequate rain gauge density in and around the study catchments, and the characteristics of short duration storm intensity in the area, there are significant inconsistencies between days with notable observed rainfall and corresponding notable observed flow hydrographs (Loots and Smithers, 2020). Given the lack of short duration rainfall data to associate with the observed hydrographs, the time-to-peak (T_P) of the hydrograph was used to estimate catchment response time to rainfall events. The historical rainfall series used in this study was previously shown by Loots *et al.* (2022) to be stationary and thus trends in runoff-rainfall ratios were assumed to not be influenced by trends in rainfall.

The T_P is defined as the time elapsed between the start of stormflow producing rainfall and the resulting peak discharge as identified from a single-peaked hydrograph (McCuen *et al.*, 1984; Gericke and Smithers, 2017). This study applied the approach proposed by Gericke and Smithers (2017), where the inflection point on the hydrograph of total flow is considered as the start of the direct runoff, which theoretically coincides with the start of effective rainfall during an event. For multi-peaked hydrographs, T_P was estimated as the duration of total net rise (Du Plessis, 1984; Gericke and Smithers, 2017). This method therefore does not require the need for representative stormflow producing catchment rainfall data, as T_P is derived directly from the observed streamflow data (Figure 5.2).

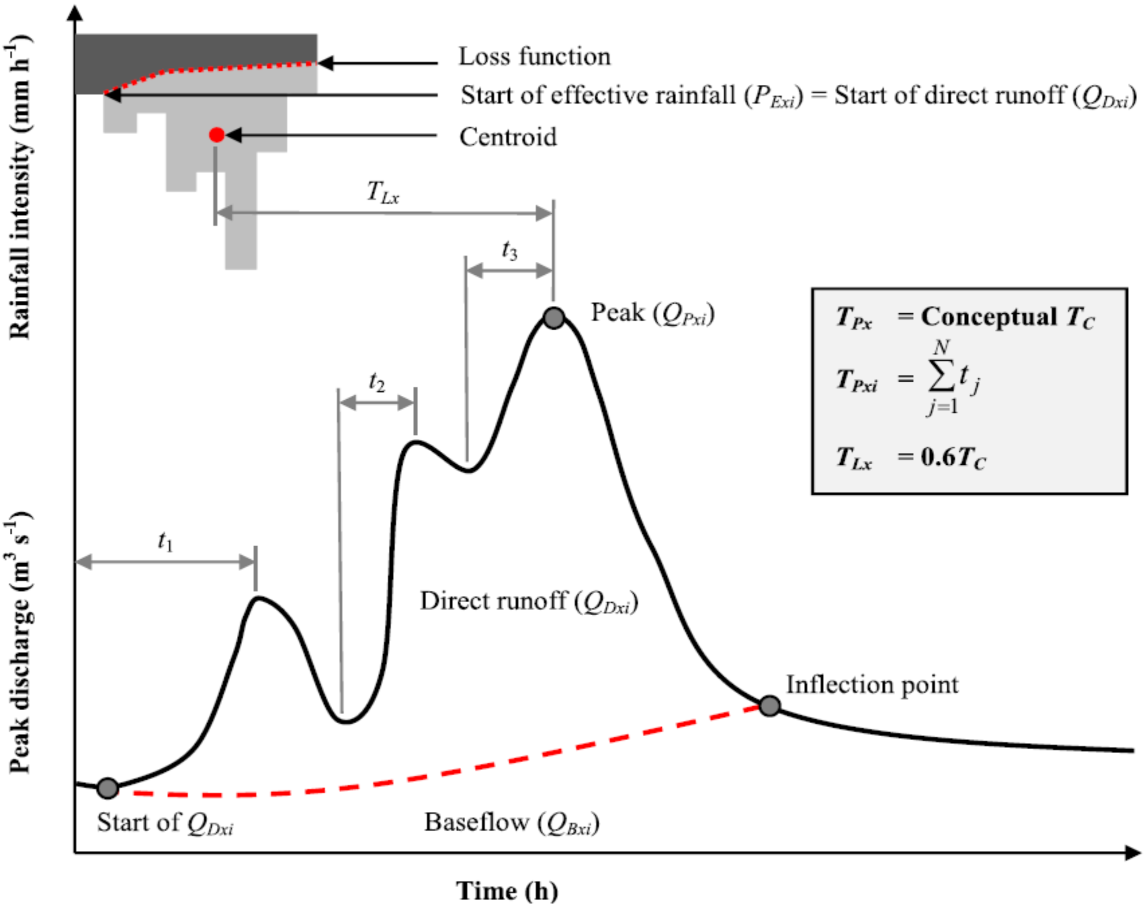


Figure 5.2 Illustration of T_P and Storm runoff estimation (Gericke and Smithers, 2017)

The available instantaneous flow data for each catchment was obtained from DWS for each station and each event hydrograph of the Annual Maximum Series (AMS) was extracted at 30-minute time steps with the HYBASE application in the HYDSTRA/TS data management system, as used by DWS, with peaks also included in the dataset. For each individual event in the annual maximum series, direct runoff was separated from baseflow using recursive digital filtering as first proposed by Lyne and Hollick (1979), adapted and applied in previous South African studies (Smakhtin and Watkins, 1997; Hughes *et al.*, 2003; Gericke and Smithers, 2017; Allnutt *et al.*, 2020):

$$Q_{Dxi} = \alpha Q_{Dx(i-1)} + \beta(1+\alpha)(Q_{Txi} - Q_{Tx(i-1)}) \tag{5.1}$$

where

Q_{Dxi} = filtered direct runoff at time step i [m^3/s],

α = filter parameter between 0 and 1,

β = filter parameter between 0 and 0.5, and

Q_{Txi} = total streamflow at time step i [m^3/s].

Smakhtin and Watkins (1997) established that α-parameters of between 0.995 and 0.997 were applicable for most catchments in South Africa and Hughes *et al.* (2003) found a β-parameter of 0.5 to be acceptable. Gericke and Smithers (2017) found that catchments with sub-daily flow measurements produced better results when an α-parameter 0.997 was used. Since all the data sets for this study had sub-daily measurements, a fixed α-parameter of 0.997 and β-parameter of 0.5 was used to separate the base flow from the primary flow time series. For some years the maximum recorded flow rate is very small and is almost undistinguishable from baseflow. Therefore, hydrographs associated with annual maximum peak flow rates where the peak flow rates are less than 1% of the median of the AMS peak flows, were excluded from the analysis in order to remove AMS events with very small peak discharges. The storm hydrograph volume was calculated as the total volume of direct runoff (Q_{Dxi}) under both the rising and recession limbs of the direct runoff hydrograph, with direct runoff excluding the baseflow subtracted from total runoff as calculated using the Lyne and Hollick (1979) approach, as shown in Figure 5.2.

The degree of correlation between $TIA_{\%}$ and (a) direct runoff volumes, (b) T_p and (c) peak flow rates was evaluated. Degrees of correlation between the peak flow rates and (d) direct runoff volumes and (e) T_p were also tested.

The distribution of each data set was tested and since the majority of the data sets are not normally distributed, the existence of correlation between the variables was tested for statistical significance using the non-parametric Spearman's ρ test (Ahmad et al., 2015; Hu et al., 2020; Hamilton et al., 2021). The magnitude of the Spearman's ρ-value indicates the degree of monotonic association between the two variables, with 0 indicating no association and 1 indicating perfect association (Cohen, 1988; Helsel *et al.*, 2020). Although there is some debate regarding quantification of the applicable strength ranges of ρ-values (Akoglu, 2018), various authors (Yan *et al.*, 2019; Santos *et al.*, 2021) use the interpretation shown in Table 5.3. The sign of the ρ-value provides an indication of positive or negative correlation. The statistical significance was assessed at the 95% level, therefore, any p-value less than 0.05 indicates statistical significance.

Table 5.3 Interpretation of Spearman ρ-values (Yan *et al.*, 2019; Santos *et al.*, 2021)

Spearman's ρ-value	**Interpretation of degree of correlation**
0.00 to 0.19	Very weak
0.20 to 0.39	Weak
0.40 to 0.59	Moderate
0.60 to 0.79	Strong
0.80 to 1.00	Very strong

5.5 Results

Changes over time for (a) direct runoff volumes of the AMS, (b) T_p of the AMS and (c) AMS peak flow rates are shown for each catchment in Figure 5.3, Figure 5.4 and Figure 5.5, respectively. The most noteworthy trend from these graphs is the rising trend of direct runoff volumes. No consistent trend is evident from the peak floods. T_p seems to have increased slightly in most of the catchments. However, the coefficient of determination (R^2) is unsatisfactory in all cases due to the significant variation of the hydrological data, with $R^2>0.5$ considered satisfactory (Moriasi *et al.*, 2007; de Castro Ferreira *et al.*, 2022). Therefore, as TIA has increased in all the catchments over time, a non-parametric correlation test between TIA and each variable would indicate if the trends are statistically significant.

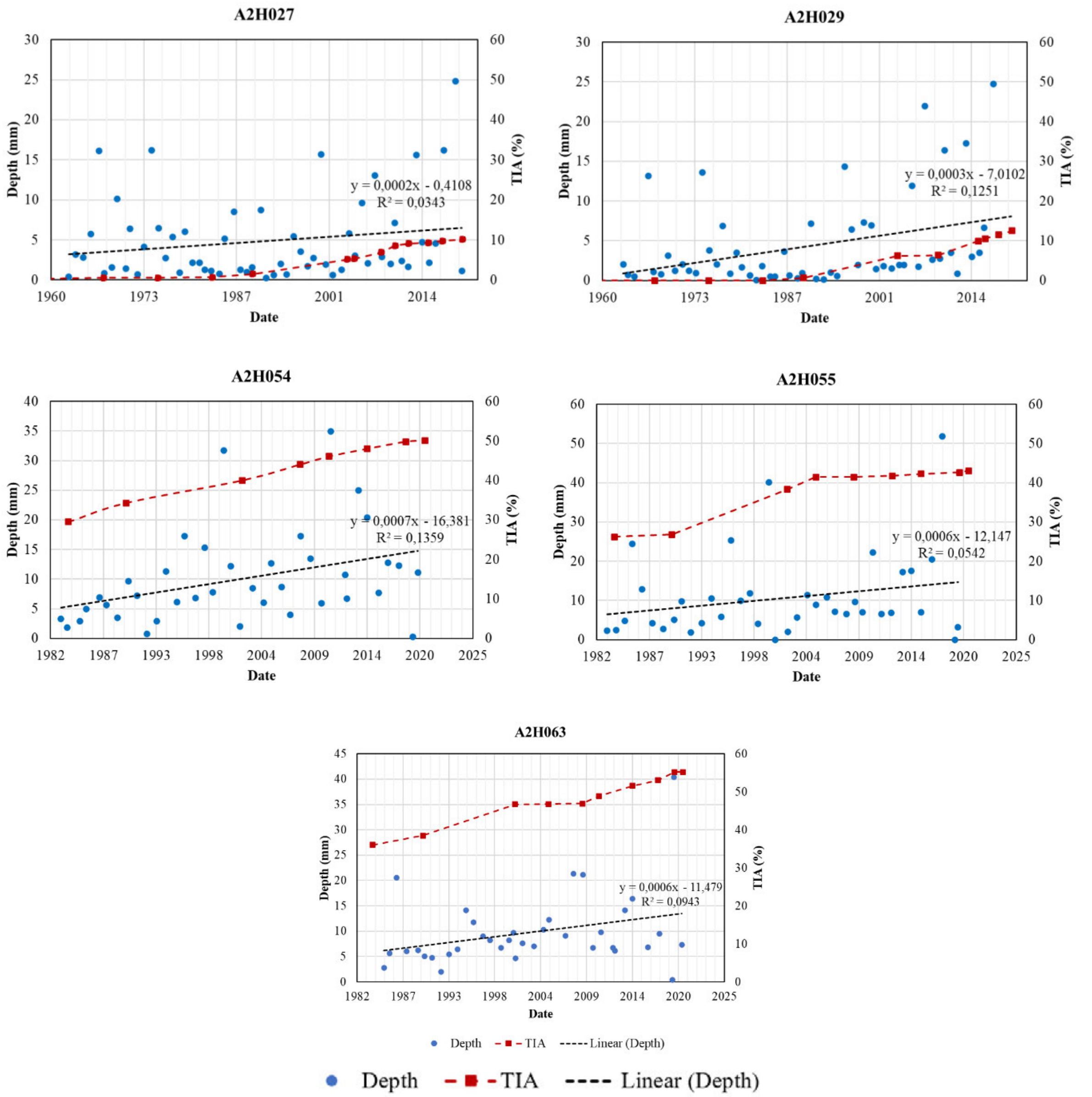


Figure 5.3 Trends in direct runoff volumes of the AMS (reported as depth, mm) and TIA changes in each catchment over the study period

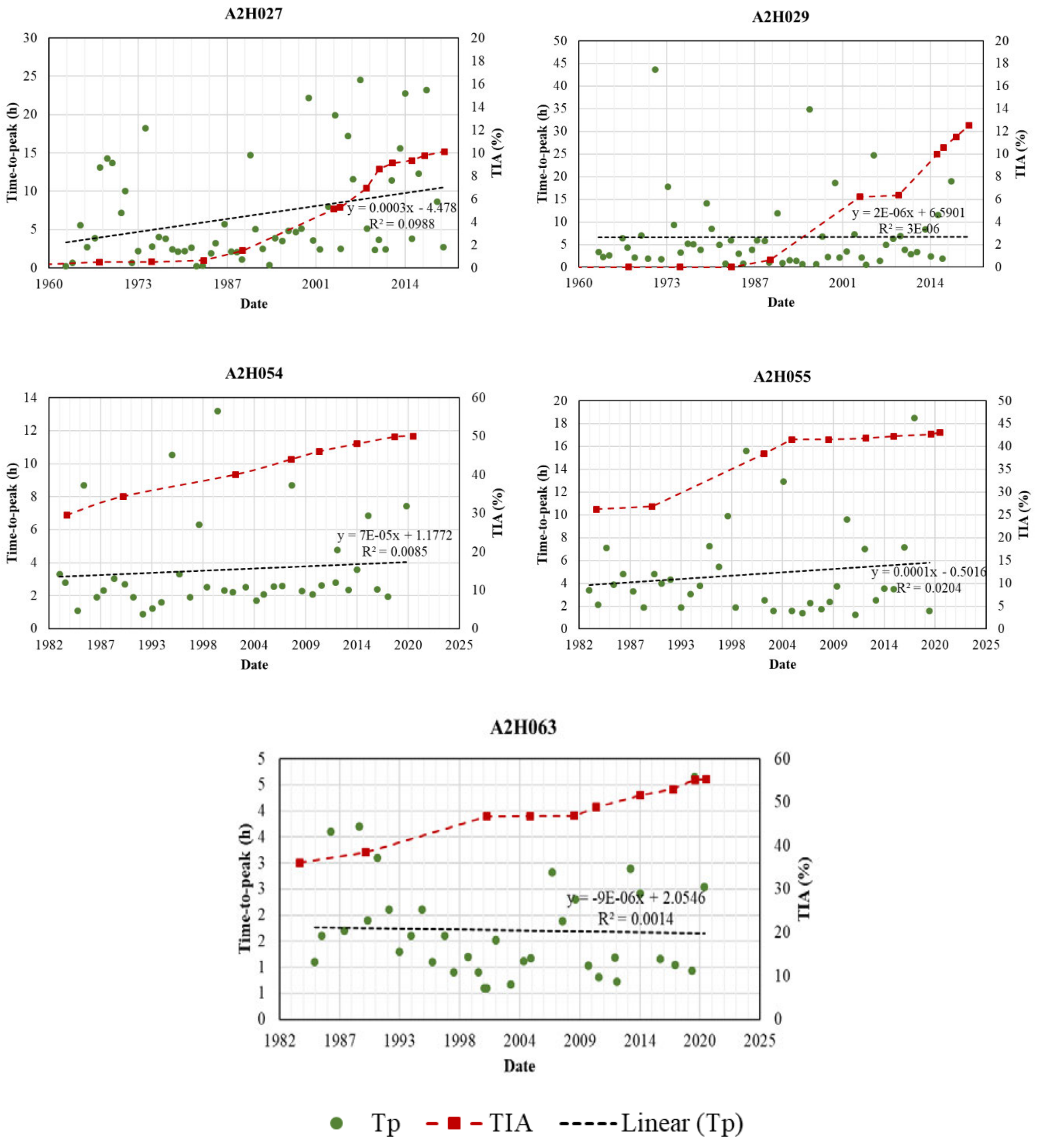


Figure 5.4 Trends in T_p of the AMS and TIA changes for each catchment over the study period

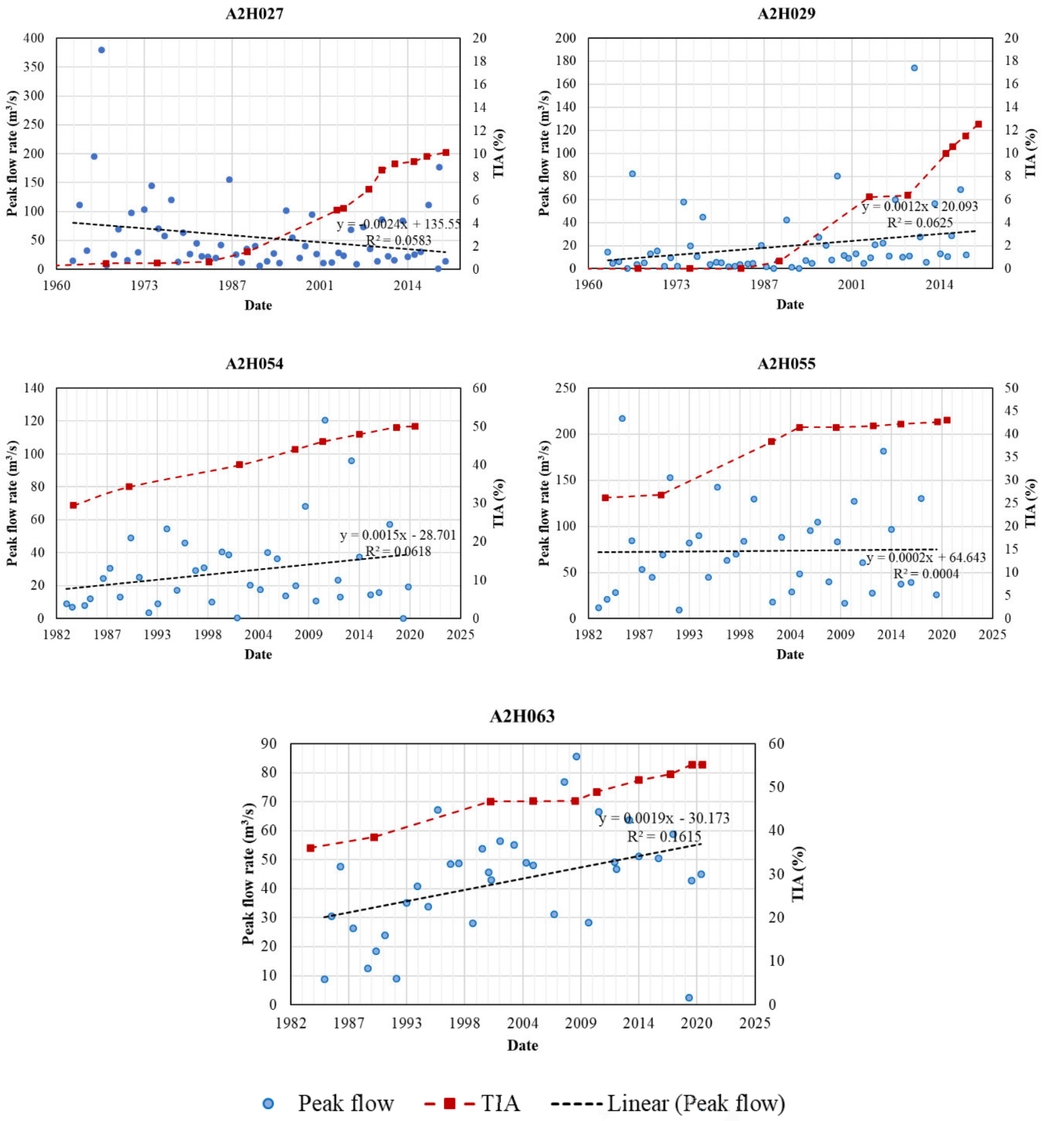


Figure 5.5 Trends in annual maximum peak flow rates and TIA changes for each catchment over the study period

The degree of correlation was tested between TIA and (a) direct runoff volumes, (b) T_P and (c) AMS peak flow rates. The results are summarised in Table 5.4. The degree of correlation between AMS peak flow rates and (d) T_P and (e) direct runoff volumes were also tested. The results are shown in Table 5.5.

The correlation between TIA and volume is significant at the 1% level for Catchments A2H029 and A2H054 and at the 5% significance level for Catchments A2H055 and A2H063.

Catchment A2H027 is the only catchment that showed statistically significant correlation between TIA and T_p, at the 5% significance level. The correlation tests indicated statistically significant correlation between TIA and peak flow rates in Catchments A2H029 and A2H063, both at the 1% significance level. Even though the degrees of association of statistically significant results are classified as weak to moderate (Table 5.3), and there is significant scatter of the results plotted in Figure 5.3, one needs to consider the inherent variability of hydrological data when interpreting the results. Therefore, even results with weak degrees of correlation contribute to our understanding of hydrological trends.

Table 5.4 Spearman ρ correlation results of the TIA with other variables

DWS Gauging Station	**TIA:Volume**		**TIA: T_p**		**TIA:Peak Flow**	
	ρ	***p*-value**	**ρ**	***p*-value**	**ρ**	***p*-value**
A2H027	0.134	0.314	0.312*	0.017	-0.205	0.119
A2H029	0.365**	0.006	-0.011	0.937	0.406**	0.002
A2H054	0.453**	0.004	0.175	0.301	0.225	0.174
A2H055	0.350*	0.037	-0.066	0.704	0.074	0.670
A2H063	0.371*	0.026	-0.317	0.424	0.458**	0.005

*Statistically significant trend at the 5% significance level

**Statistically significant trend at the 1% significance level

Strong to very strong correlation at the 1% significance level was found between AMS peak flow rates and the volume of the associated stormflow for all five catchments. Correlation between AMS peak flow rates and T_p was statistically insignificant for all five catchments in this study.

Table 5.5 Spearman ρ correlation results of the AMS peak flow rates with other variables

DWS Gauging Station	**Peak:Volume**		**Peak: T_p**	
	ρ	***p*-value**	**ρ**	***p*-value**
A2H027	0.846**	<0.001	0.219	0.099
A2H029	0.882**	<0.001	0.163	0.234
A2H054	0.839**	<0.001	0.031	0.857
A2H055	0.703**	<0.001	0.134	0.436
A2H063	0.698**	<0.001	-0.194	0.257

*Statistically significant trend at the 5% significance level

**Statistically significant trend at the 1% significance level

5.6 Discussion

The aim of this study was to investigate whether correlation exists between imperviousness associated with different types of formal and informal urban development and catchment response time, flood volumes and flood peaks, as well as between flood peaks and volumes and catchment response time. There is a statistically significant, positive, correlation between catchment imperviousness (TIA) and direct storm runoff volumes in four of the five urban study catchments, including those with formal (Catchments A2H054, A2H055 and A2H063) and informal development (Catchment A2H029). Even though the degrees of association of statistically significant results are classified as weak to moderate (Table 5.3), and there is significant scatter of the results plotted in Figure 5.3, the inherent variability of hydrological data needs to be considered when interpreting the results. Therefore, even results with weak degrees of correlation contribute to our understanding of hydrological trends. Catchment A2H027 is the only catchment that does not show statistically significant correlation. This result is consistent with the findings of most other studies (Konrad, 2003; Putro *et al.*, 2016) in developed countries. Increased storm runoff volumes should be considered in the planning and design of any infrastructure related to flood attenuation or sustainable urban drainage systems, as increased flood volumes would need to be accommodated with increased catchment imperviousness, in both formal and informal developments. The fact that direct storm runoff increase was statistically insignificant in Catchment A2H027 could be attributed to the size and shape of the catchment, with urban development only occurring in the lower third of the catchment. However, this cannot be proven from the data analysed and further research is recommended. The strong correlation between direct runoff volume and AMS peak flow rates in all study catchments was expected, as a hydrograph with a larger peak would usually have a larger total volume contributing to the peak.

The only catchment with statistically significant correlation between TIA and T_p is Catchment A2H027. This catchment exhibited a positive correlation between TIA and T_p, signifying an increase in T_p with increasing TIA. This result is contrary to the generally accepted notion that increased imperviousness would decrease catchment response times (Fletcher *et al.*, 2013; McGrane, 2016), although some studies have found similar results (Miller and Hess, 2017; Requena *et al.*, 2017). However, as this is the only catchment with a statistically significant correlation, the lack of statistically significant results in the other four study catchments may be more informative. It has been shown that the flood volumes in these catchments increased with increased TIA, so the increased volumes without reduced T_p is postulated to be attributed to unexpected attenuation in the catchments, as suggested by Van Vuuren (2012).

The above argument is strengthened by the statistical insignificance of peak flow rate increases in the majority of the study catchments, which is also contrary to results from many studies in developed countries (Konrad, 2003; Lee and Heaney, 2003; Todeschini, 2016). It is thus recommended that attenuation be incorporated in hydrological models of South African urban catchments. The anomalies in the AMS flood peak analyses are Catchments A2H029 and A2H063. Catchment A2H029 contains informal settlements that, in contrast to many formal South African settlements, are typically not surrounded by boundary walls that could act as attenuating structures during and after storm events, although informal settlements are generally not connected to formal drainage infrastructure (Parkinson *et al.*, 2007; Gogate and Rawal, 2015). The statistically insignificant change in T_p, but with increasing AMS and direct storm runoff volumes in Catchment A2H029 is an interesting result that should be investigated further in other catchments with informal settlements, by considering the complexities of increasing impervious areas without increased impervious area connectivity. Catchment A2H063 is the only catchment with a significant proportion of formal development that showed a statistically significant increase in peak flow rates with increasing TIA. It was determined in Chapter 4 that Catchment A2H063 has similar current levels of RES_{Formal} and INDCOM developments as Catchments A2H054 and A2H055. It has the highest historical $URB_{TOT\%}$ throughout the study period. It also had the highest TIA throughout the study period, with similar trends to Catchments A2H054 and A2H055. It was shown in Chapter 4 that the development density in this catchment has been lower than in Catchments A2H054 and A2H055 for most of the study period. However, this catchment was the only catchment with constantly increasing impervious area density within the $URB_{TOT\%}$ (Chapter 4). Many studies have shown a link between impervious area connectivity and runoff (Lee and Heaney, 2003; Roy and Shuster, 2009; Yao *et al.*, 2015; Redfern *et al.*, 2016; Miller *et al.*, 2020). It is possible that the connectivity of impervious areas to drainage systems increased with increased TIA density, thereby leading to less attenuation and larger flood peaks in this catchment. It is thus recommended that the direct and indirect connectivity of formal and informal settlements to drainage systems needs to be investigated further.

5.7 Conclusions

The applicability of the widely accepted impacts of the change in urban imperviousness on catchment response in the form of flood peaks, flood volumes and response times, were investigated. The study found a statistically significant correlation between increased catchment imperviousness and direct runoff volume in both formally and informally developed catchments. It is therefore recommended that this aspect be considered in the planning and design of any infrastructure related to flood attenuation or sustainable urban drainage systems, whether the upstream development is formalised or not. Contrary to most studies, insignificant changes were evident in catchment response times and flood peaks for most of the catchments with formalised development. The seeming paradox of increased flood volumes without corresponding increase in flood peaks is attributed to the temporary storage and subsequent unexpected attenuation of peaks in the in catchments. It is recommended that attenuation be incorporated in hydrological models of ungauged urban areas with similar characteristics and levels of development. The catchment with the highest relative proportion of informal development showed increased flood volumes and increased flood peaks, but without a statistically significant decrease in catchment response time. It is recommended that this result be investigated further by considering the complexities of increasing impervious areas without increased impervious area connectivity. It is also recommended that the direct and indirect connectivity of formal and informal settlements to drainage systems be investigated further.

6 DERIVATION AND ESTIMATION OF IMPERVIOUS SURFACE CONNECTIVITY OF URBAN LAND COVER IN SOUTH AFRICA

The studies presented in Chapter 3 and Chapter 5 recommended further investigation into the connectivity of South African formal and informal settlements to drainage systems. This chapter describes the derivation of methods for predicting connectivity of impervious areas for different SANLC classes. This contributes to addressing study objective (a) to improve understanding of the complexity of urban areas in South Africa as well as study objective (c) to identify the causes of different hydrological trends in catchments with different development types. The study is presented as a draft version of a journal paper.

6.1 Authorship Statement

Status	Draft manuscript
Details	Loots, I., Smithers, J.C., Kjeldsen, T.R. 2023. Derivation and estimation of impervious surface connectivity of urban land cover classes in South Africa.
Authors' contribution	The author of this thesis was the primary author of this original research manuscript. I Loots contributed to the formulation of the research question (90%), design of the methodology (80%), data collection (25%), processing and analysis of data (100%) and manuscript preparation (90%). J.C. Smithers contributed to the formulation of the research question (10%), design of the methodology (10%) and manuscript preparation (5%). T.R. Kjeldsen contributed to the design of the methodology (10%) and manuscript preparation (5%). G Mogale, L Moleka and T Mposhomali assisted with data collection in the field (75%). They were not listed as authors, but thanked as contributors.
Purpose	This paper presents original research that flows from the recommendations made in Chapters 3 and 5 of this thesis and contributes to achieving both aims of this thesis.

6.2 Abstract

The connectivity of impervious areas to drainage systems can have a significant influence on runoff response to rainfall in urban catchments. However, quantifying Directly Connected Impervious Areas (DCIA) can be difficult and time consuming. Therefore, this study aims to investigate if DCIA can be reliably estimated from urban land use classes in South Africa. The connectivity of 292 sample sites, covering 477 parcels of land when considering that some sites contained sections with different South African National Land Cover (SANLC) classes, were measured in the City of Tshwane in South Africa. Connectivity was determined by measuring Total Impervious Area (TIA) of sample sites and then determining on site which proportions of TIA were directly connected to drainage systems, either via pipes directly, or via other impervious areas. Sample sites from all urban residential SANLC classes were included in the study, as well as commercial and industrial areas. Three different methods to predict DCIA from total impervious area (TIA) were investigated: (a) relationships derived in previous studies, (b) median values from DCIA measured for each SANLC class in this study and (c) linear regression relationships derived based on the DCIA measured for each assigned DCIA group in this study. The accuracy of the predictions was assessed using the Root Mean Square Error (RMSE) and coefficient of determination (R^2). It was found that DCIA estimated from TIA using relationships from previous studies did not perform well for the catchments used in this study, with RMSE values of over 30% and R^2 values lower than 0.5 for most equations applied to formal residential areas, and RMSE values of over 20 and R^2 values lower than 0.2 for most equations applied to informal residential areas. The prediction equations provided better results for the INDCOM group, with RMSE values of less than 20 and R^2 values higher than 0.8 for most equations. From the results derived in this study, it is proposed that median DCIA percentages be used for formal and informal residential areas. A relationship was derived in this study to estimate DCIA from TIA for industrial and commercial areas where direct measurement of DCIA is not possible.

6.3 Introduction

Numerous studies over the past two decades have highlighted the significance of the connectivity of impervious areas to drainage systems on runoff responses in urban areas (Lee and Heaney, 2003; Jacobson, 2011; Miller *et al.*, 2014; Yao *et al.*, 2015; Sahoo and Sreeja, 2016; Sohn *et al.*, 2017; De Mello Silva and Da Silva, 2020; Sultana *et al.*, 2020; Sankalp and

Sahoo, 2021). However, it is difficult and often costly to confirm which sections of impervious cover on a property are directly connected to constructed or natural drainage systems, either through other impervious areas or pipes (Boyd *et al.*, 1993; Sutherland, 1995; Yang *et al.*, 2011; Sahoo and Sreeja, 2016). In this study, these areas are referred to as Directly Connected Impervious Areas (DCIA). Therefore, a number of previous studies have investigated the relationship between Total Impervious Area (TIA), calculated as a percentage of total sample site area ($TIA_{\%}$), and Directly Connected Impervious Area (DCIA), and developed methods to predict the percentage of DCIA ($DCIA_{\%}$) from $TIA_{\%}$ (Alley and Veenhuis, 1983; Sutherland, 1995; Wenger *et al.*, 2008; Roy and Shuster, 2009; Phillips *et al.*, 2014; Sahoo and Sreeja, 2016; Sultana *et al.*, 2020). However, few studies have focussed on the connectivity of impervious areas in developing countries, with very little information on the characteristics of informal settlements (Parkinson *et al.*, 2007; Gogate and Rawal, 2015; Sankalp and Sahoo, 2021), and no information is currently available specifically for typical South African urban developments.

Therefore, the aim of this study is to investigate if DCIA can be reliably estimated using formal and informal urban land use classes in South Africa. In order to achieve this aim, this study has two objectives. Firstly, to measure impervious area connectivity to drainage systems for different urban South African Land Cover (SANLC) classes. Secondly, to derive and test prediction equations from the measured data to estimate typical representative connectivity percentages of impervious area for use in hydrological modelling of urban areas in South Africa.

6.4 Methodology

The following sections detail the methodology applied and study areas used in this study. The methodology followed to measure DCIA in different South African urban land cover classes is discussed. The derivation of methods to estimate $DCIA_{\%}$ from $TIA_{\%}$ is also detailed.

6.4.1 Study areas

The study focussed on data from five gauged catchments located in the eastern suburbs of the City of Tshwane Metropolitan Municipality in South Africa, as shown in . The city contains a variety of urban land use classes. The relevant urban SANLC classes from the 2020 land cover assessment (Geoterraimage, 2021) are shown in Table 6.1, with Classes 47-50 representing formal residential areas (RES_{Formal}); Classes 51-54 representing informal residential areas ($RES_{Informal}$); Class 65 representing commercial and Class 66 representing industrial classes (INDCOM). These land cover classifications are applicable to all similarly developed areas across South Africa (Geoterraimage, 2019; Geoterraimage, 2021). The total urban footprint, described as a percentage of catchment area ($URB_{TOT\%}$) within each of the five study catchments, was delineated using topographical maps and the SANLC data sets (Geoterraimage, 2021). The $TIA_{\%}$ for each catchment was estimated using remote sensing of satellite images, as described in Chapter 4.

Table 6.1 SANLC classes used in this study

SANLC Class No.	**Description**	**Assigned DCIA Group**
47	Residential Formal (Tree)	RES_{Formal}
48	Residential Formal (Bush)	
49	Residential Formal (Grass)	
50	Residential Formal (Bare)	
51	Residential Informal (Tree)	$RES_{Informal}$
52	Residential Informal (Bush)	
53	Residential Informal (Grass)	
54	Residential Informal (Bare)	
65	Commercial	INDCOM
66	Industrial	

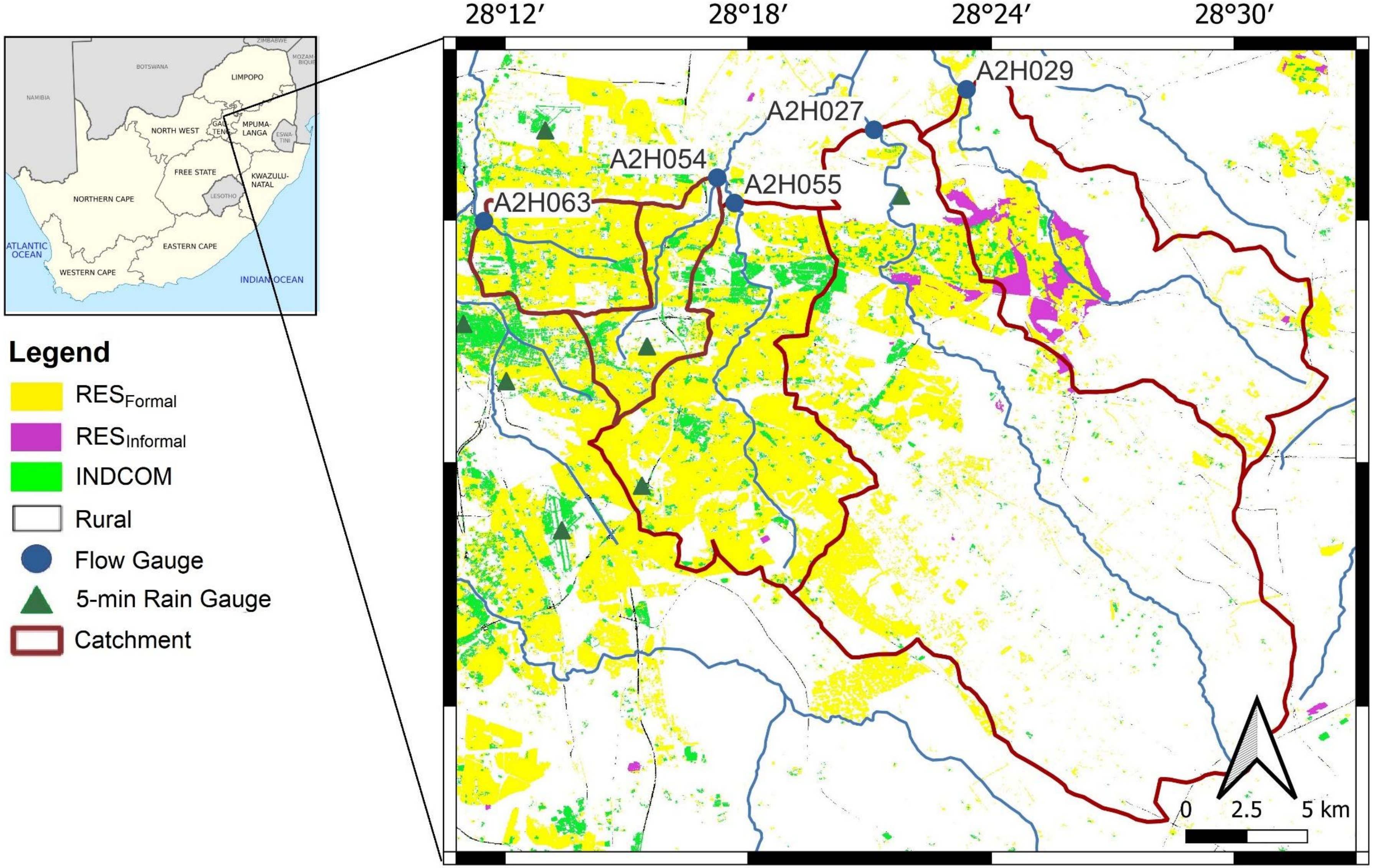


Figure 6.1 Location of study catchments and distribution of groupings of urban areas

6.4.2 Review of previous urban drainage connectivity studies

Remote sensing is often applied to quantify the TIA of a catchment (Marcinkowska-Ochtyra *et al.*, 2017; Castaldi *et al.*, 2019; Cipta Ramadhan Kete *et al.*, 2019; Pan *et al.*, 2020). However, it is difficult and costly to quantify DCIA (Boyd *et al.*, 1993; Sutherland, 1995; Yang *et al.*, 2011; Sahoo and Sreeja, 2016). Therefore, numerous previous studies have investigated the relationship between $TIA_{\%}$ and $DCIA_{\%}$. Some studies refer to hydraulically connected impervious areas as Effective Impervious Area (EIA), with Ball *et al.* (2019) defining EIA as a combination of DCIA and flow from impervious areas onto pervious areas that are saturated soon after a storm event starts. For the purpose of this study, EIA is assumed to be equal to DCIA. Many studies developed equations to predict $EIA_{\%}$ or $DCIA_{\%}$ from $TIA_{\%}$. All the prediction models developed in previous studies have the same basic structure, with:

$$EIA_{\%} = A \times (TIA_{\%})^{B} - C \tag{6.1}$$

Values for the multiplication factor A, exponent B and constant C have been derived based on the areas used in each study, with B equal to 1 and C equal to 0 in some cases. A summary of the approaches followed in previous studies is contained in this section in order to assess their performance in South Africa and to inform the methodology applied to predict DCIA in this study.

Using data from Denver, Colorado, Alley and Veenhuis (1983) developed an empirical formula to estimate $EIA_{\%}$ from $TIA_{\%}$, both measured as percentages of the total area, as shown in Equation 6.2, with a reported coefficient of determination (R^2) of 0.98:

$$EIA_{\%} = 0.15 \times (TIA_{\%})^{1.41} \tag{6.2}$$

Sutherland (1995) proposed a number of relationships between $TIA_{\%}$ and $EIA_{\%}$ based on a general power relationship. Values for the multiplication factor A and exponent B were proposed by Sutherland (1995) based on sub-catchment characteristics as shown in Table 6.2, based on the assumption that $TIA_{\%}$ greater than 1% for all equations.

Table 6.2 Sutherland EIA equations (Sutherland, 1995)

Catchment Description	Equation	Equation Number
Average catchments	$EIA_{\%} = 0.1 \times (TIA_{\%})^{1.5}$	(6.3)
Highly connected catchments	$EIA_{\%} = 0.4 \times (TIA_{\%})^{1.2}$	(6.4)
Totally connected catchments	$EIA_{\%} = TIA_{\%}$	(6.5)
Somewhat connected catchments	$EIA_{\%} = 0.04 \times (TIA_{\%})^{1.7}$	(6.6)
Extremely disconnected catchments	$EIA_{\%} = 0.01 \times (TIA_{\%})^{2}$	(6.7)

Wenger *et al.* (2008) assumed that DCIA and EIA would be similar. They used DCIA data estimated from high-resolution aerial photographs of the Etowah River Basin, located North of Atlanta, Georgia in the USA. They proposed Equation 6.8 for estimating $EIA_{\%}$ from $TIA_{\%}$, with R^2 of 0.98. Both $EIA_{\%}$ and $TIA_{\%}$ were calculated as percentages based on the entire study area, with DCIA being 0 for $TIA_{\%}$ values of less than 6.23%:

$$EIA_{\%} = (1.046 \times (TIA_{\%})^{B}) - 6.23 \tag{6.8}$$

A study by Roy and Shuster (2009) using data collected for Cincinnati, Ohio in the USA confirmed the variability between TIA and DCIA. They derived Equation 6.9 for calculating $DCIA_{\%}$ from $TIA_{\%}$, both calculated as percentages based on their entire study area, with $DCIA_{\%}$ being 0 for $TIA_{\%}$ values of less than 1.86%, based on Equation 6.3:

$$DCIA_{\%} = (0.627 \times TIA_{\%}) - 1.86 \tag{6.9}$$

However, Roy and Shuster (2009) found that the equation created for the entire study area from reliable data did not accurately estimate $DCIA_{\%}$ in many of the sub-catchments, with R^2 of 0.57. They suggested that, although TIA could be accurately determined using aerial photos, it is necessary to conduct field investigations to determine DCIA.

Phillips *et al.* (2014) used regression analysis of runoff from storm events in gauged Australian catchments and found that $EIA_{\%}$ is typically between 55% and 65% of TIA, with $TIA_{\%}$ typically between 40% and 60% of the catchment area. $DCIA_{\%}$ was estimated between 81% and 95% of TIA using GIS methods.

Sultana *et al.* (2020) analysed rainfall and runoff data from seven catchments in southern California in the USA. EIA was estimated from measured or modelled runoff from each catchment, assuming runoff from small homogeneous rainfall events were from hydraulically connected impervious areas only. Runoff depths of more than 1 mm above the linear regression line of all events were removed to isolate small rainfall events. A weighted least square method was used to derive a relationship for $DCIA_{\%}$ from $TIA_{\%}$, as shown in Equation 6.10. The equation is valid for areas with $TIA_{\%}$ of more than 2.54%.

$$DCIA_{\%} = (0.842 \times TIA_{\%}) - 2.1594 \tag{6.10}$$

In contrast with the effects of dense urban development in first-world countries, Parkinson *et al.* (2007) found that runoff from informal settlements is generally lower than expected. They cite possible reasons for this as a combination of a lack of paved surfaces, resulting in higher infiltration rates, and incomplete drainage systems, which lead to ponding in low-lying areas. Gogate and Rawal (2015) also found that in developing countries, such as India, storm water drainage structures have not been constructed for many of the roads, resulting in stagnation, ponding and potholes in roads. Sahoo and Sreeja (2016) attempted to quantify $EIA_{\%}$ in Guwahati, Northeast India, through a semi-automated direct method that integrated remote sensing, spatial drainage details and digital elevation models. They derived a power equation (Eq. 6.11) not dissimilar to Sutherland's equation (Sutherland, 1995) for extremely disconnected catchments (Eq. 6.7):

$$EIA_{\%} = 0.0035 \times (TIA_{\%})^{2.17} \tag{6.11}$$

The performance of the equations derived from the above studies was assessed using data from the five study catchments and are compared with the regression equations and median values derived from measured $DCIA_{\%}$ in this study. The methodology applied to measure DCIA and derive prediction equations for different South African urban areas in this study is described in the next section.

6.4.3 Measurement of impervious area connectivity

As noted by Roy and Shuster (2009), the connectivity of impervious areas cannot be accurately measured remotely. Hence, the TIA and DCIA of representative accessible sample sites from all eight of the residential urban SANLC classes (Geoterraimage, 2021), as well as commercial and industrial land cover classes, were measured on site. On properties where access was denied, detailed notes were taken from the street regarding the drainage paths of impervious areas and DCIA measurements were taken using high resolution 2020 Google Earth images. Only sites with good visibility of drainage paths were used in instances where this methodology had to be followed. Sample sites from different neighbourhoods with similar SANLC classes were included in the sampling in order to improve representation of the sampled sites for other areas in South Africa with similar SANLC classes. The characteristics of impervious areas and drainage systems were observed and noted during field investigation in order to improve the analysis of results.

For each sample site, the total area with impervious land cover was measured. Of the total impervious area, all areas that are directly connected to drainage systems either via pipes directly, or via other impervious areas, were identified and measured. The total sample area was 0.45 km^2 from 292 individual sample sites. A number of the sampled sites cover multiple SANLC classes and were therefore divided into parcels based on SANLC class coverage. In total, 477 sample parcels were included, with distribution per SANLC class and assigned DCIA group as shown in Table 6.3. This table also shows the number of sample parcels per assigned DCIA group. A descriptive figure showing the differentiation between parcels, sample sites, SANLC classes and assigned DCIA group (Table 6.1) is provided in Figure 6.2. The different colours depict different SANLC classes, sample sites indicate stands used in the sampling process, parcels are individual classes within sample sites, and assigned DCIA groups show similar types of developments grouped together.

Informal settlements in South Africa generally do not have formalised stormwater drainage systems. This was confirmed through the field assessment, where the only formalised drainage systems close to informal settlements were identified on major roads next to the settlements. Therefore, sample sites of the $RES_{Informal}$ areas were identified and the DCIA of these areas were estimated based on proximity of less than 10 m from impervious areas to watercourses or clearly visible drainage paths.

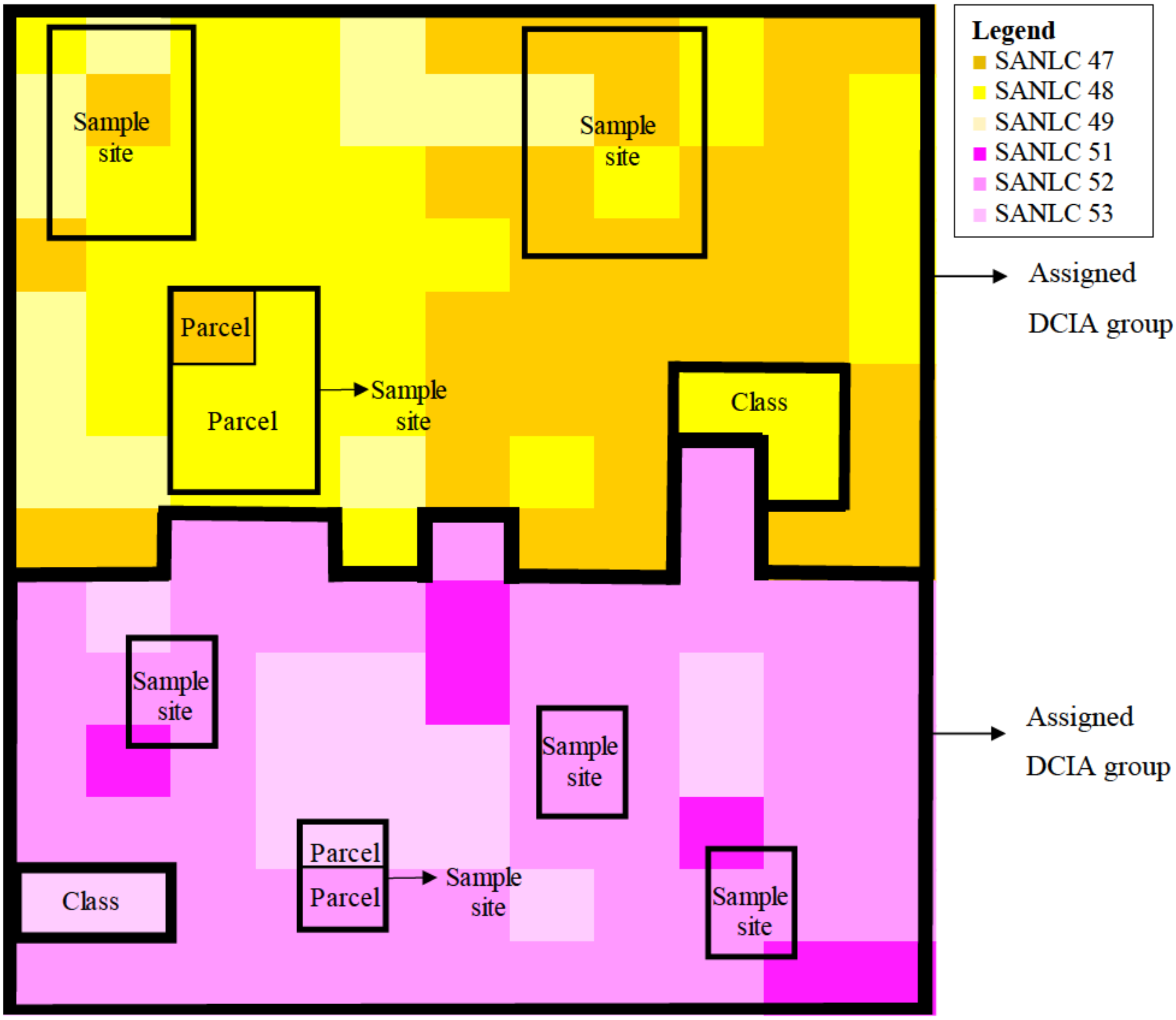


Figure 6.2 Differentiation between sample parcels, sample sites, SANLC classes and assigned DCIA groups

Table 6.3 Sample representation per SANLC class

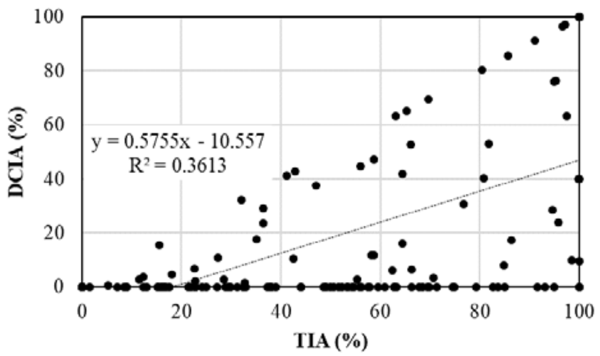
SANLC Class	Description	Number of Sample SANLC Parcels per Class	Assigned DCIA Group	Number of Sample Parcels per Group
47	Residential Formal (Tree)	87	RES_{Formal}	297
48	Residential Formal (Bush)	84		
49	Residential Formal (Grass)	67		
50	Residential Formal (Bare)	59		
51	Residential Informal (Tree)	54	$RES_{Informal}$	131
52	Residential Informal (Bush)	30		
53	Residential Informal (Grass)	9		
54	Residential Informal (Bare)	38		
65	Commercial	32	INDCOM	51
66	Industrial	17		

6.4.4 Assigning and assessing DCIA of urban SANLC classes

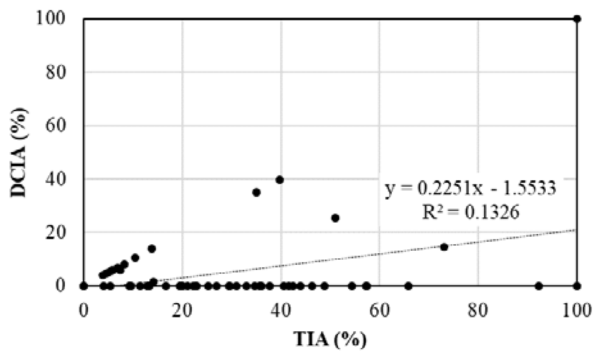
A number of approaches were tested in order to find the best method for the estimation of DCIA for different urban SANLC classes where direct measurement is not feasible. This included testing of the equations derived in previous studies, linear regression equations derived using the data in this study and median values for $DCIA_{\%}$ in each SANLC class as measured in this study. For this study a split sample approach was adopted with the measured DCIA data for each SANLC class randomly split in two data sets, with half the data used for the derivation and testing of DCIA prediction methods and the other half used to independently verify the applicability of prediction methods. The measured $DCIA_{\%}$ from each assigned DCIA group were compared with $DCIA_{\%}$ estimated using the relationships described in previous studies, as summarised in Table 6.4. Figure 6.4 shows a comparison of predicted DCIA using different equations. Where previous studies did not provide limits for final $DCIA_{\%}$ values, a lower limit of 0% and upper limit of 100% was applied. Linear regression equations were also derived for each assigned DCIA group from half of the data gathered in this study and included in the analysis. Scatter plots, with corresponding linear regression equations, are shown in

Figure 6.3. The derived equations are also shown in Table 6.4. The Root Mean Square Errors (RMSE), calculated as the mean of the error between predicted and measured $DCIA_{\%}$ of each sampled parcel, as well as R^2, were used to determine the performance of the relationships from previous studies and from this study to estimate $DCIA_{\%}$ for urban catchments in South Africa. Formal and informal residential urban land cover areas, as well as industrial and commercial areas, were analysed separately for RES_{Formal}, $Res_{Informal}$ and INDCOM groups, as defined in Table 6.1.

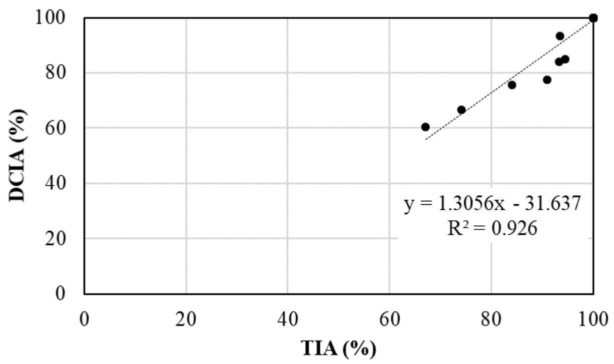
In addition to the linear regression equations, the median, 25th and 75th percentiles of $DCIA_{\%}$, as well as maximum and minimum percentages of DCIA were also calculated for each SANLC class from measured DCIA values. The median values of individual classes, rather than assigned DCIA groups, were used for this derivation, as significant differences were evident between median value of SANLC classes within assigned DCIA groups (as defined in Table 6.1.) The performance of the median values as predictors of $DCIA_{\%}$ for SANLC classes was evaluated. Improved prediction methods for DCIA based on the SANLC classes are proposed and verified using the random samples that were not included in the primary analysis.



(a) RES_{Formal}



(b) $RES_{Informal}$



(c) INDCOM

Figure 6.3 Linear regression plots using half the data gathered for each sampled parcel in: (a) RES_{Formal}, (b) $RES_{Informal}$ and (c) INDCOM assigned DCIA groups

Table 6.4 Connectivity relationships tested in this study

Authors	Equation	Equation Number
Alley and Veenhuis (1983)	$EIA_{\%} = 0.15 \times TIA_{\%}^{1.41}$	(6.2)
Sutherland (1995)	$EIA_{\%} = 0.1 \times TIA_{\%}^{1.5}$	(6.3)
Sutherland (1995)	$EIA_{\%} = 0.4 \times TIA_{\%}^{1.2}$	(6.4)
Sutherland (1995)	$EIA_{\%} = TIA_{\%}$	(6.5)
Sutherland (1995)	$EIA_{\%} = 0.04 \times TIA_{\%}^{1.7}$	(6.6)
Sutherland (1995)	$EIA_{\%} = 0.01 \times TIA_{\%}^{2}$	(6.7)
Wenger *et al.* (2008)	$EIA_{\%} = (1.046 \times TIA_{\%}) - 6.23$	(6.8)
Roy and Shuster (2009)	$DCIA_{\%} = (0.627 \times TIA_{\%}) - 1.86$	(6.9)
Sultana *et al.* (2020)	$DCIA_{\%} = (0.842 \times TIA_{\%}) - 2.1594$	(6.10)
Sahoo and Sreeja (2016)	$EIA_{\%} = 0.0035 \times TIA_{\%}^{2.17}$	(6.11)
RES_{Formal} (linear regression of data gathered in this study)	$EIA_{\%} = (0.5755 \times TIA_{\%}) - 10.557$	(6.12)
$RES_{Informal}$ (linear regression of data gathered in this study)	$EIA_{\%} = (0.2251 \times TIA_{\%}) - 1.5533$	(6.13)
INDCOM (linear regression of data gathered in this study)	$EIA_{\%} = (1.3056 \times TIA_{\%}) - 31.637$	(6.14)

TIA refers to Total Impervious area, EIA to Effective Impervious area and DCIA to Directly Connected Impervious Area

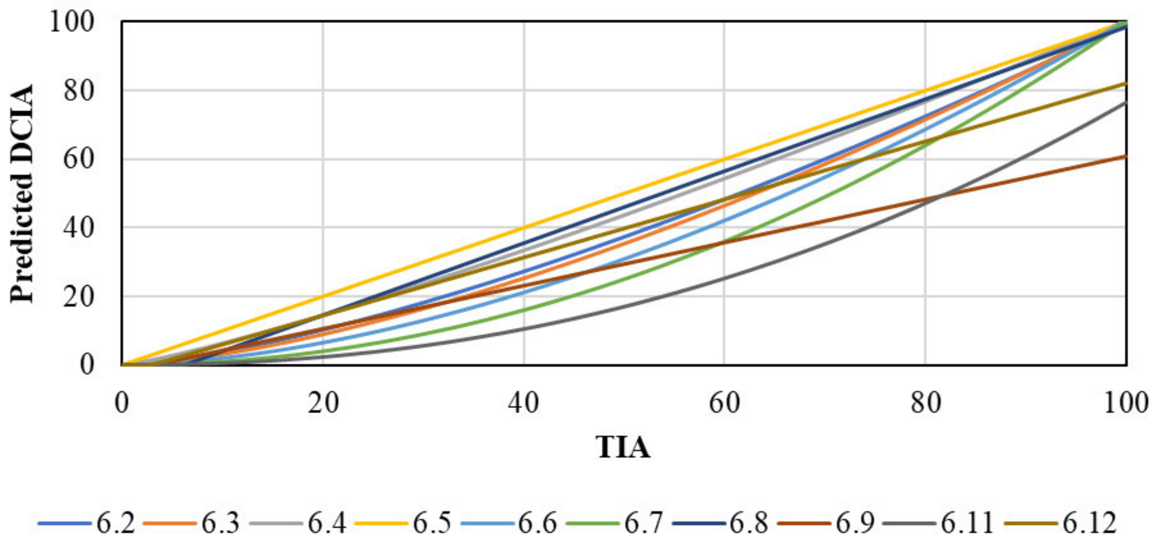
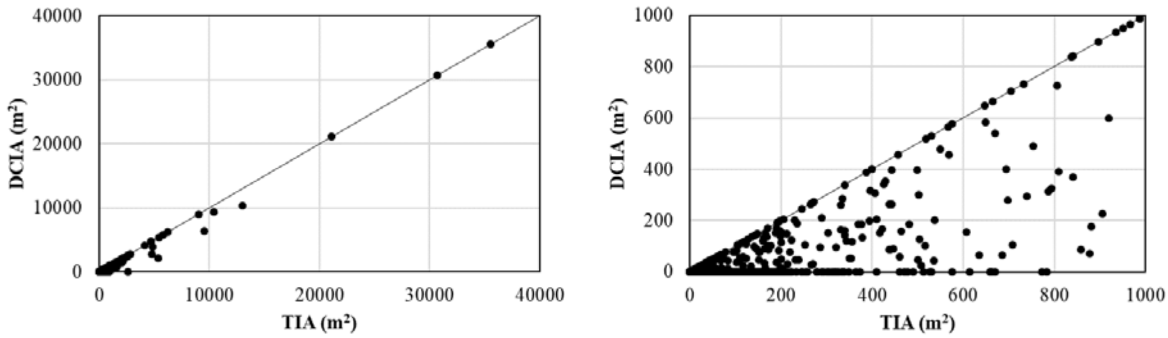


Figure 6.4 Comparison of predicted DCIA for different equations used in previous studies, with applicable equation numbers shown

6.5 Results

6.5.1 Quantifying impervious area connectivity in study catchments

The relationship between measured DCIA and TIA values for all sample parcels were first compared as shown in Figure 6.5, with no differentiation between assigned DCIA groups. These results indicate that, while larger areas tend to have high proportions of connected impervious surfaces, the DCIA:TIA ratios vary considerably for sample parcels with areas smaller than 1 000 m^2. When percentages of DCIA and TIA are compared, the variation is even more evident (Figure 6.6), and it is evident that the data contains a number of sample parcels with no DCIA as well as parcels where the impervious areas are classified as being completely connected ($DCIA_{\%}=TIA_{\%}$).



(a) (b)

Figure 6.5 Comparison between DCIA and TIA per sample parcel: (a) shows all sample parcels and (b) shows sample parcels up to 1000 m^2

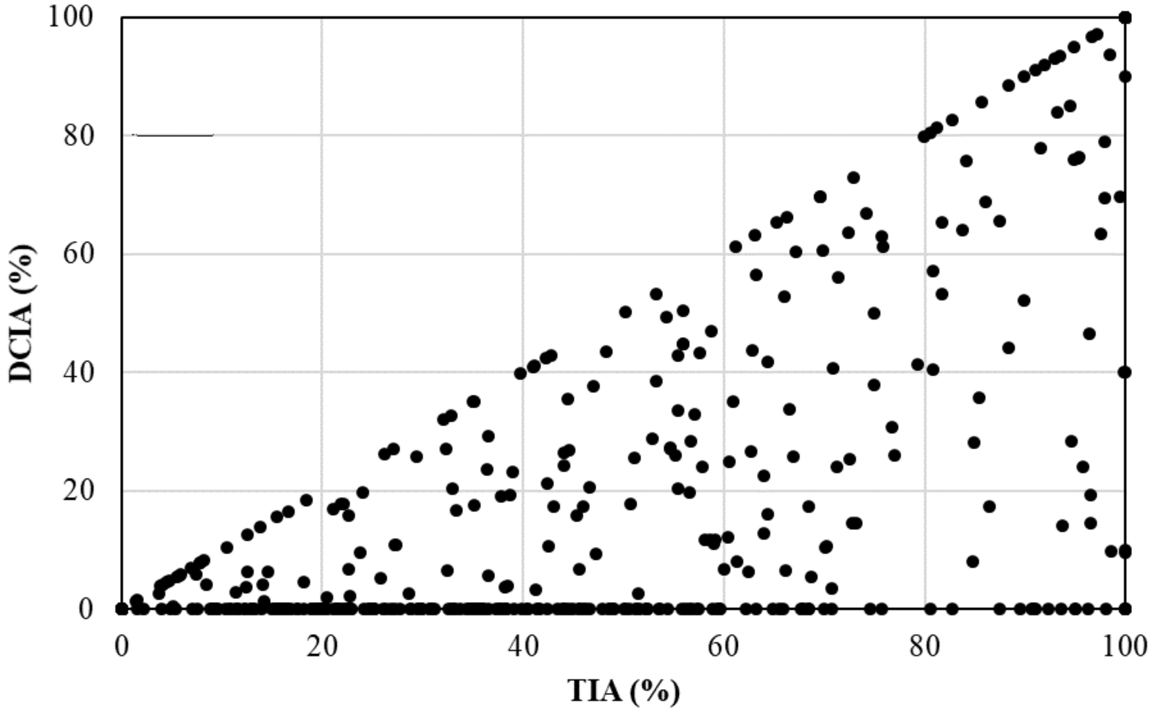


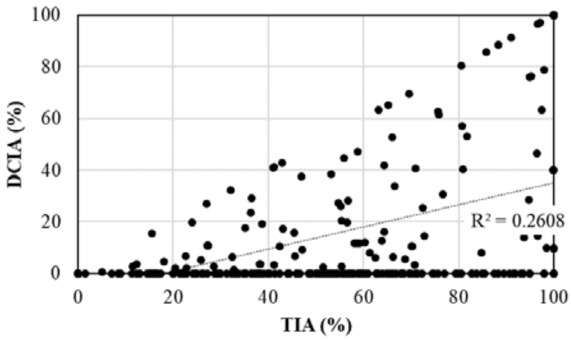
Figure 6.6 Comparison between $DCIA_{\%}$ and $TIA_{\%}$ at sample parcels

Since considerable scatter and no trends are evident from Figure 6.5 and Figure 6.6, the results were evaluated separately for the three assigned DCIA groups (from Table 6.3) in Figure 6.7. Figure 6.8 shows box-and-whiskers percentile plots of $DCIA_{\%}$ for each assigned DCIA group. Figure 6.9 shows the distribution of measured $TIA_{\%}$ and Figure 6.10 shows the distribution of measured $DCIA_{\%}$ for each SANLC class included in this study.

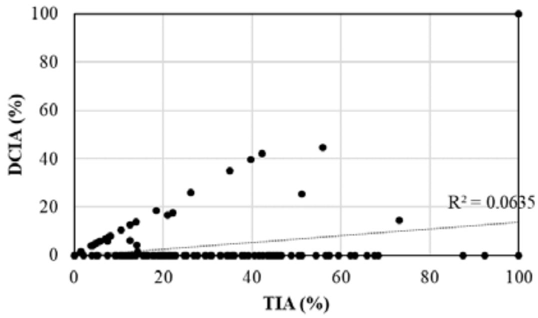
Figure 6.7 and Figure 6.10 show significant variation of DCIA within formal residential (RES_{Formal}) areas, but Figure 6.8 shows that the percentage of DCIA is generally lower than reported in previous studies (Phillips *et al.*, 2014; Sultana *et al.*, 2020). During the field assessment it was observed that sample sites located within formal residential areas and characterised by large DCIA are generally found at intensive residential developments, where a number of dwellings are built in close proximity on a single plot. The majority of these developments are classified as SANLC Classes of 49 (RES_{Formal} (grass)) or 50 (RES_{Formal} (bare)). Although SANLC Class 50 represents formal residential areas with high $TIA_{\%}$, it was observed during field investigation that many of the areas are situated in unpaved streets with no formal drainage systems, while other sample parcels within this class represents cluster developments with high proportions of both TIA and DCIA. Many of the larger formal residential plots have no DCIA, with buildings surrounded by lawns. The median for both

SANLC Classes 47 ((RES_{Formal} (trees)) and 48 (RES_{Formal} (bush)) is 0%, with the maximum value for SANLC Class 47 being 100%. Figure 6.7 indicates less variation within $RES_{Informal}$ areas, with Figure 6.8 and Figure 6.10 indicating that DCIA is zero in most cases. For $RES_{Informal}$ (bush), the 75th percentile is 0% and the max DCIA% is 7%.

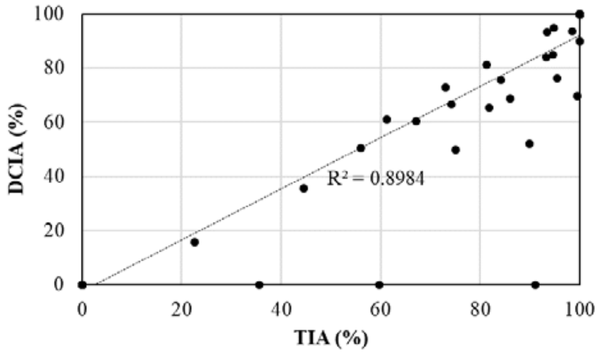
INDCOM samples had high percentages of TIA (Figure 6.9) and DCIA (Figure 6.7 and Figure 6.10). All further analyses consider the SANLC classes or assigned DCIA groups separately in order to distinguish whether generalisations could be made for different types of urban development.



(d) RES_{Formal}



(e) $RES_{Informal}$



(f) INDCOM

Figure 6.7 Relationship between DCIA and TIA percentages for each sampled parcel in: (a) RES_{Formal}, (b) $RES_{Informal}$ and (c) INDCOM assigned DCIA groups

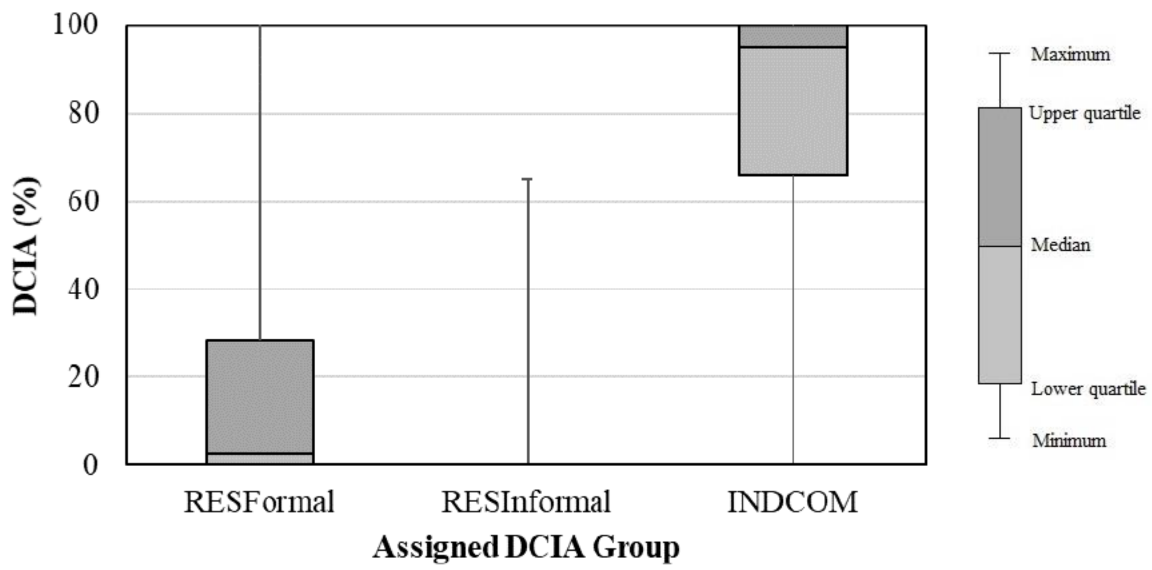


Figure 6.8 Field measurement of DCIA, expressed as percentage of TIA, per assigned DCIA group

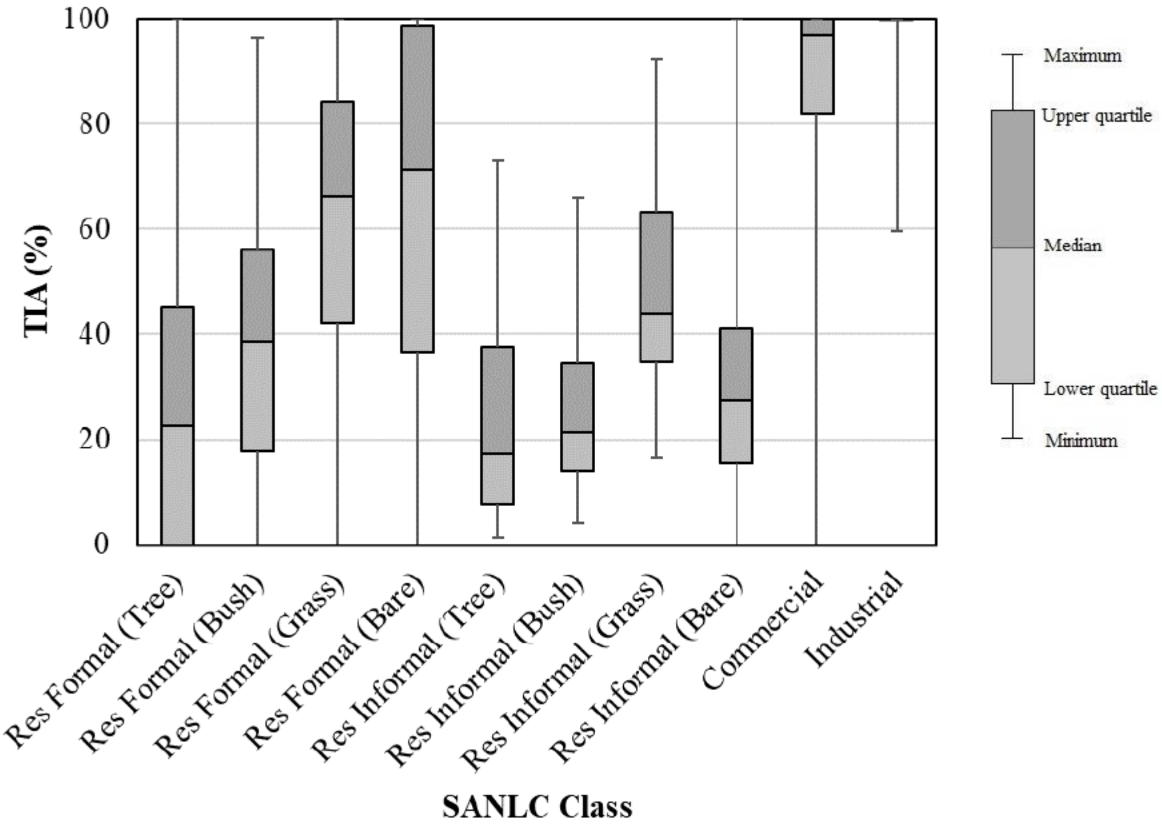


Figure 6.9 Distribution of field measured $TIA_{\%}$ per SANLC class

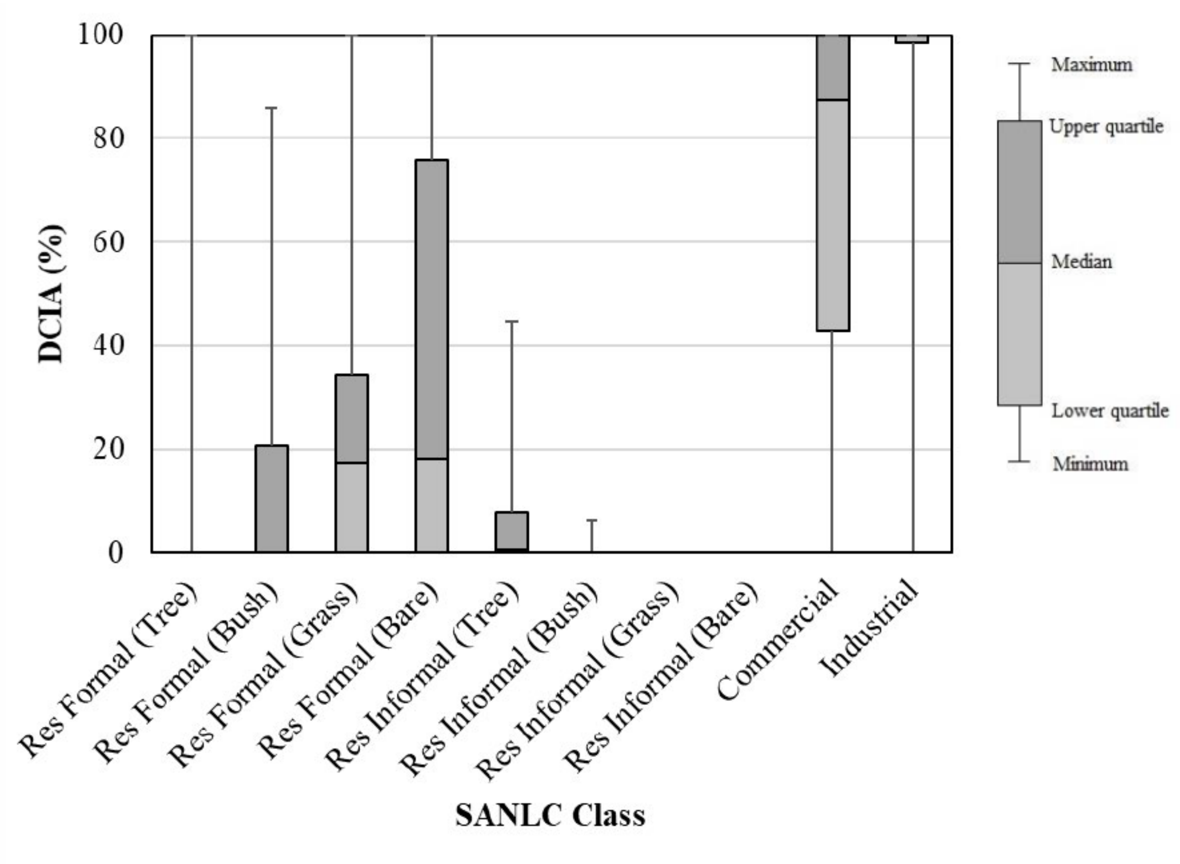


Figure 6.10 Distribution of field measured DCIA, expressed as percentage of total sample parcel, per SANLC class

6.5.2 Assigning DCIA of urban SANLC classes

Observed versus estimated $DCIA_{\%}$ was tested and verified for the equations derived in previous studies, linear regression equations derived using the data in this study (Equations 6.12 to 6.14) and median values for DCIA in each SANLC class as measured in this study. Table 6.5 contains the coefficients of determination and RMSE values determined, from half of the observed data set, using Equations 6.2 to 6.11 from previous studies, as well as Equations 6.12 to 6.14 derived in this study and median values of DCIA in this study. The results were verified using the other half of the data from this study. The verification results are also summarized in Table 6.5.

Table 6.5 shows that the median values performed best at estimating $DCIA_{\%}$ for the RES_{Formal} analysis. The median value method performed the best in the verification study as well. The median values of DCIA also performed significantly better than any other estimation method for $RES_{Informal}$ classes (Table 6.5). The median value method performed the best in the verification study as well as shown in Table 6.5.

Table 6.5 Coefficient of determination and RMSE between observed DCIA% and DCIA% estimated by equations from other studies and this study's proposed methods using half of the dataset for derivation and the other half for verification (green shaded cells = best result)

Equation Name	Equation No.	Original Study R^2	RES_{Formal}				$RES_{Informal}$				INDCOM			
			Derivation		Verification		Derivation		Verification		Derivation		Verification	
			RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2
Alley and Veenhuis (1983)	6.2	0.98	36.69	0.40	41.94	0.15	26.27	0.15	24.07	0.00	3.10	0.93	14.85	0.82
Sutherland (1995)	6.3	Not provided	36.12	0.41	41.24	0.16	25.56	0.16	23.06	0.00	3.19	0.93	14.74	0.83
Sutherland (1995)	6.4	Not provided	39.81	0.38	45.55	0.15	29.41	0.14	27.83	0.00	4.03	0.93	16.57	0.82
Sutherland (1995)	6.5	Not provided	42.68	0.36	48.80	0.14	32.85	0.12	31.98	0.00	4.92	0.92	18.24	0.80
Sutherland (1995)	6.6	Not provided	34.51	0.42	39.30	0.16	23.95	0.17	20.89	0.00	3.59	0.94	14.37	0.83
Sutherland (1995)	6.7	Not provided	32.25	0.44	36.53	0.16	22.01	0.19	18.23	0.00	4.74	0.94	14.21	0.83
Wenger et al. (2008)	6.8	0.98	40.34	0.37	46.24	0.15	30.14	0.12	28.86	0.00	4.05	0.92	16.74	0.81
Roy and Shuster (2009)	6.9	0.57	27.60	0.36	28.81	0.14	19.36	0.12	18.93	0.00	35.59	0.92	29.98	0.80
Sahoo and Sreeja (2016)	6.11	0.90	34.26	0.44	38.93	0.16	26.09	0.20	25.32	0.00	15.63	0.94	17.37	0.83
Sultana et al. (2020)	6.10	0.80 to 0.99	25.30	0.36	27.11	0.14	16.76	0.12	13.92	0.00	23.23	0.92	21.99	0.80
Linear regression (this study)	6.12, 13, 14		39.80	0.38	45.56	0.15	30.64	0.12	29.80	0.00	5.48	0.92	14.80	0.80
Median (this study)			24.84	0.40	22.09	0.03	6.85	0.28	8.23	0.06	13.98	N/A*	40.78	N/A*

*R^2 value could not be calculated as all predicted values are equal

Neither the median values, nor the linear regression equation derived for INDCOM sample parcels in this study (Eq. 6.14), performed the best at predicting $DCIA_{\%}$ from $TIA_{\%}$ for INDCOM sample parcels. However, a number of equations performed similarly well (Eq. 6.2 to Eq. 6.8 and Eq. 6.14), with the equation proposed by Alley and Veenhuis (1983) (Eq. 6.2) performing the best in the testing and the equation proposed by Sutherland (1995) for extremely disconnected catchments (Eq. 6.7) in the verification analysis. As the field analysis showed that INDCOM areas in this study were generally connected to drainage systems (Figure 6.7, Figure 6.8 and Figure 6.10), it is uncertain why this equation outperformed equations for catchments with higher proportions of connectivity. Therefore, Eq. 6.14 as developed using linear regression of INDCOM DCIA was adopted.

Different degrees of connectivity were measured for the different assigned DCIA groups (as defined in Table 6.1), as shown in Figure 6.7 and Figure 6.8. Significant differences were also evident between SANLC classes within assigned DCIA groups, especially for $RES_{Formal,}$ as shown in Figure 6.10. Therefore, the median values for DCIA in each SANLC residential land use type was used in the analysis and adopted as best estimate values in this study. The median percentage values for DCIA of each of the urban residential SANLC classes derived in this study are shown in Table 6.6 as proposed parameter values of DCIA, with 75^{th} percentile and 25^{th} percentile values provided as upper and lower confidence interval ranges. As noted by Roy and Shuster (2009), site-specific values are recommended for hydrological modelling if possible. However, as safety concerns and resource constraints generally do not allow for direct measurement of DCIA in South Africa, these values could be used in South African urban hydrological modelling applications that requires DCIA parameter values. It is emphasised that the results from this study are limited to one geographic area. However, it is postulated that the results are applicable to other regions given the relationships developed with national land cover classes in this study. Also, the specific climate of a study area will be represented by a local climate station during modelling. Thus, until further research is undertaken to improve the results, it is proposed that the imperviousness values in Table 6.6 be considered for hydrological modelling of South African urban areas, where site-specific data are not available.

Table 6.6 Proposed DCIA percentages for urban residential SANLC classes

SANLC Class No.	SANLC Description	DCIA$_{\%}$ (%)		
		25th	50th	75th
47	Residential Formal (Tree)	0	0	0
48	Residential Formal (Bush)	0	0	2
49	Residential Formal (Grass)	0	16	40
50	Residential Formal (Bare)	0	43	100
51	Residential Informal (Tree)	0	6	10
52	Residential Informal (Bush)	0	0	0
53	Residential Informal (Grass)	0	0	0
54	Residential Informal (Bare)	0	0	0

6.6 Discussion

A particularly important influence of urban development on runoff is the impact of development on the drainage paths in a catchment which is closely linked to the presence and influence of DCIA. However, drainage paths are not always made more efficient by urban development (Van Vuuren, 2012). In order to realistically configure acceptable hydrological models, it is important to have a reasonable estimate of the connectivity of impervious areas in a study catchment. Therefore, impervious area connectivity to drainage systems for different urban SANLC classes was measured and prediction equations were derived from the measured data to estimate typical representative DCIA in South Africa.

6.6.1 Assessing impervious area connectivity

Comparison of DCIA$_{\%}$ to TIA$_{\%}$ showed considerable variation of DCIA$_{\%}$ within RES$_{Formal}$ areas, but with DCIA$_{\%}$ values generally below 50%, which is lower than reported DCIA$_{\%}$ in previous studies (Phillips *et al.*, 2014; Sultana *et al.*, 2020). The variation is partly attributed to some intensive residential developments in SANLC Classes 49 and 50. SANLC Class 50 has additional variation due to some sample sites being located in unpaved streets without direct connectivity to drainage systems. Many of the larger formal residential developments have no DCIA, with buildings surrounded by lawns.

Less variation than in RES_{Formal} areas was evident within informal urban $RES_{Informal}$ areas, where DCIA values of zero were found in most cases, reflecting that informal settlements in South Africa generally do not have formalised stormwater drainage systems. This was confirmed through field assessment. Furthermore, as also reported in previous studies (Parkinson *et al.*, 2007; Gogate and Rawal, 2015), ponding was reported by residents of informal areas and evidence of this was also observed during the field assessment.

INDCOM areas were found to be characterised by high percentages of TIA and DCIA. The high proportion of DCIA in these areas is attributed to efficient drainage systems in areas with high TIA.

6.6.2 Assessing DCIA of urban SANLC classes

This study has shown that, although there is significant variation in $DCIA_{\%}$ relative to $TIA_{\%}$, some general trends are evident when assigned DCIA groups and SANLC classes are considered separately. $DCIA_{\%}$ estimated from $TIA_{\%}$ using relationships from previous studies did not perform well for the catchments used in this study, with RMSE values of over 30 and R^2 values lower than 0.5 for most equations applied to formal residential areas. This shows that the equations from those studies do not reasonably estimate $DCIA_{\%}$ from $TIA_{\%}$ in South African formal residential areas. In addition, the equations derived in previous studies do not reasonably predict DCIA from TIA in informal settlements in South Africa, with RMSE values of over 20 and R^2 values lower than 0.2 for most equations applied to informal residential areas. This is attributed to the fact that informal settlements generally do not have formal drainage systems, but all equations from previous studies predict some degree of impervious area connectivity. The prediction equations provided better results for the INDCOM group, with RMSE values of less than 20 and R^2 values higher than 0.8 for most equations. This indicates that the connectivity of South African INDCOM land cover classes to drainage systems are more similar to that of other countries.

6.7 Conclusions

This study achieved its aim to investigate if DCIA can be reliably estimated for formal and informal urban land use classes in South Africa. Field assessment was used to quantify impervious area connectivity to drainage systems for different SANLC classes. The authors agree with Roy and Shuster (2009) that site-measured DCIA should be used in hydrological modelling if available. However, in the South African context, site-specific data are very rarely available. Therefore, typical representative connectivity values were determined for use in hydrological modelling of South African urban areas and a comparison of performance was made with results obtained using equations developed in previous studies. It is proposed that the median values for DCIA in each SANLC residential land use type be used, with sensitivity analyses performed using the 75^{th} percentile and 25^{th} percentile values. The equation developed for industrial and commercial areas is recommended for estimating DCIA from TIA if measured DCIA are not available. It is recommended that the results of this study be verified through additional field investigation in other South African cities, as well as other cities with similar land uses in other countries.

7 MODELLING OF HYDROLOGICAL RESPONSES IN SOUTH AFRICAN URBAN AREAS

The studies presented in Chapter 3 and Chapter 5 both concluded that temporary storage and subsequent unexpected attenuation of flood peaks is prevalent in formally developed catchments in South Africa. It was therefore recommended in Chapter 5 that attenuation be incorporated in hydrological models of urban areas with similar characteristics.

The aims of this thesis are to gain new understanding of hydrological processes in the diverse range of South African urban environments and to use this understanding to develop an improved approach to hydrological modelling in South African urban areas. The final objective of this study is to (d) recommend a new approach to model runoff from ungauged South African urban catchments by incorporating the improved understanding obtained in the previous objectives. The catchments used for hydrological modelling in this study contain areas with formal development only, due to the lack of suitable rain gauges and relatively large (129 km^2 and 357 km^2) catchment areas of the gauged catchments containing informal settlements, making the estimation of rainfall in the catchments unreliable.

This chapter describes application and evaluation of the Storm Water Management Model (SWMM) using imperviousness and connectivity parameters derived from literature for a gauged catchment with formal urban development. The model is then run again using the new imperviousness and connectivity results obtained in Chapter 4 and Chapter 6 of this thesis. Calibration is achieved through the inclusion of small pseudo attenuation ponds distributed throughout the catchment. The applicability of parameter sets as well as the calibration parameter is evaluated by simulating an adjacent gauged catchment. The study is presented as a draft version of a journal paper.

7.1 Authorship Statement

Status	Draft manuscript
Details	Loots, I., Smithers, J.C., Kjeldsen, T.R. 2023. Improved modelling of hydrological responses in South African urban areas
Authors' contribution	The author of this thesis was the primary author of this original research manuscript. I Loots contributed to the formulation of the research question (90%), design of the methodology (90%), model configuration and data collation (50%), processing and analysis of data (100%) and manuscript preparation (90%). J.C. Smithers contributed to the formulation of the research question (10%), design of the methodology (5%) and manuscript preparation (5%). T.R. Kjeldsen contributed to the design of the methodology (5%) and manuscript preparation (5%). A Scholtz, HS Oberholzer and JA Akura assisted with model configuration and data collation (50%). They were not listed as authors, but thanked as contributors.
Purpose	This paper presents original research in order to achieve the second aim of this thesis, namely to use the knowledge gained in previous chapters to develop an improved approach for hydrological modelling in South African urban areas.

7.2 Abstract

A previous study (Chapter 4) has shown that the imperviousness of South African urban areas varies considerably for different land cover classes. The direct connectivity of impervious areas in urban residential developments to drainage systems is also lower than the connectivity measured in most previous studies (Chapter 6). The aim of this study is to assess if the incorporation of characteristics of hydrological responses from formal urban areas determined in previous studies (Chapter 4 and Chapter 6) improves hydrological modelling of South African urban catchments with formal development. Additionally, despite observed increases

in flood volumes, no significant change was found in observed flood peaks and catchment response times across formal urban developments in South Africa. Scientific consensus and modelling results typically show increased flood peaks and decreased catchment response times with development. Since this is not apparent in formally developed urban areas in South Africa, this study postulated and evaluated additional improvements, specifically if the inclusion of small pseudo attenuation ponds at urban sub-catchment outlets resulted in improved hydrological modelling of formal urban areas in South Africa. Storm Water Management Model (SWMM) configurations were developed for two gauged urban catchments in Tshwane, South Africa. Both catchments experienced relatively little change in urban footprint during the study period. The one catchment was used as a calibration catchment and the other as a verification catchment. This was undertaken to run the model as a continuous simulation model using the maximum available data in each catchment in order to compare flow duration curves for observed and simulated data. The model was (i) initially run using two sets of conventional parameter values, (ii) then with imperviousness and connectivity parameter values derived in previous South African studies (Chapter 4 and Chapter 6), and (iii) with the additional inclusion of small pseudo attenuation ponds distributed throughout the catchment. Simulation results improved in both the calibration and verification catchments with parameterisation using more accurate imperviousness and connectivity parameter values and further improvement was achieved through the inclusion of pseudo attenuation ponds. It is recommended that the new South African imperviousness and connectivity values, as well as the pseudo storage values derived in this study, be applied in future hydrological modelling in ungauged South African urban catchments. It is also recommended that the causes and capacities of unexpected attenuation be quantified in order to provide more realistic attenuation modelling in ungauged urban catchments with similar land cover.

7.3 Introduction

Hydrological modelling of heterogeneous urban catchments presents numerous challenges. Although the influence of impervious surfaces on runoff is widely understood and accepted, the impact of pervious areas within the urban environment is still not fully understood (Braud *et al.*, 2013; Fletcher *et al.*, 2013; McGrane, 2016). Heterogeneous urban catchments have a combination of fast and slow hydrologic responses, resulting from significantly different flow paths, mainly caused by the interaction between natural portions of the catchment and sections dominated by engineered drainage, for example, by pipe flow (Braud *et al.*, 2013).

Previous studies (Chapter 4 and Chapter 6) have demonstrated the range of catchment characteristics that are typical of different types of urban development in South Africa. Some land cover classes tend to have higher percentages of total impervious areas and more impervious areas that are directly connected to natural or engineered drainage systems than others. These characteristics need to be considered in hydrological modelling of South African urban areas. This requires the use of a hydrological model with the ability to model catchment heterogeneity as well as routing through the catchment. The Storm Water Management Model (SWMM) is one of the most widely used storm water models both internationally (Elliot and Trowsdale, 2007; Fletcher *et al.*, 2013; Arjenaki *et al.*, 2021; Dell *et al.*, 2021; Zeng *et al.*, 2021) and in South Africa (City of Cape Town Development Service, 2002; Barnard *et al.*, 2019). This semi-distributed model can be run as an event-based or a continuous runoff quantity and quality model (Fletcher *et al.*, 2013). Time steps of between one second 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. Hydraulic routing can be simulated using steady wave routing, kinematic wave routing or dynamic wave routing (Bisht *et al.*, 2016). 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). Based on the above, the SWMM was selected for use in this study.

Previous studies (Chapter 3 and Chapter 5) have shown that, despite increased flood volumes, flood peaks and catchment response times do not change significantly with development in South African formally developed areas. However, modelling results typically show increased flood peaks and decreased catchment response times with development (Gumindoga *et al.*, 2014; Schütte and Schulze, 2017; Seidl *et al.*, 2020). It is hypothesised that unexpected attenuation within formally developed urban catchments could contribute to this disparity.

The aim of this study is to assess if the incorporation of characteristics of hydrological responses from formal urban areas determined in previous studies (Chapter 4 and Chapter 6) improves hydrological modelling of South African urban catchments with formal development and to evaluate additional improvements to the modelling. The specific objectives are to: (a) determine the performance of a rainfall-runoff model that is applicable for use in South African urban areas with parameter values derived from literature; (b) propose an improved approach to model runoff from formally developed urban catchments in South Africa using the catchment attributes derived in Chapters 4 and 6 and knowledge gained in Chapters 3 and 5.

7.4 Methods

The following sections describe the methodology applied to achieve the study aim. The study catchments are described. Data sources and data processing are discussed. The model configuration, calibration and verification are also described.

7.4.1 Study areas

Two neighbouring gauged urban catchment areas with comparable sizes and land uses, but different catchment shapes, were used for this study. Both catchments are located in the City of Tshwane in Gauteng. The first catchment was used to evaluate and calibrate parameter value sets and the second catchment was used to verify the calibrated parameter values. The two catchments were chosen based on their relatively small areas (30 km^2 and 35 km^2), relatively homogeneous urban land cover and the location of rain gauges with more than 20 years of 5-minute interval rainfall data in the vicinity. Smaller catchment areas were preferred for this analysis due to the limited number of rain gauges and significant spatial variation of storms in the region (Mouton *et al.*, 2022).

The calibration catchment is a 30 km^2 catchment situated north-east of the City of Tshwane’s central business district in South Africa. The Department of Water and Sanitation (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 7.1. The verification catchment area is 35 km^2 with the outflow monitored at DWS Station A2H054. The Hartbees Spruit drains an urban area in the East of Pretoria, comprising suburban areas and some industrial and business areas, as shown in Figure 7.1.

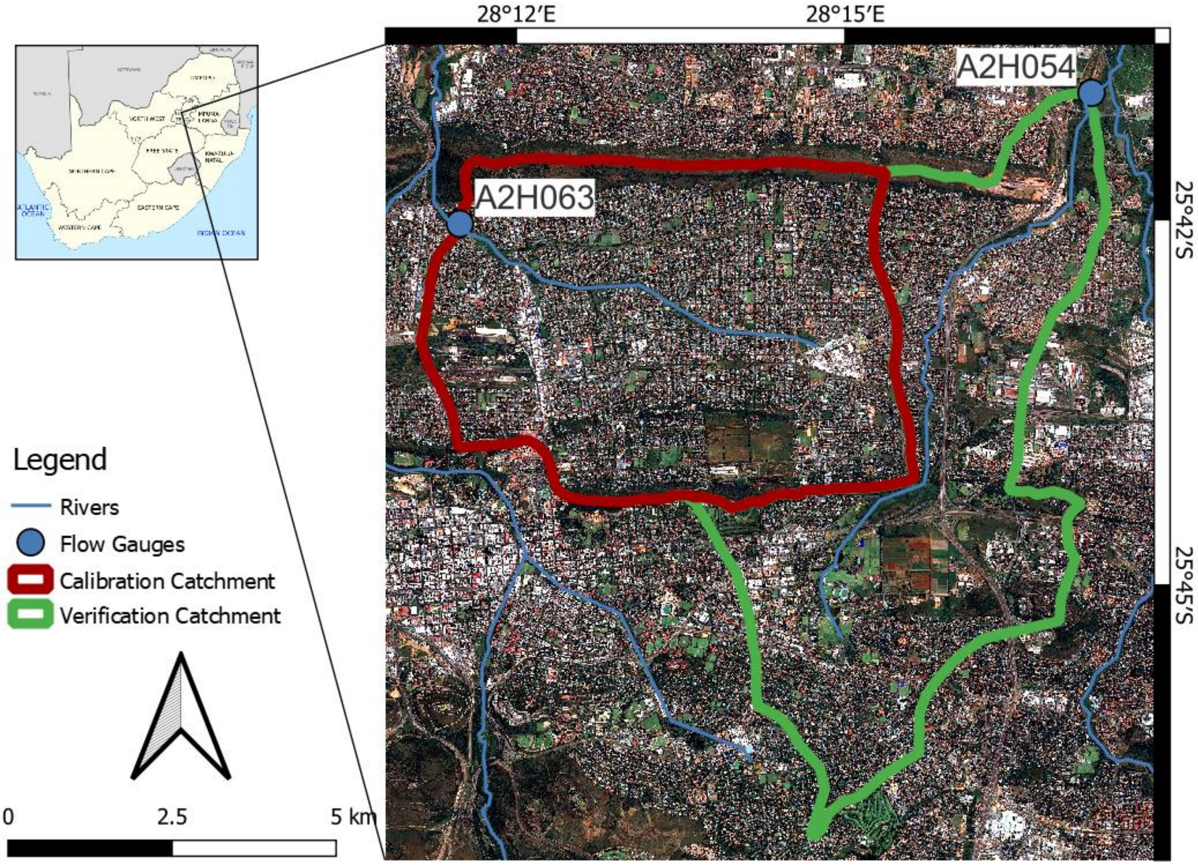


Figure 7.1 Study catchments used for SWMM analysis

7.4.2 Observed rainfall and streamflow data

Historical rainfall data was obtained from the South African Weather Service (SAWS). Figure 7.2 shows that no rainfall stations measuring sub-daily data are situated in Catchment A2H063, but three stations are within 5 km of the catchment. One rainfall station (University of Pretoria) with sub-daily data is located in Catchment A2H054. Thiessen polygons were used to assign applicable rain gauges for simulating each sub-catchment's rainfall, as shown in Figure 7.2.

The historic rainfall records for Wonderboom, Eendracht, Unisa, Bolepi House and UP (University of Pretoria) have record periods of between 8 and 27 years, as shown in Table 7.1. Although a small part of Catchment A2H063 falls within Unisa's Thiessen rainfall polygon, the likely impact of this record was disregarded. None of the rainfall stations had complete datasets. The records of the adjacent rainfall stations, including the Unisa and Bolepi House gauges, were used to infill missing values in order to form three complete records of 8 898 days from 1994 to 2022 (almost 25 years), each with 5-minute rainfall intervals. This method was deemed acceptable since the rainfall stations in the vicinity of the study catchments have similar median annual precipitation, and since there are no major topographical or meteorological differences between different sections of any catchments in the study area.

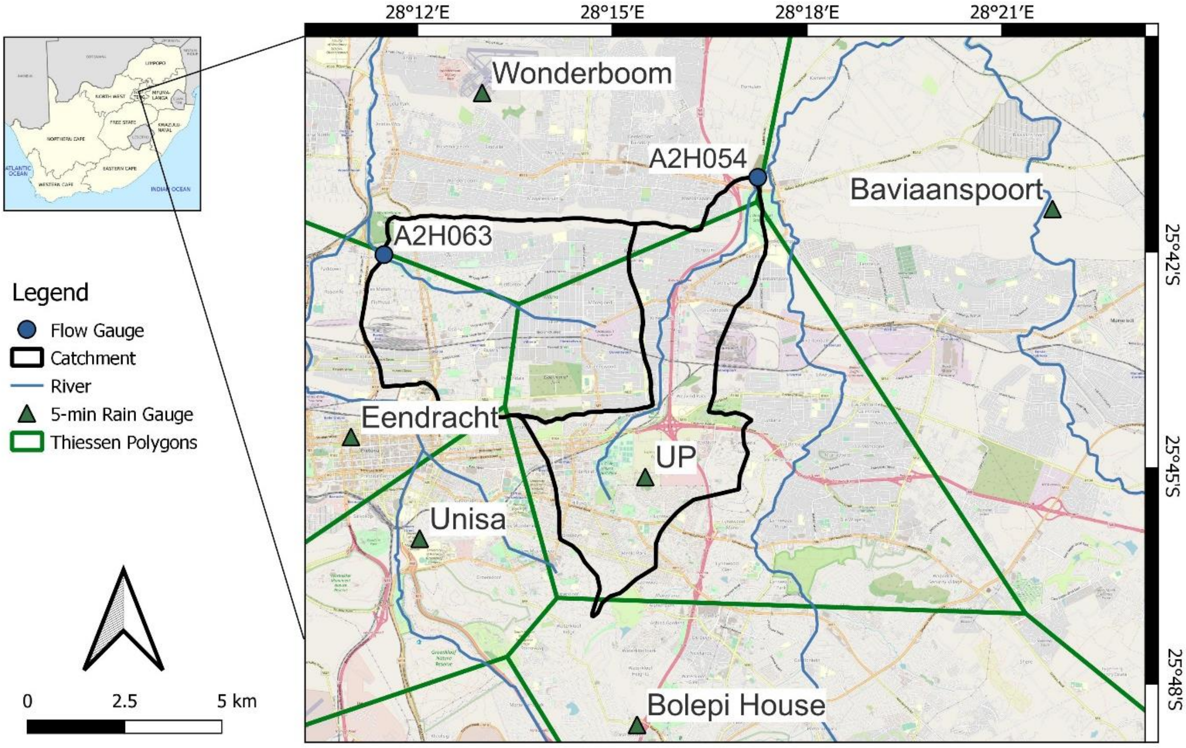


Figure 7.2 Rainfall gauges across the study area

Table 7.1 Rainfall gauges used for Catchments A2H054 and A2H063

Rainfall Gauge Name	Date	Length of Rainfall Record
Wonderboom	06/2008 to 09/2022	Approximately 14 years
Pretoria Eendracht*	10/1994 to 03/2014	Approximately 20 years
Pretoria University	02/2011 to 09/2022	Approximately 11 years
Pretoria Unisa*#	10/1994 to 09/2022	Approximately 27 years
Bolepi House*	09/2003 to 06/2018	Approximately 15 years

* *Rainfall record used for infilling of other records for Catchment A2H054.*
\# *Rainfall record used for infilling of other records for Catchment A2H063.*

Instantaneous streamflow records for both catchments were acquired from the Department of Water and Sanitation (DWS). Prior to December 2003 the stations recorded water levels at intervals determined by relative water levels between measurements. The loggers recorded every 15 minutes during periods when changes in river stage were detected, and did not record when the stage levels were not changing. Post December 2003 the stations recorded water levels at intervals determined by changing water levels between measurements, but at an average of 20-minute time intervals. Periods of missing flow data were manually inspected. Any gaps in the flow data during periods with rainfall were removed from both the flow and rainfall datasets and were not included in the analyses. Flow was infilled using representative base flow for the relevant period if no rain was measured. The infilled data set, with gaps removed as described above, was used to compare simulated flow data with observed flow data for the entire study period.

The representative catchment rainfall generated with infilled rainfall records from the three rainfall stations were compared with the streamflow data for both catchments. Disparity was observed between the observed rainfall and runoff data with, for example, some significant rainfall events not always resulting in significant runoff events and significant runoff events not always being preceded by significant rainfall events, as shown through a scatter plot in Figure 7.3, depicting representative areal catchment rainfall and runoff, both shown as depths in mm. This disparity was evident despite the exclusion of gaps in the flow data. As none of the rain gauges are situated inside the catchment area and the region experiences storms with considerable spatial distribution (Dyson, 2009; Mouton *et al.*, 2022), it is possible that the flow gauging station might sometimes register runoff from rainfall events for which the representative catchment intensity is not recorded at the rainfall stations, and vice versa. The infilling of rainfall data could also contribute to the disparity. However, the rainfall stations are all in the nearby vicinity of the catchment and experience the same type of weather patterns. Given some inconsistencies between observed event rainfall and corresponding observed flow data for the same event, and based on the assumption that the distribution of catchment rainfall data is reliable, the distributions of simulated and observed flow data were used to calibrate and assess the performance of the model (Gioia *et al.*, 2008; Moretti and Montanari, 2008; Stein *et al.*, 2012; Caltrans, 2015). The exceedance probabilities of the simulated flow generated versus observed flow data for the continuous simulation period were compared. Records for the study period from 1994 to 2022 were used for calibration and verification of the SWMM model.

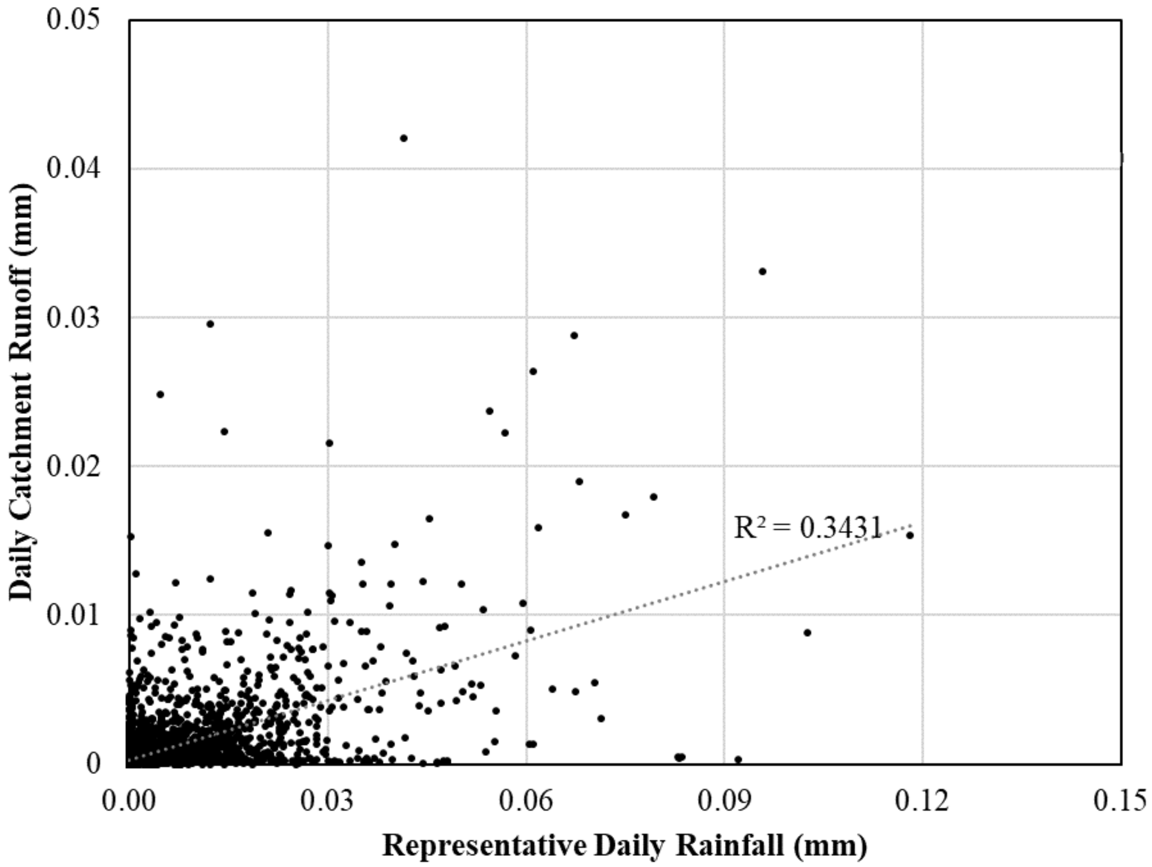


Figure 7.3 Scatter plot showing representative daily rainfall depth and daily catchment runoff, both reported in mm

7.4.3 Land cover data

It was shown in Chapter 4 that the percentage of impervious areas in Catchments A2H054 and A2H063 changed the least of the five gauged urban catchments studied in previous chapters, with only approximately 15% change during the study period (1994 to 2022). Land use development levels were obtained from the available South African National Land-Cover (SANLC) Datasets. The first year with available land cover data is 1990 (Geoterraimage, 2015b), the second is 2013/2014 (Geoterraimage, 2015a), followed by 2018 (Geoterraimage, 2019) and 2020 (Geoterraimage, 2021). Comparison of the 1990 SANLC data with aerial photographs obtained from National Geo-spatial Information (NGI) for 1990 and 1:50 000 topographical maps from 1995 (Surveyor General, 1995) showed significant discrepancies. For example, the 1990 SANLC data indicated 57% larger developed urban area than the 1990 aerial photo and 55% larger developed urban area than the 1995 topographical map for Catchment A2H054. In Catchment A2H063 the discrepancies were 15% for both data sets. In addition, Jacobson (2011) cautions that short streamflow records, for example 10 years of record, can generally not be assumed as sufficient when gauging the influence of urbanisation, as other factors, like climate variability, also impact streamflow variability. Given that rainfall data with 5-minute time steps is available from 1994 to 2022 and the 1990 SANLC data contained significant errors, the hydrological modelling was undertaken using catchment land cover characteristics determined using the SANLC data for 2013/2014, as shown in Figure 7.4, as this was the closest available SANLC data set to the centre of the analysis period from 1994 to 2022.

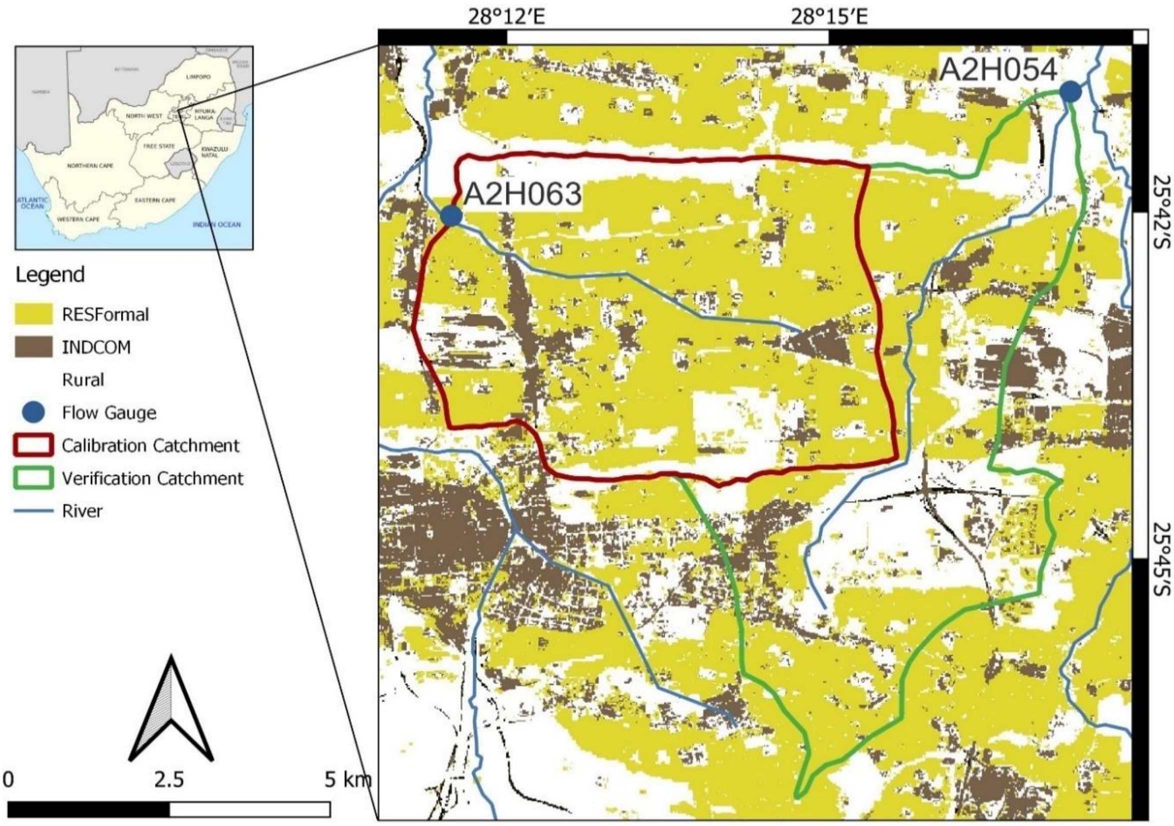


Figure 7.4 SANLC data used for hydrological modelling (from Geoterraimage (2015a))

7.4.4 Soils data

Schulze and Schütte (2019) developed an SCS Terrain Unit (TU) map using the Agricultural Research Council (ARC) Terrain Unit database (), with 27 491 terrain units in South Africa. This dataset was used as it represents the best available soils data for the area, at the finest resolution. It represents integration of the previously published South African Binomial System of Soil Classification (Schulze *et al.*, 1985), Land Type polygons (SIRI, 1987) and SCS soil groups (Schulze, 2012) with digital elevation modelling. The SCS TUs were related to the SCS soil groupings as summarised and compared with the United States Department of Agriculture (USDA) classifications in Table 7.2.

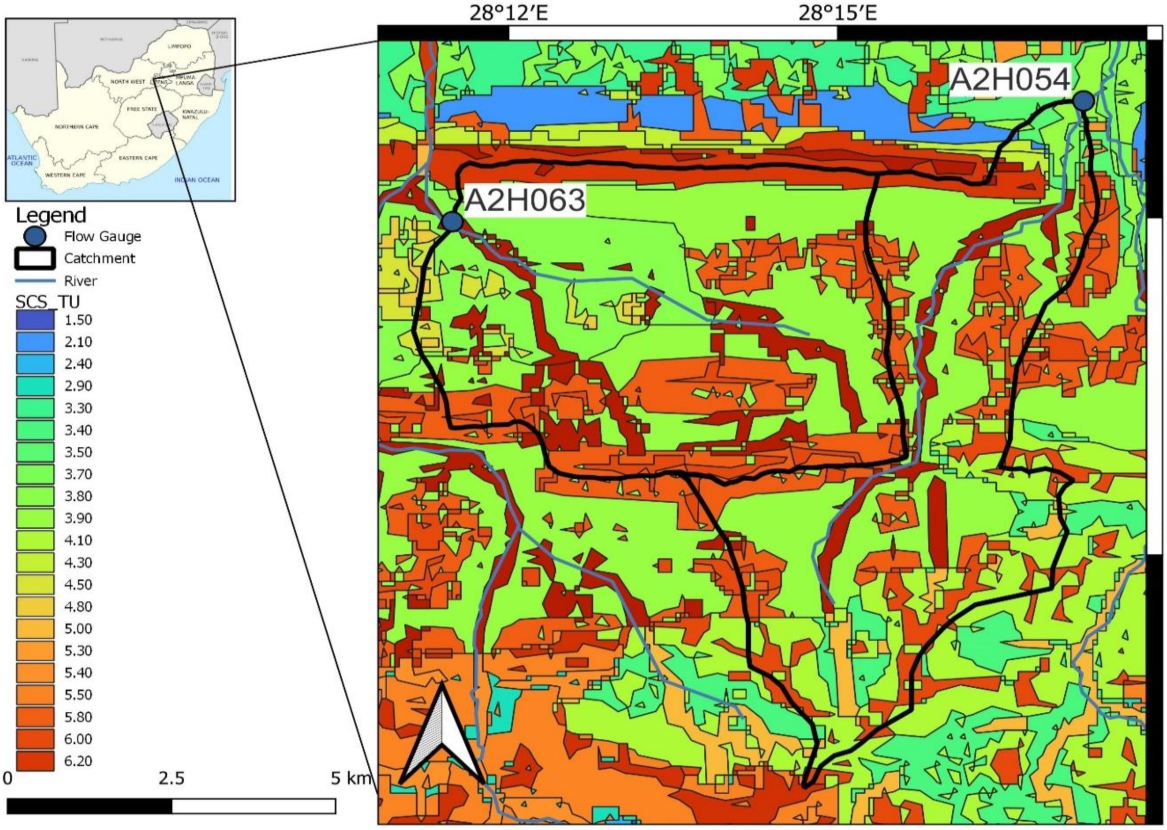


Figure 7.5 Soil classification based on the SCS TU map (Schulze and Schütte, 2019)

Table 7.2 Soil classification association

SCS TU	SCS Soil Grouping	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

7.4.5 Model configuration

The SWMM is a semi-distributed model that uses the principle of the conservation of mass (Rossman and Huber, 2016) to calculate runoff from a sub-catchment. A sub-catchment is assumed to be a rectangular, non-linear reservoir with a uniform slope that drains to a single outlet. Inflow is generated by precipitation and evaporation and infiltration losses are simulated. The net excess water forms a pond of depth d on the sub-catchment surface. Depression storage depth (d_s) is included to account for surface ponding on flat areas and by vegetation. The d_s, of a sub-catchment may be simulated as the initial abstraction (I_a) when using the Curve Number (CN) infiltration approach in the SWMM (Rossman and Huber, 2016). The Manning equation is used to compute the runoff volumetric flow rate, Q (Rossman and Huber, 2016). Combining these principles, Equation 7.1 is used to compute the mass balance over a time step (Rossman and Huber, 2016):

$$\frac{\delta d}{\delta t} = i - e - f - \frac{WS^{1/2}}{An}(d - d_s)^{5/3} \tag{7.1}$$

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 7.1 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 7.2 and Equation 7.3 (Rossman and Huber, 2016):

$$q = \frac{WS^{1/2}}{An}(d - d_s)^{5/3} \tag{7.2}$$

where

q = runoff rate [m/s], and

$$Q = \frac{WS^{1/2}}{n}(d - d_s)^{5/3} \tag{7.3}$$

where

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

PCSWMM (CHI, 2022) is a commercial product that allows interaction with the underlying SWMM engine. This product was used as it includes superior user interaction capability to the Environmental Protection Agency's open-source version of EPASWMM.

The SWMM model was first configured to simulate runoff from Catchment A2H063. The catchment was divided into 263 distinct sub-catchments based on the land cover classifications as contained in the SANLC data (Figure 7.4) (Geoterraimage, 2015a), as shown in Figure 7.6. Sub-catchment areas with similar land cover characteristics, as well as small land parcels like trees lining roads, were incorporated into larger sub-catchments. Soils data was added based on the dominant SCS Terrain Unit in each sub-catchment. As the catchment configuration had 263 sub-catchments, it was not practical to model each stormwater drain as obtained from the Tshwane as-built drainage drawings. Only drainage pipes downstream of entire sub-catchments were included in the configuration. Streams and rivers were added based on satellite imagery. Inlets to the drainage system were modelled as junctions (Figure 7.6). 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.

For the SWMM model configuration of Catchment A2H054, 146 sub-catchments were selected following a similar methodology as for Catchment A2H063 and based on the land use in the SANLC data (Geoterraimage, 2015a), as shown in Figure 7.7.

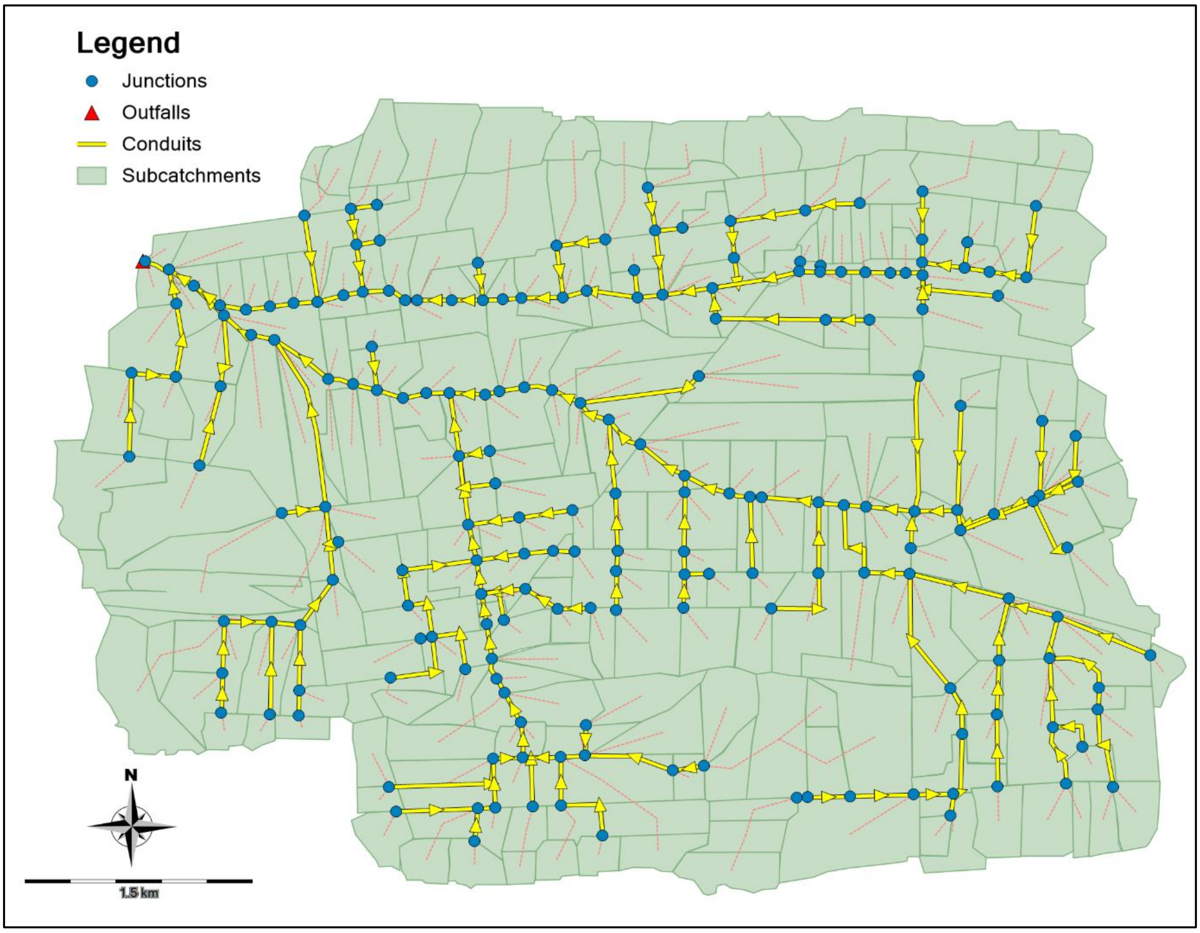


Figure 7.6 SWMM configuration for Catchment A2H063, with the red lines depicting overland flow to sub catchment outlets

The Curve Number infiltration method in the SWMM is based on the widely used (Boughton and Droop, 2003) SCS (Soil Conservation Service) method (Rossman and Huber, 2016). 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 (Rossman and Huber, 2016).

It is a combined loss method where all losses due to interception, depression storage and infiltration are lumped together to predict rainfall excess. The SWMM applies a modified, incremental form of the method that accounts only for infiltration losses, since other losses are modelled separately (Rossman and Huber, 2016).

As the SWMM has the ability to incorporate catchment attributes such as the Total Impervious Areas (TIA) of a sub-catchment, as well as impervious areas that are directly connected to drainage systems, or Directly Connected Impervious Areas (DCIA), two alternative approaches are generally followed to derive CN values for modelling (Rossman and Huber, 2016).

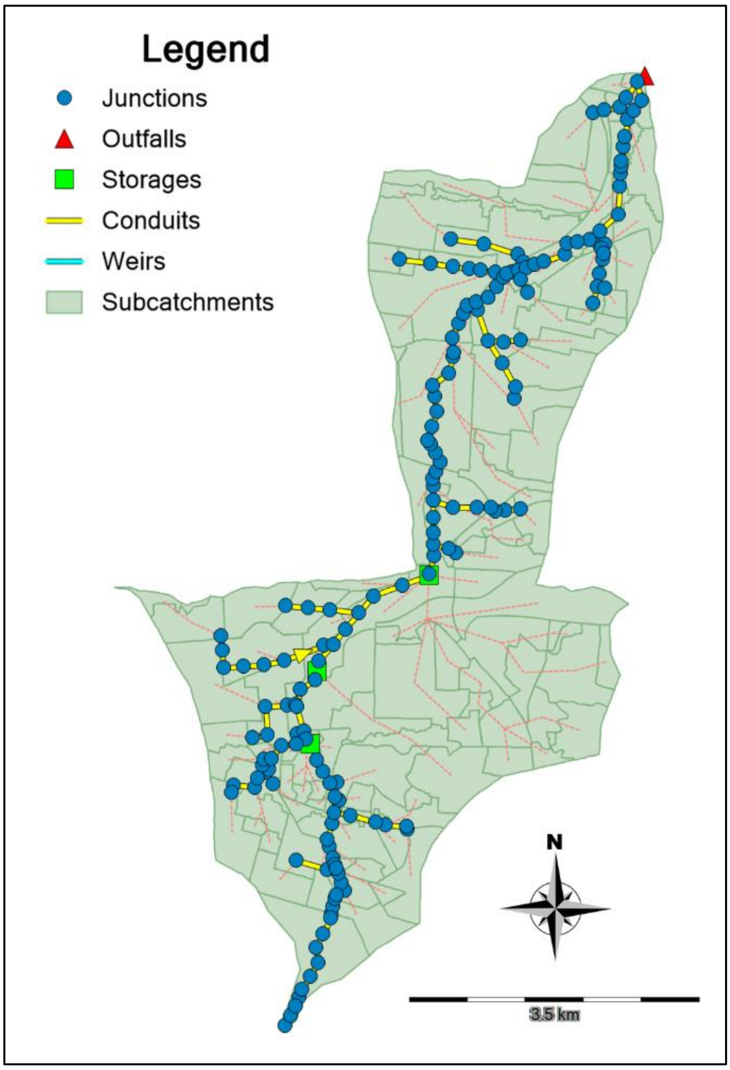


Figure 7.7 SWMM configuration for Catchment A2H054, with the red lines depicting overland flow to sub catchment outlets

In the first approach, overall urban CN values that incorporate TIA and DCIA are assigned to sub-catchments, with TIA in the SWMM set to zero. For sub-catchments with impervious areas that are directly connected to drainage systems, or areas with more than 30% TIA, the USDA (2004) proposes using Equation 7.4 to derive a composite CN:

$$\mathrm{CN}_C = \mathrm{CN}_P + \frac{TIA_{\%}}{100}(98 - \mathrm{CN}_P) \tag{7.4}$$

where

CN_C = composite Curve Number,

CN_P = pervious Curve Number, and

$TIA_{\%}$ = total impervious area (%).

For catchments with impervious areas that are unconnected from drainage systems, or less than 30% TIA, the USDA (2004) proposes using Equation 7.5:

$$\mathrm{CN}_C = \mathrm{CN}_P + \frac{TIA_{\%}}{100}(98 - \mathrm{CN}_P)(1 - 0.5R) \tag{7.5}$$

where

CN_C = composite Curve Number,

CN_P = pervious Curve Number,

$TIA_{\%}$ = total impervious area (%), and

R = ratio of unconnected impervious area to total impervious area

In the second approach natural CN values are applied, with TIA and DCIA added separately in the SWMM (Rossman and Huber, 2016). The SWMM accommodates directly connected versus Unconnected Impervious Areas (UIA) by routing the unconnected portion of the runoff generated on impervious areas over pervious areas before reaching the sub-catchment outlet. The remainder of the runoff is routed directly to the outlet as DCIA. The input parameter for the SWMM is therefore the proportion of TIA that is not connected to drainage systems, with the subarea routing set to *Pervious*. It should be noted that $\mathrm{DCIA}_{\%}$ is reported in this chapter as a proportion of the total sub-catchment area to achieve consistency with other chapters.

The model was run using two alternative approaches described in the preceding paragraphs, with parameter values as found in the literature and summarized in Table 7.3. After the initial model runs were completed, the model was run twice more, with Parameter Set (PS) values as derived in Chapters 4 and 6. For the first model runs, two conventional parameter sets were evaluated:

PS (A) Composite urban CN values were derived with 0% TIA and flow routed directly to sub-catchment outlets. CN values were derived as proposed by the USDA (2004), with Equation 7.4 used for areas with 30% or more TIA and Equation 7.5 for areas with less than 30% TIA, based on the assumption that areas with less than 30% TIA would generally be unconnected from drainage systems (USDA, 2004). CN_P values for all residential, commercial and industrial areas were set to model pasture in good hydrologic condition (USDA, 2004). TIA for urban land cover as required for Equations 7.4 and 7.5 was estimated based on the imperviousness proposed by Schulze *et al*. (2004), described in Table 7.4.

PS (B) CN values for natural land cover were applied with TIA for urban land cover estimated based on the imperviousness proposed by Schulze *et al*. (2004), as described in Table 7.4. DCIA was estimated based on the assumption made by the USDA (2004) that areas with less than 30% TIA are unconnected, and areas with 30% or more TIA are connected to drainage systems.

Next, the knowledge gained in Chapters 4 and 6 was used to create two additional parameter sets in order to evaluate whether the derived values would improve results:

PS (C) Composite urban CN values were derived with 0% TIA and flow routed directly to sub-catchment outlets. CN values were derived as proposed by the USDA (2004), with Equation 7.4 used for areas with 30% or more TIA and Equation 7.5 for areas with less than 30% TIA, based on the assumption that areas with less than 30% TIA would generally be unconnected from drainage systems (USDA, 2004). CN_P values for all residential, commercial and industrial areas were set to model pasture in good hydrologic condition (USDA, 2004). TIA for urban land cover as required for Equations 7.4 and 7.5 was estimated based on the parameter values proposed in Chapters 4 and 6 for different SANLC classes.

PS (D) CN values for natural land cover were applied with TIA for urban land cover estimated based on the imperviousness proposed in Chapter 4. DCIA values were applied as derived in Chapter 6.

A summary of the parameter sets used for the different model runs is provided in Table 7.3.

Table 7.3 SWMM parameter set sources and values for Catchment A2H063

Modelled Parameter	PS A	PS B	PS C	PS D	Calibration
CN	From USDA (2004): Eq 7.4 for $TIA_{\%} \geq 30\%$, Eq 7.5 for $TIA_{\%} < 30\%$, TIA from Schulze *et al.* (2004)	From USDA (2004): Natural CN for pervious land cover	From USDA (2004): Eq 7.4 for $TIA_{\%} \geq 30\%$, Eq 7.5 for $TIA_{\%} < 30\%$, TIA from Chapter 4	From USDA (2004): Natural CN for pervious land cover	From USDA (2004): Natural CN for pervious land cover
$TIA_{\%}$	From USDA (2004): 0%	From Schulze *et al.* (2004): RES_{Formal} (Tree): 38% RES_{Formal} (Bush): 38% RES_{Formal} (Grass): 65% RES_{Formal} (Bare): 65% COM: 85% IND: 72%	From USDA (2004): 0%	From Chapter 4: RES_{Formal} (Tree): 17% RES_{Formal} (Bush): 44% RES_{Formal} (Grass): 58% RES_{Formal} (Bare): 61% COM: 81% IND: 89%	From Chapter 4: RES_{Formal} (Tree): 17% RES_{Formal} (Bush): 44% RES_{Formal} (Grass): 58% RES_{Formal} (Bare): 61% COM: 81% IND: 89%
$DCIA_{\%}$	From USDA (2004): 0%	From USDA (2004) (for $TIA_{\%} \geq 30\%$): RES_{Formal} (Tree): 38% RES_{Formal} (Bush): 38% RES_{Formal} (Grass): 65% RES_{Formal} (Bare): 65% COM: 85% IND: 72%	From USDA (2004): 0%	From Chapter 6: RES_{Formal} (Tree): 0% RES_{Formal} (Bush): 0% RES_{Formal} (Grass): 16% RES_{Formal} (Bare): 43% COM: Eq. 6.14 IND: Eq. 6.14	From Chapter 6: RES_{Formal} (Tree): 0% RES_{Formal} (Bush): 0% RES_{Formal} (Grass): 16% RES_{Formal} (Bare): 43% COM: Eq. 6.14 IND: Eq. 6.14
Other	None	None	None	None	Pseudo storage (Table 7.7)

Table 7.4 Imperviousness used in PS A and PS B (adapted from (Schulze *et al.*, 2004)

SANLC Class	Associated SCS Land Use Class	TIA (%)
Urban Residential (Trees)	Residential: lot size 1000 m^2	38
Urban Residential (Bush)	Residential: lot size 1000 m^2	38
Urban Residential (Grass)	Residential: lot size 500 m^2	65
Urban Residential (Bare)	Residential: lot size 500 m^2	65
Commercial	Commercial/business areas	85
Industrial	Industrial districts	72

The 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 model were based on the hydraulic conductivity (Rawls *et al.*, 1983) and the equation proposed for calculating drying times in the Green-Ampt method (Rossman and Huber, 2016) and adapted for SI units:

$$T_{dry} = \frac{15.78}{\sqrt{(K)}} \tag{7.6}$$

where

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

K = hydraulic conductivity [mm/h].

Table 7.5 Drying times used in the SWMM model (using hydraulic conductivity values from Rawls *et* al., 1983)

SCS Soil Grouping	Hydraulic Conductivity K (mm/h)	Drying Time (days)
A	120.00	1.4
A/B	30.00	2.9
B	11.00	4.8
B/C	3.30	8.7
C	1.25	14.1
C/D	0.75	18.2
D	0.25	31.6

As it has been shown (Chapter 3) that base flow occurs continually in the study catchments, a constant base flow was added manually to the model configurations for both catchments. Other parameter values were chosen according to the available information and values indicated in literature, and described in Loots and Smithers (2020). All parameter set model runs were analysed as continuous models for the study period with available and infilled 5-min interval rainfall data (November 1994 to September 2022).

7.4.6 Model calibration

The performance of each parameter set was assessed through a combination of visual interpretation of flow frequency curves and quantitative evaluation. The maximum simulated flow rates, as well as average and total flow volumes over the study period were compared. The widely-used Root Mean Square Errors (RMSE) (Remondi *et al.*, 2015; Talisay *et al.*, 2019; Adeyeri *et al.*, 2020; Igulu and Mshiu, 2020; Arjenaki *et al.*, 2021; Hodson, 2022) and Coefficients of Determination (R^2) were also reported. Given some inconsistencies between observed event rainfall and corresponding observed flow data for the same event, and based on the assumption that the distribution of catchment rainfall data is reliable, the distributions of simulated and observed flow data were used for visual assessment of the performance of the model (Gioia *et al.*, 2008; Moretti and Montanari, 2008; Stein *et al.*, 2012; Caltrans, 2015).

It has previously been postulated that unexpected attenuation is prevalent in the study catchments (Chapters 3 and 5). Therefore, small pseudo storages were added throughout the study catchments with storage volume as a calibration parameter to further improve the model by simulating flow attenuation during major storm events (Figure 7.8). For this study, the hydraulic outlets of the pseudo storage areas were set to be weir flow, with dimensions equal to the downstream conduit. All junctions directly downstream of sub-catchments with a majority urban land use were replaced by storage areas.

Storage area volumes were determined based on the dominant land cover in the sub-catchment draining to the storage area. Based on observation of imperviousness percentages, boundary walls, kerbs and general layout of different properties in the catchment, commercial land cover [COM] was deemed to have the largest potential for flow attenuation. Industrial [IND] and Formal Residential (Bare) [RES_{Formal} (Bare)] also have significant potential for flow attenuation. They are followed, in decreasing order, by Urban Residential (Grass) [RES_{Formal} (Grass)], Urban Residential (Bush) [RES_{Formal} (Bush)] and Urban Residential (Tree) [RES_{Formal} (Tree)].

Based on comparison of the frequencies of observed versus simulated flow, pseudo storage volumes were manually adjusted to better simulate observed large flow rates and total flow volume, with the lowest recorded AMS peak flow rate used as a lower threshold. This threshold was used as an indicator of significant stormflow events. Initial comparison was made through visual inspection of the flow-duration curves, total flow volume, maximum flow rates and the RMSE. Adjustments were then made to pseudo storage volumes to improve these values, with iterations applied until no further improvement was evident. A summary of the parameter set applied in the calibration study is provided with summaries of the initial parameter sets in Table 7.3. The SWMM model configuration for Catchment A2H063 was calibrated to better simulate observed large flow rates and total flow volume. The parameter set (A, B, C or D) that best simulated the total flow volume was used for calibration.

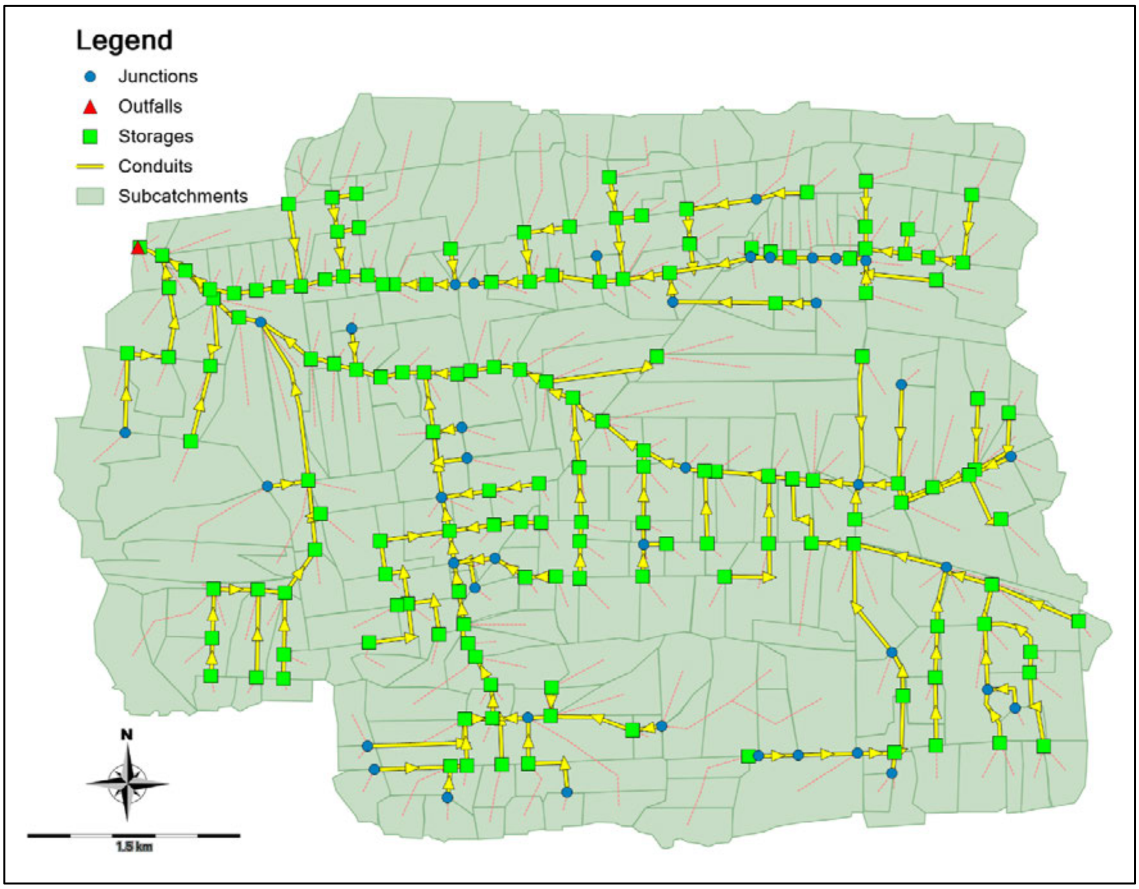


Figure 7.8 Storage areas added for calibration of the SWMM configuration for Catchment A2H063, with the red lines depicting overland flow to sub catchment outlets

7.4.7 Model verification

After the model configuration for Catchment A2H063 was calibrated by including small pseudo storages throughout the catchment, the calibrated pseudo storage values were verified on the adjacent Catchment A2H054. DWS gauged Catchment A2H054 was used for the model verification, with the model configured as shown in Figure 7.7 and similar parameter sets to the calibration catchment, as described in Table 7.3. Small pseudo storages were added using the same methodology as for the calibration catchment. The locations of these ponds are shown in Figure 7.9. The model was run with continuous 5-min rainfall data for the period from November 1994 to September 2022. As shown in Figure 7.2, one rainfall station is located within the catchment, with an additional two stations' Thiessen polygons overlapping the catchment area.

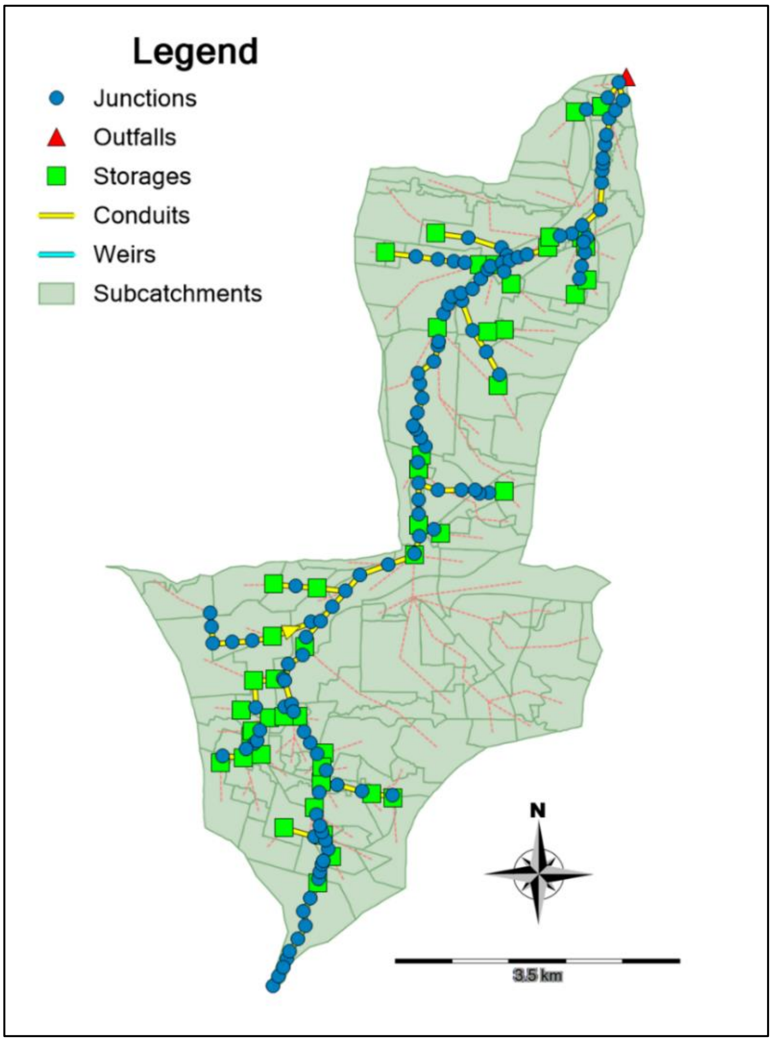


Figure 7.9 SWMM verification configuration for Catchment A2H054, with the red lines depicting overland flow to sub catchment outlets

7.5 Results

The results for model Configurations A, B, C and D, as summarized in Table 7.3, as well as the calibration results for Catchment A2H063, are described. The verification results of all five parameter sets for Catchment A2H054 are also described.

7.5.1 Uncalibrated results

shows a scatter graph of the observed and simulated flow hydrographs for the study period between 1994 and 2022 for the SWMM model configuration of Catchment A2H063 with PS A as an example. The model with PS A, PS B, PS C and PS D all overestimated flow rates for numerous events, but for some events the simulated runoff was significantly lower than observed flow. The data was checked for phasing and total volume simulated. No phasing issues were evident. However, disparity exists between observed rainfall and measured runoff for certain events. Examples are shown in Figure 7.11. As none of the rain gauges are situated inside the catchment area and the region experiences storms with considerable spatial distribution (Dyson, 2009; Mouton *et al.*, 2022), it is possible that the flow gauging station might sometimes register runoff from rainfall events for which the representative catchment intensity is not recorded at the rainfall stations, and vice versa. The infilling of rainfall data could also contribute to the disparity. However, as the rainfall stations are all in the nearby vicinity of the catchment and experience the same type of weather patterns, frequency distribution was used to compare the exceedance probabilities of the simulated flow generated versus observed flow data for the continuous simulation period.

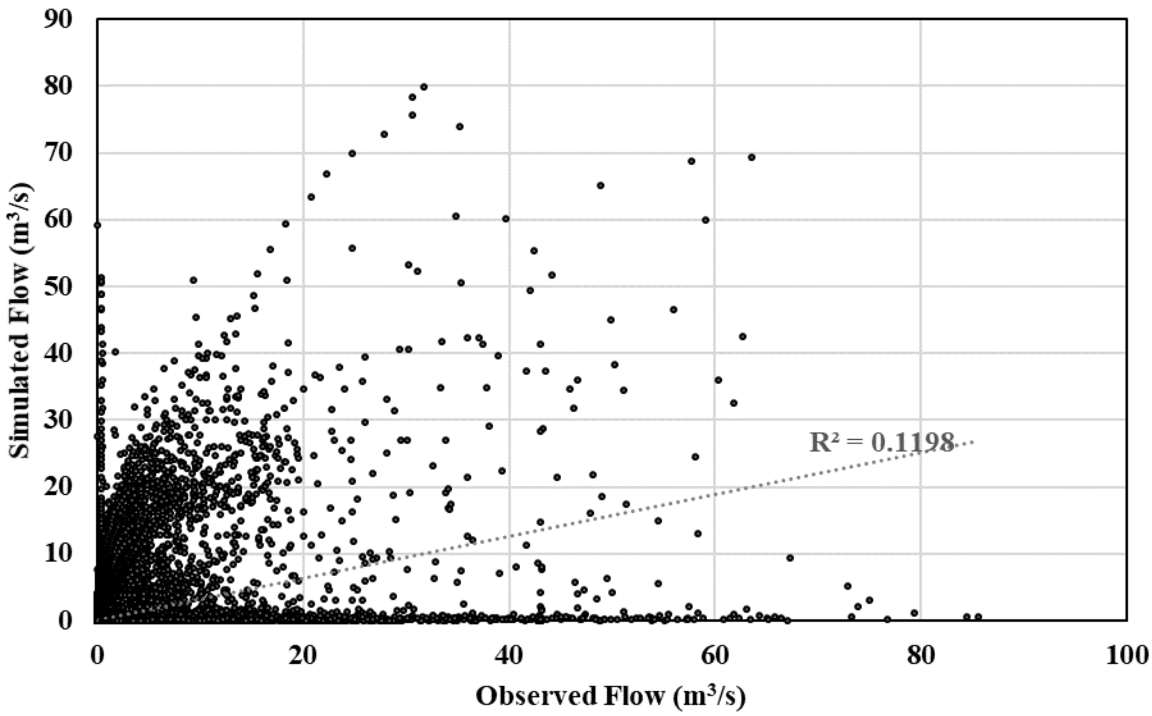
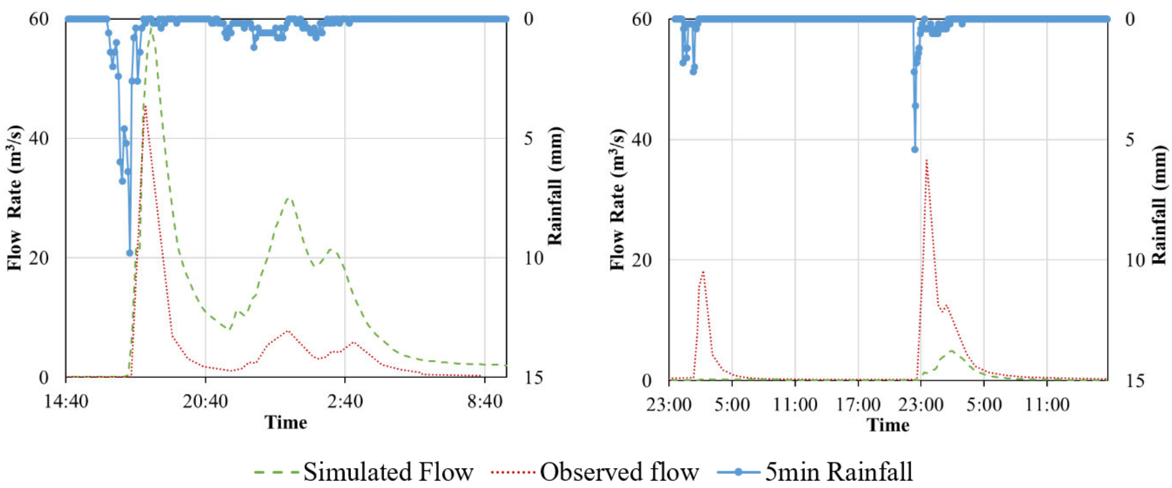


Figure 7.10 Scatter plot of SWMM results versus observed flow for Catchment A2H063 for the period from 1994 to 2022: PS A



(a) 20 October 2000 (b) 25 October 2000

Figure 7.11 Examples of observed flow and SWMM simulated hydrographs for Catchment A2H063: PS A

The frequency distributions of the simulated and observed flows were compared to assess if flow rates were generally over- or underestimated. This comparison eliminates the possible inconsistences in the data at a time step or event level due to the spatial distribution of rainfall.

Figure 7.12 shows the frequency distribution curve of the observed flow data, compared with the curves for the model run with PS A and PS B (as described in Table 7.3), up to 2.5% exceedance probability. Both configurations overestimated flows in this range. The largest simulated peak flow rate for PS A was 104 m^3/s, compared with 131 m^3/s for PS B. This represents errors of 21% and 52% respectively when compared with the maximum observed flow rate of 86 m^3/s. PS A overestimated flow rates larger than 3.1 m^3/s, but underestimated flows for minor rainfall events with flows between 1.1 m^3/s and 3.1 m^3/s. PS A underestimated the total runoff volume by 6%. The total volume simulated with PS B approximately 170% higher than the observed volume over the study period. At 164, the RMSE for PS A higher lower than for PS B, that had an RMSE of 151. The R^2 value for PS B (0.471) was better than for PS A (0.321), although neither R^2 value represented an acceptable correlation of simulated data with observed data, assuming $R^2>0.5$ as being satisfactory (Moriasi *et al.*, 2007; de Castro Ferreira *et al.*, 2022). This was attributed to the significant spatial distribution of rainfall in the study area (Makgopa, 2015; Mouton *et al.*, 2022) and low rain gauge density and presents further justification for the use of frequency distributions as the primary source for comparison of results.

Both parameter sets applying data from literature to the SWMM configuration of Catchment A2H063 tended to overestimate the frequency distribution for the majority of flow rates above the minimum recorded peak flow rate in the AMS of 2.4 m^3/s. However, PS A underestimated minor runoff events below 3.1 m^3/s and PS B overestimated the total flow volume by 170%. Therefore, both configuration philosophies were further evaluated, incorporating the knowledge acquired during this study.

As shown in Figure 7.12 and Table 7.6, the incorporation of imperviousness and impervious area connectivity values derived in this study (Chapter 4 and 6) with PS C and PS D improved the results. The frequency of flow rates for PS A and PS C are similar for flow rates between 5 m^3/s and 100 m^3/s, with PS C underestimating flows between 1.2 m^3/s and 3.5 m^3/s. PS D overestimates the frequency of flows above 2.7 m^3/s, with underestimation between 1.3 m^3/s and 2.7 m^3/s. However, PS A underestimates the total flow volume by 13%, while PS D overestimates the total flow volume by less than 6%. PS D was therefore used as the basis for the calibration model run.

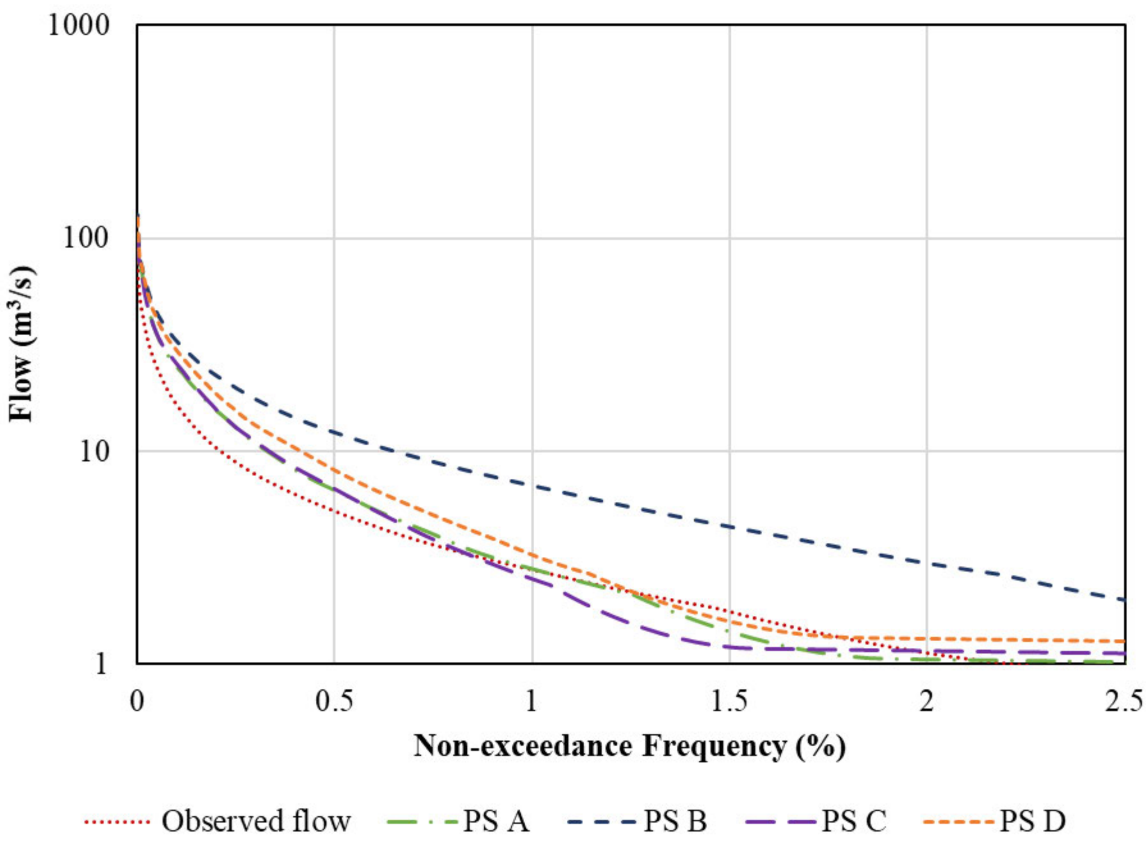


Figure 7.12 Non-exceedance frequency distribution curves for PS A, PS B, PS C and PS D for Catchment A2H063, for all flow rates above 1 m^3/s

7.5.2 Calibration results

The inclusion of small pseudo storages throughout the study catchment significantly improved results compared with all other parameter sets in the calibration catchment, as shown in Figure 7.13. The maximum simulated flow rate was, however, under-simulated at 80 m^3/s. Simulation results improved for flow rates between 5.5 m^3/s and 75 m^3/s, with the mean flow rate of the calibration configuration at 0.181 m^3/s and the total volume simulated within 1% of the total observed flow volume. The R^2 value decreased to 0.120, but the RMSE improved to 148. The low R^2 value and high RMSE were attributed to the significant spatial distribution of rainfall in the study area (Makgopa, 2015; Mouton *et al.*, 2022) and low rain gauge density. A summary of the results for the uncalibrated and calibrated model configurations is provided in Table 7.6. A table summarizing the calibrated storage per hectare for each of the modelled urban land cover classes at different conduit flow depths is shown in Table 7.7

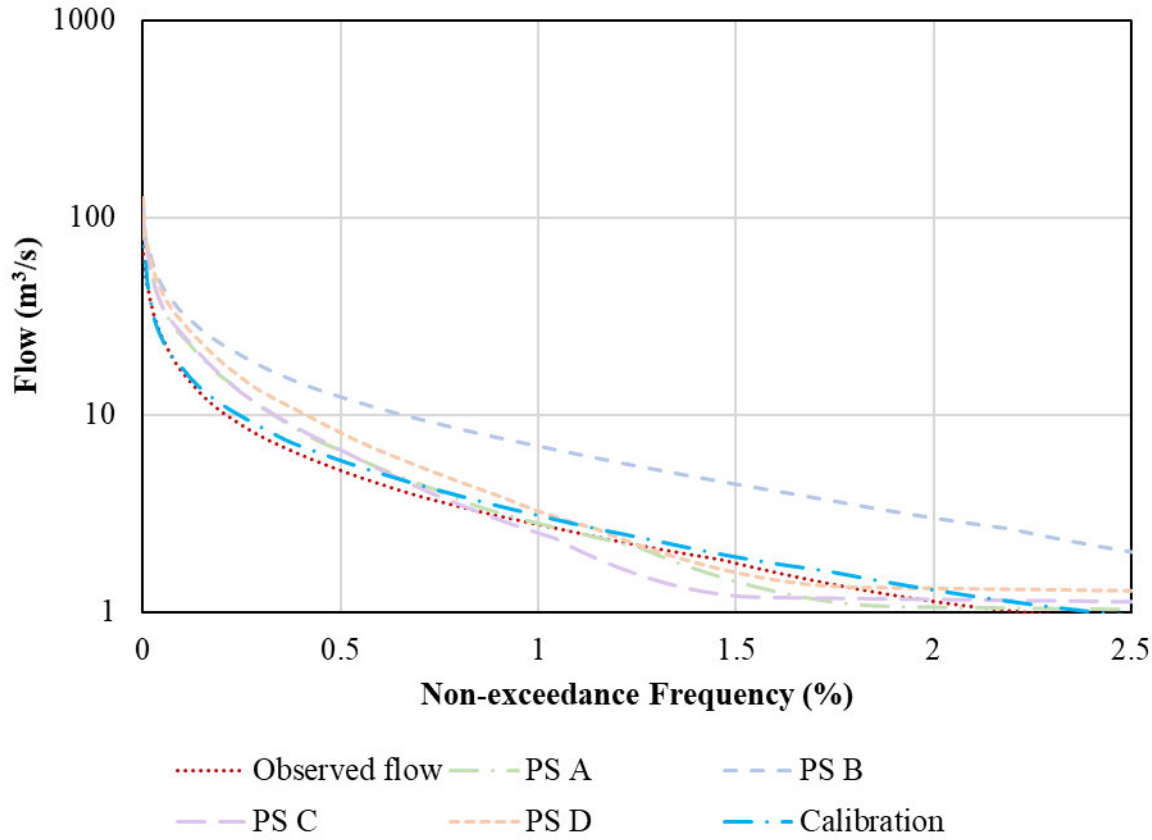


Figure 7.13 Calibration results for Catchment A2H063, for all flow rates above 1 m^3/s

Table 7.6 SWMM result comparison for Catchment A2H063

Data set	Max Flow (m^3/s)	Mean Flow (m^3/s)	Total Volume (Mm^3)	R^2	RMSE
Observed	91.4	0.181	160.7		
PS A	104.3	0.170	149.8	0.321	164
PS B	130.8	0.305	269.1	0.471	151
PS C	117.0	0.160	141.3	0.267	183
PS D	131.1	0.191	168.0	0.356	189
Calibration	80.0	0.181	159.3	0.120	148

Table 7.7 Calibration storage area volumes

SANLC Class	Land Use Type	Storage Volume (m^3/ha)
47	Residential Formal (Tree)	232
48	Residential Formal (Bush)	253
49	Residential Formal (Grass)	327
50	Residential Formal (Bare)	549
65	Commercial	581
66	Industrial	511

7.5.3 Verification results

The parameter sets and storage area curves used in the calibration for Catchment A2H063 were verified using a continuous SWMM model configuration generated using the same methodology as described in Table 7.3 in Catchment A2H054 for the study period from 1994 to 2022. The maximum simulated flow rates for PS A, PS B, PS C and PS D were all less than the maximum observed flow rate of 96 m^3/s, but the mean flow rates and total simulated flow volumes all represent overestimation, as shown in Table 7.8. This could possibly be attributed to the relatively large proportion of the catchment reliant on rainfall from one rain gauge in the model configuration (Figure 7.2), while it is known that considerable spatial distribution of rainfall exists in the study area (Makgopa, 2015; Mouton *et al.*, 2022). This would result in overestimation of flow during any rainfall event observed at the UP rain gauge, resulting in overestimation of total flow volume. The maximum simulated flow rate for the verification simulation with pseudo storages included (Figure 7.9) was 83.6 m^3/s, which represents an underestimation of 15%. However, at 0.191 m^3/s, the mean flow rate of this configuration was almost 16% higher than the observed mean of 0.165 m^3/s. This over simulation is also attributed to the large proportion of the catchment with rainfall simulated from one rain gauge. No R^2 values represented an acceptable fit of simulated data, assuming R^2>0.5 as being satisfactory (Moriasi *et al.*, 2007; de Castro Ferreira *et al.*, 2022). This was attributed to the significant spatial distribution of rainfall in the study area (Makgopa, 2015; Mouton *et al.*, 2022) and low rain gauge density. The results are summarised in Table 7.8. Despite the discrepancies, Figure 7.14 shows that the inclusion of small pseudo storages in Catchment A2H054 improves the results. Although the errors in the verification configuration were more pronounced, Figure 7.13 and Figure 7.14 show curves with similar shapes, where large flow rates are generally overestimated, but flow rates from minor storms are generally underestimated. Figure 7.14 also shows that the inclusion of storage throughout the catchment improved the simulation of the majority of large flow rates in the verification catchment.

Table 7.8 SWMM verification results

Data Set	Max Flow (m^3/s)	Mean Flow (m^3/s)	Total Volume (Mm^3)	R^2	RMSE
Observed	96.1	0.165	145.9		
PS A	92.0	0.189	167.0	0.421	169
PS B	94.1	0.209	184.5	0.413	142
PS C	91.5	0.178	157.3	0.413	146
PS D	90.9	0.189	167.5	0.395	153
Verification	83.6	0.191	168.6	0.409	139

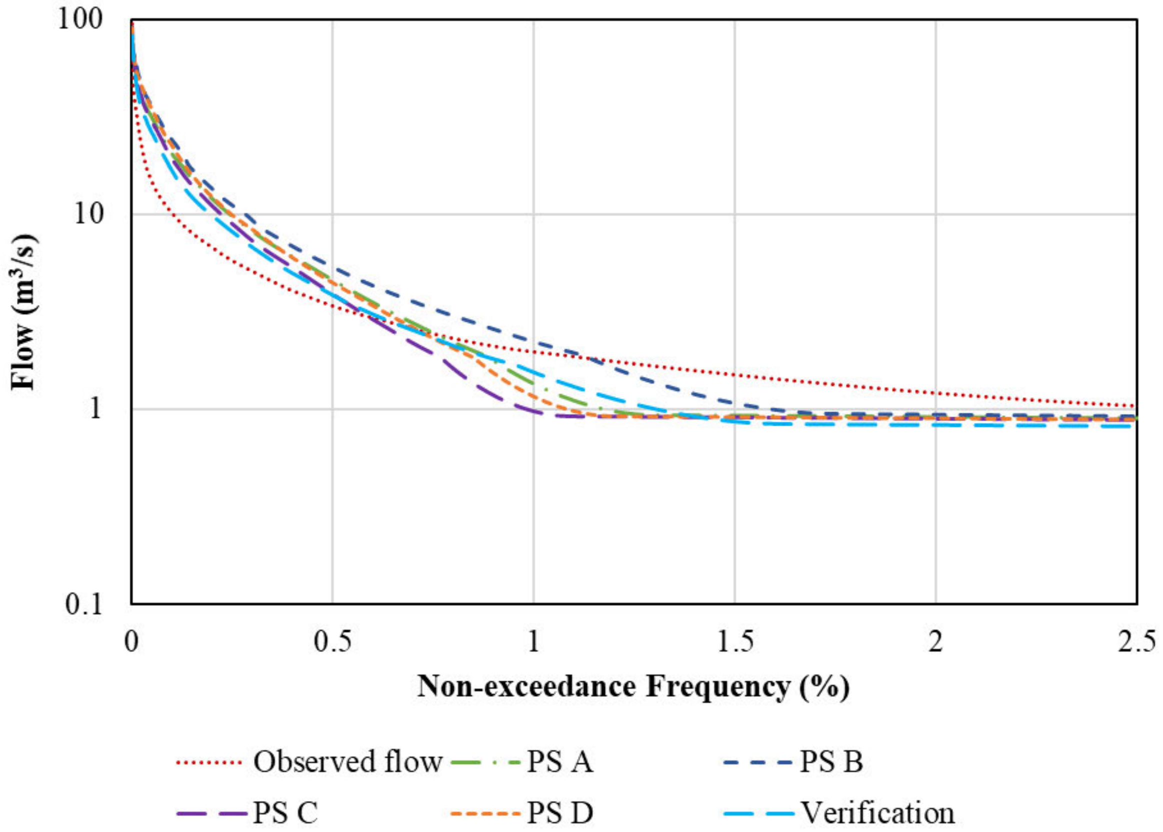


Figure 7.14 Frequency distribution curves with the parameter sets of Catchment A2H054, for all flow rates above 2.4 m^3/s

7.6 Discussion and Conclusions

The SWMM was identified as an applicable rainfall-runoff model for use in South African urban areas. SWMM configurations were set up for two adjacent urban catchments to test the performance of this model for South African urban areas. The study catchments were chosen due to the relatively long period for which 5-minute interval rainfall data was available. Catchment size and comparatively homogeneous land cover also contributed to the choice of study areas. One catchment was used in the model calibration and the other for verification in order to maximise the simulation period used for the derivation of flow duration curves in each catchment. Despite the relatively small catchment sizes, disparity exists between observed rainfall and measured runoff for certain events. As none of the rain gauges are situated inside the catchment area and the region experiences storms with considerable spatial distribution, it is possible that the flow gauging station might sometimes register runoff from rainfall events for which the representative catchment intensity is not recorded at the rainfall stations, and vice versa. The infilling of rainfall data could also contribute to the disparity. However, as the rainfall stations are all in the nearby vicinity of the catchment and experience the same type of weather patterns, frequency distribution was used to compare the exceedance probabilities of the simulated flow generated versus observed flow data for the continuous simulation period. The model was initially run as per SWMM convention, with junctions at sub-catchment outlets. Curve Numbers were derived using two approaches and both parameter sets were run for the catchment used in the calibration (A2H063): (PS A) Composite urban CN values were derived with 0% impervious areas and flow routed directly to sub-catchment outlets; and (PS B) CN values for natural land cover were applied with imperviousness and impervious area connectivity as obtained from literature (Table 7.3). It was found that both parameter sets over-estimated large flow rates, but PS A underestimated minor runoff events 6% error in total flow volume over the study period and PS B overestimated the total flow volume by 170%. These results show that neither parameter set was able to properly mimic the observed rainfall-runoff interaction in the catchment. Therefore, both configuration philosophies were evaluated further by incorporating the knowledge acquired during this study. The incorporation of imperviousness and impervious area connectivity values derived in this study with PS C and PS D improved the results. The frequency of flow rates for PS A and PS C are similar for flow rates between 5 m^3/s and 100 m^3/s, with PS C underestimating flows between 1.2 m^3/s and 3.5 m^3/s. PS D overestimates the frequency of flows above 2.7 m^3/s, with underestimation between 1.3 m^3/s and 2.7 m^3/s. However, PS A underestimates the total flow volume by 13%, while PS D overestimates the total flow volume by less than 6%. These results show that even the best available imperviousness and impervious area connectivity values are unable to mimic the rainfall-runoff interaction in the catchment.

As it has previously been shown that unexpected attenuation is prevalent in the study catchments, further improvement was achieved through the replacement of junctions at urban sub-catchment outlets by small pseudo storages. Storage volumes were set individually per formal urban land cover, with Commercial areas having the highest attenuation potential based on a combination of high permeability and typical property layout in those areas, followed by Industrial and Formal Residential (Bare), then by Urban Residential (Grass), Urban Residential (Bush) and Urban Residential (Tree). The calibrated configuration showed improved simulation on the significant higher flow portion of the flow-duration curve, although flow rates above 75 m^3/s were underestimated. The calibration parameter values were subsequently tested in the verification catchment. The verification configuration over-simulated the majority of storm flow rates, but the inclusion of pseudo storages as determined in the calibration catchment, improved simulated results.

The aim of this study was to assess if the incorporation of characteristics of hydrological responses from formal urban areas determined in previous studies (Chapter 4 and Chapter 6) improves hydrological modelling of South African urban catchments with formal development and to test additional improvements. It was shown that the incorporation of imperviousness and impervious area connectivity values derived in previous studies improved results, with additional improvement achieved through the addition of pseudo storages at the outlets to urban sub-catchments. The SWMM has the capability to model both hydrological and hydraulic components of rainfall-runoff interaction. The physical attributes of development types are expected to be similar in other regions of SA, because the SANLC, which was used as the basis for physical parameters, is applicable to the entire country. Slopes and soils are accounted for explicitly in the SWMM, so if the relevant data is applied in other regions, the results should be valid. It is recommended that this be verified using data from additional catchments in other regions when sufficient data is available.

Storage volume was used as the only calibration parameter in this study. It is recommended that typical storage potential be quantified for properties with formal urban land cover in South Africa in order to confirm whether the calibration parameters are realistic. Catchments with informal development were not included in this study, since the smallest gauged catchment in Tshwane with informal development has an area of 109 km^2, with no SAWS rain gauges located in the catchment. It is therefore recommended that the parameter values used in this study be tested on additional gauged catchments, particularly catchments with informal development, in other regions in South Africa to determine whether the results are applicable to all ungauged catchments.

8 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

This chapter contains a discussion of the results obtained in previous chapters. The discussion is followed by conclusions drawn from this study and a summary of new knowledge created. Recommendations are made for improved hydrological modelling in South African urban areas and for future studies.

8.1 Discussion

The results presented in previous chapters were based on analysis of a limited number of urban catchments in South Africa. The lack of gauged urban catchments with long term discharge data of good quality impacted the scale at which this study could be conducted. Gauged catchments selected for this study included areas with both formal and informal settlements, and land cover assessment was applied using the South African National Land Cover (SANLC) database, that is applicable throughout South Africa. Hydrological modelling was limited to two catchments with relatively small catchment areas, relatively homogeneous development that did not change significantly over the study period, and with rain gauge proximity and density suitable for catchment rainfall estimation and with a sufficient period of data.

The most important results from previous chapters are discussed in the following sections. The results are collated into three sections with the first focused on the influence of urban development in South Africa on hydrological responses. The quantification of imperviousness and impervious area connectivity is discussed. This is followed by a discussion on proposed improvements to hydrological modelling of South African urban areas based on the new understanding gained in characterising the hydrological responses from different types of urban development, using data from the stations selected for this study.

8.1.1 Influence of development on runoff

The significance of correlation between the extent of the urban footprint on Q/P ratios, base flows and flood peaks were assessed. Analysis of Q/P ratios in catchments with increasing areas of urban development showed that an increase in total flow volumes followed from an increase in urbanisation for all urban study areas, for both formal and informal urban development. The increase in total runoff with increased urbanisation is consistent with findings of most other studies (Konrad, 2003; Putro *et al.*, 2016) in developed countries. In addition to the increase in total Q/P ratios, there was a strong correlation between catchment imperviousness (TIA) and direct storm runoff volumes in most of the study catchments, including those with formal (Catchments A2H054, A2H055 and A2H063) and informal development (Catchment A2H029). Catchment A2H027 is the only catchment that does not show statistically significant correlation. It is postulated that the results from the catchments selected for this study would be applicable in other South African urban catchments as well, due to similar development characteristics (Geoterraimage, 2021) and similar challenges with aging and leaking water infrastructure (Ruiters and Amadi-Echendu, 2022). Until additional data are available for other South African urban areas, it is recommended that the results from this study should be considered in hydrological modelling for the planning and design of any infrastructure related to flood attenuation or sustainable urban drainage systems, in both formal and informal developments, as increased flow volumes would need to be accommodated with increased catchment imperviousness.

Analysis of base flow rates indicated that base flow tends to increase with an increase in the extent of the urban footprint, both in catchments with formal and informal development. The increasing base flow trends are contrary to findings in most other studies (Smakhtin, 2001; Shuster *et al.*, 2005; Jacobson, 2011; Braud *et al.*, 2013; Gogate and Rawal, 2015). Some activities associated with urbanisation, including inter-catchment transfers and wastewater discharges, may well change the net impact on hydrological responses (Brandes *et al.*, 2005; Meyer, 2005; Whitney *et al.*, 2015; Schütte and Schulze, 2017). Although the specific causes of the base flow trends cannot be determined from the data collated for this study, it should be noted that South Africa is a water-scarce country with developmental hubs far away from natural water sources. The country therefore has a large number of potable water transfer schemes that supply water to urban regions through long piped distribution networks. It is postulated that the water transferred into the catchments may contribute to baseflow through pipe bursts, pipe leaks, garden irrigation, swimming pool backwashing and other activities. The effect of water transfer into the catchments is potentially combined with aging, poorly maintained, or poorly installed infrastructure leading to leakage of potable water and waste water into the river systems (Ruiters and Amadi-Echendu, 2022). The reasons for this phenomenon need to be further investigated and quantified for both formal and informal developments, since it is expected that this phenomenon will occur in other South African urban areas, as well as urban areas in other water-scarce countries. Base flow, whether naturally occurring or due to urban activities and infrastructure failure, needs to be incorporated into hydrological models and drainage system design, especially when lower-order flood events are of significance.

With one exception, the catchments did not show statistically significant decreasing catchment response time with either formal or informal development. This result is contrary to the generally accepted view that increased imperviousness results in decreased catchment response times (Fletcher *et al.*, 2013; McGrane, 2016), although some studies in developed countries have found similar results (Miller and Hess, 2017; Requena *et al.,* 2017). Results from this study have shown that the flood volumes in these catchments increased with increased development, hence the increased volumes without reduced time to peak is postulated to be attributed to unexpected flow attenuation in the catchment, as suggested by Van Vuuren (2012). The above argument is strengthened by the statistical insignificance of peak flow rate increases in the majority of formally developed study catchments, which is also contrary to results from many studies in developed countries (Konrad, 2003; Lee and Heaney, 2003; Todeschini, 2016), although this observation has previously been made in some international studies (Burns *et al.*, 2005; Aichele and Andresen, 2013; Miller and Hess, 2017). Since the analysis of runoff volumes, catchment response time and peak flow rates found increased storm runoff volume, without decreased response times or increased peak flow rates, it is recommended that flow attenuation should be modelled in South African urban catchments with formal development. These findings should be verified when additional data is available in other South African urban catchments.

Contradictory results were found in the analysis of flood peaks for the catchment with the highest proportion of informal development (Catchment A2H029), with statistically insignificant change with increasing catchment imperviousness in the time-to-peak (T_p), but with increasing AMS of flood peaks. In contrast to many formal South African settlements, informal developments are typically not surrounded by boundary walls that could act as attenuating structures during and after storm events, although it was shown that runoff from informal settlements is generally not directly connected to formal drainage. The statistically insignificant change with increasing catchment imperviousness in time-to-peak (T_p), but with increasing AMS of flood peaks in Catchment A2H029 (informal development) is an interesting result that should be investigated further by considering the complexities of increasing impervious areas without increased impervious area connectivity.

8.1.2 Quantifying imperviousness and impervious area connectivity of South African urban areas

This study has shown that, despite variation, it is possible to estimate imperviousness values for the urban SANLC classes considered in this study. It was shown that imperviousness is different in RES_{Formal} and $RES_{Informal}$ areas, and also for SANLC classes within land cover groups. Commercial and Industrial areas are typically more than 80% impervious. It is proposed that the imperviousness values derived in this study be used for hydrological modelling of South African urban areas or other areas and regions with similar development characteristics, where site-specific conditions are not easy to quantify. Where available, site-specific values are, however, still recommended for hydrological modelling.

It is widely accepted that not only total imperviousness, but also the connectivity of impervious areas to drainage systems, plays a major role in runoff response (Lee and Heaney, 2003; Roy and Shuster, 2009; Yao *et al.*, 2015; Redfern *et al.*, 2016; Miller *et al.*, 2020). This study has shown that, although there is considerable variation in connectivity of impervious areas for different plots and areas within the study catchments, most residential areas had limited to no direct connections to drainage systems. Industrial and commercial areas were shown to be generally connected to drainage systems. It is proposed that the impervious area connectivity values derived in this study be used for hydrological modelling of South African urban areas or other areas and regions with similar development characteristics, where site-specific conditions are not easy to quantify.

8.1.3 Modelling hydrological responses from South African urban areas

The Storm Water Management Model (SWMM) was identified as a semi-distributed rainfall-runoff model capable of modelling heterogeneous catchments with hydraulic routing between catchments. It is widely used globally and locally in South Africa. It was therefore selected as an applicable model for use in South African urban areas. As with many other models currently used for urban hydrological modelling, the SWMM requires a significant amount of input data (Parkinson *et al.*, 2007). Much of the required input data for the SWMM was not available for

South Africa prior to this study. In order to develop an improved approach for hydrological modelling in South African urban areas, imperviousness, impervious area connectivity to drainage systems, and representative infiltration parameters were derived as discussed in the previous section and applied in the model.

The performance of the model was tested using two gauged urban catchments with more than 20 years of representative 5-minute interval rainfall data. One catchment was used as the calibration catchment to test parameter values and the other as the verification catchment. The SWMM configurations set up using conventional methods and parameter values from literature overestimated large flow rates. Although large flow rates were still overestimated, the inclusion of imperviousness and connectivity derived in this study improved the simulation results. The incorporation of small pseudo storages at urban sub-catchment outlets, to mimic what was observed, further improved the results. The results were verified in an adjacent catchment, with similar results. Storage volume was used as a calibration parameter in this study and storage volumes per hectare were proposed based on land cover for pseudo storages in other models, but volumes were not quantified through field investigation and recommendations for further investigation are made in Section 8.4.

8.2 Conclusions

The aims of this study were to gain new understanding of hydrological processes in the diverse range of South African urban environments and to use this knowledge to develop an improved approach for hydrological modelling in South African urban areas. Due to the limited amount of reliable, long-term, measured urban flow data in South Africa, the focus of this study was on five urban and three rural catchments in the Gauteng Province, but with discussion on the wider applicability of certain results and recommendation for further studies in other South African urban areas when additional data are available. The aims were achieved through four objectives.

Objective (a) was to improve understanding of the complexities of urban areas and urban hydrological processes in South Africa as a diverse and developing country. In order to achieve this objective, a literature review was conducted to define the complexities of urban heterogeneity and the effects on hydrological processes. Consideration of the methodologies followed and results obtained in previous studies, as well as consideration of South Africa being a diverse and developing country with distinct types of urban development, led to the conclusion that South Africa may have differing hydrological responses to those reported in literature (summarised in Chapter 2 and relevant literature incorporated in subsequent chapters). The complexities of South African urban areas were investigated through quantification of imperviousness (Chapter 4) and impervious area connectivity (Chapter 6) characteristics of catchments with different formal and informal land cover classes in South Africa.

Objective (b) was to investigate the influence of formal and informal South African development types on runoff, based on analysis of currently available long-term data. This was achieved by quantifying the effects of the extent of urban development on: (a) runoff volumes, (b) base flow volumes and (c) flood peaks in catchments with typical urban development types found in South Africa (Chapter 3). It was concluded that both formal and informal development in the study catchments resulted in increasing Q/P ratios and increasing base flows. The magnitudes of flood peaks are not affected to the same extent by the level of formal urban development, although areas with informal development seem to experience increasing flood peaks with increased development. Further analysis compared changing catchment imperviousness with (a) flood volumes, (b) catchment response times and (c) peak flow rates (Chapter 5). It was concluded that increased catchment imperviousness leads to increased direct runoff volume in areas with formal and informal development. However, catchment response times and flood peaks are not significantly affected by formal urban development. The apparent paradox of increased flood volumes without corresponding increase in flood peaks and decreased catchment response is attributed to the temporary storage and subsequent attenuation of peaks in catchments with formal developments in the study catchments. However, the catchment with the largest proportion of informal development shows increasing trends in both volume and flood peaks, although catchment response times do not show significant change. It is postulated that the complexity of increased imperviousness without increased connectivity of impervious areas to drainage systems could contribute to this result. Due to the similar development trends and infrastructure conditions between the study catchments and other urban catchments in South Africa, similar hydrological responses are expected for other, ungauged, urban South African catchments. This could be confirmed when additional long-term data is available for other regions.

Objective (c) was to identify the causes of different hydrological trends in catchments with different development types. The causes of different hydrological trends in catchments with different development types were identified through quantification of typical imperviousness, (Chapter 4) and connectivity of impervious areas (Chapter 6). Imperviousness (calculated as $TIA_{\%}$) in the study was shown to vary significantly between different formal and informal residential land cover classes. It was concluded that the connectivity of impervious areas to storm water drainage systems in the study (calculated as $DCIA_{\%}$), varies considerably between land cover class groups and even within land cover class groups. It was also concluded that unexpected flow attenuation contributes to lower-than-expected flood peaks and slower-than-expected catchment response times in catchments where the majority of development is formal.

Objective (d) was to recommend a new approach to model runoff from ungauged South African urban catchments, using data from the stations selected for this study, by incorporating the improved understanding obtained in the previous objectives. It was concluded in Chapter 7 that the new knowledge gained in this study by deriving imperviousness (Chapter 4) and impervious area connectivity (Chapter 6) resulted in improved modelling. Based on conclusions from Chapters 3 and 5, further improvement was achieved through the addition of pseudo storages at the outlets to urban sub-catchments. Specific recommendations for hydrological modelling are listed in Section 8.4.

The aim of gaining new understanding of hydrological processes in the diverse range of South African urban environments was therefore achieved through Objectives (a), (b) and (c) and the aim of developing an improved approach for hydrological modelling in South African urban areas, using data from the stations selected for this study, was achieved through Objectives (c) and (d).

8.3 Contributions to New Knowledge

In terms of generation of new knowledge, this study has contributed to a new understanding and characterisation of hydrological processes in formal and informal urban environments in Tshwane, South Africa. It was shown that, despite increased flow volumes with increased development, flood peaks and catchment response times are not affected significantly in catchments with formal urban development. It was concluded that this would be caused by unexpected attenuation in catchments with formal development. Analysis of the catchment in this study with the highest proportion of informal development showed contradictory results, with increased flow volumes and flood peaks with development, but without a decrease in catchment response time. It is postulated that the complexity of increased imperviousness without increased connectivity of impervious areas to drainage systems could contribute to this result.

Imperviousness and impervious area connectivity values were derived for different South African urban land cover classes for use in hydrological studies. It was shown that significant variation exists in both $TIA_{\%}$ and $DCIA_{\%}$ between formal and informal developments, as well as within individual land cover classes. However, the study showed that $TIA_{\%}$ and $DCIA_{\%}$ can be reasonably estimated for different land cover classes using results from this study and estimation methods are proposed for catchments where measured data are not readily available. The TIA and DCIA quantification results would be applicable nationally, since the SANLC classes were derived for similarly developed land cover classes nationally.

This study has shown that formal and informal urban developments in Tshwane respond differently to rainfall events. This is attributed to a combination of imperviousness, impervious area connectivity and flow attenuation, with both formal and informal residential areas being mostly disconnected from drainage systems and with commercial and industrial areas being mostly impervious and connected to drainage systems. It was also shown that it is possible to improve the modelling of rainfall-runoff responses from formal urban areas by incorporating the $TIA_{\%}$ and $DCIA_{\%}$ values derived in this study. Based on the understanding gained in the analysis of responses from urban areas, further model improvement was demonstrated through the incorporation of pseudo storage volumes derived in this study. Various recommendations for future research are provided in the chapters and these are summarised in the following section. It is emphasised that, although the study was conducted using limited available data, it is postulated that other, ungauged, urban catchments in South Africa will have similar hydrological responses. This will have to be studied further when additional data are available.

8.4 Recommendations

Various recommendations are contained in this thesis. Numerous recommendations were made for improved hydrological modelling of South African urban areas. A number of recommendations were also made for further investigation in future studies. This section provides summaries of both sets of recommendations.

The following recommendations are made for hydrological modelling of South African urban areas:

- Base flow, whether naturally occurring or due to urban activities and infrastructure failure, needs to be incorporated into hydrological models and drainage system design, especially when lower-order flood events are of significance.
- Increased storm runoff volume should be incorporated in the planning and design of urban drainage systems for expanding formal and informal settlements. The derived imperviousness and connectivity values were shown to improve flow volume modelling in formal urban areas. It is recommended that these values be applied in hydrological modelling to plan for increased runoff volumes with development.
- It is proposed that the imperviousness values for urban SANLC classes be used for hydrological modelling of South African urban areas or other areas and regions with similar development characteristics, where site-specific conditions are not easy to quantify.
- Typical representative connectivity values were determined for use in hydrological modelling of South African urban areas. It is proposed that the median values for DCIA in each SANLC residential land use type be used, with sensitivity analyses performed using the 75th percentile and 25th percentile values. The equation developed for industrial and commercial areas is recommended for estimating DCIA from TIA if measured DCIA are not available.
- It was concluded that unexpected attenuation in the formally developed catchments studied in this thesis does contribute to runoff characteristics and it is therefore recommended that it be incorporated in hydrological models of urban catchments with similar characteristics.

The following recommendations are made for future studies:

- The changes in surface runoff should be investigated further by considering trends between Q/P ratios and base flow.
- The causes of increased baseflow in urban catchments in Tshwane need to be further investigated and quantified, since it is expected that this phenomenon will occur in other South African urban areas, as well as urban areas in other water-scarce countries, both in developed and developing regions.
- The proposed drainage connectivity values should be verified through additional field investigation in other South African cities, as well as other cities with similar land uses in other countries. It is also recommended that the direct and indirect connectivity of formal and informal settlements to drainage systems be investigated further.
- The causes of unexpected flow attenuation in South African catchments with formal development need to be further investigated in order to generate realistic attenuation in modelling based on measured attenuation potential. It is recommended that typical storage potential be quantified for properties with urban land cover in South Africa in order to confirm whether the proposed storage values are realistic and the attenuation features need to be examined separately to consider how they are functioning as individual structures. It is also recommended that the parameter values used in this study be tested on additional gauged catchments in other regions in South Africa, and other countries with similar development patterns, to determine whether the results could be applied to all ungauged catchments. It is also recommended that hydraulically realistic outlet dimensions for the pseudo storage areas be investigated and implemented in the model in a future study.
- The statistically insignificant change in T_p, but with increasing flood peaks in Catchment A2H029 is an interesting result that should be investigated further by considering the complexities of increasing impervious areas without increased impervious area connectivity. It is recommended that the methodology be applied in other catchments with informal development, both in South Africa and other regions with similar development patterns, to determine whether this result was unique, or whether this is widely applicable.
- The catchments used for hydrological modelling in this study contain areas with formal development only, due to the sizes of the catchments in this study that contain informal settlements, as well as the locations of rain gauges in the catchments. It is therefore

recommended that the parameter values used in this study be tested on other gauged catchments, particularly catchments with informal settlements, in other regions in South Africa, to determine whether the results are applicable to all ungauged catchments.

- The CN infiltration approach was applied in this study. It is recommended that other infiltration methods be modelled and the results compared to determine whether the CN approach best models South African urban runoff.
- Hydrological modelling of informal settlements with little to no formal drainage should be investigated further, both in South Africa and other regions with similar development patterns, using the improved understanding gained in this study.

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